

REPORT OF THE  
1979 INSTRUMENTATION SUBCOMMITTEE  
of the  
DOE/NSF Nuclear Science Advisory Committee

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Submitted to:

DOE/NSF Nuclear Science Advisory Committee

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## Preamble

Quantitative observation lies at the heart of modern science. The rate of progress in a scientific area is in large measure fixed to the rate at which hypotheses can be tested and refined or unexpected results uncovered. By its very nature this experimental endeavor is an investigation of new phenomena or old phenomena with new techniques. Fundamental advances in man's ability to investigate the atomic nucleus and its interactions are the result of improvements in the characteristics of particle sources or detection systems. The former make available new energy ranges, particle types, or intensities, while the latter provide new capability in resolution or rate of information accumulation.

Present day research in Nuclear Physics represents a remarkable extension of the low-energy light-ion studies that dominated the 1960's. In addition to building on this earlier work with ever more precise experiments, new facets of the nucleus are being revealed with particle beams in excess of 100 MeV, intense meson beams, and a great variety of heavy ion projectiles. These challenge our current descriptions of nuclear phenomena. However, the requisite experimental program puts a serious strain on the instrumentation currently in use in the field. The effects of consumer inflation on more or less constant budgets have made it impossible for most nuclear scientists in the United States to have access to the necessary equipment to carry out these investigations in anything approaching an optimal fashion.

This report examines the problem and recommends to the Department of Energy and National Science Foundation the initial steps to ameliorate this situation. This is but the first of several stages required to obtain the equipment commensurate with the scientific potential of nuclear physics and the competence and dedication of its researchers.

### I. Origin of Subcommittee and Its Charge

Late in 1977 when the Department of Energy (DOE) and the National Science Foundation (NSF) set up the Nuclear Science Advisory Committee, there was a general awareness that science in the U.S. was in a relatively weak position with respect to instrumentation. There is a two-fold explanation for this effect. The budgets for basic research had not kept pace with the inflationary spiral of the 1970's. This fact impacted on instrumentation procurement and development in an especially severe way, as there was an attempt to retain trained manpower in the hope that the fiscal situation would improve. On the other hand the

vigorous support for basic research in Europe and in particular basic nuclear science has provided their research effort with annual allocations well in excess of those in the U.S. Further, because the European programs started to reinstrument at a later time due to various aftereffects of WW II, their overall equipment pool at this time is considerably more up to date.

This situation is recognized at all levels of government and was articulated by President Carter on the occasion of his awarding the National Medal of Science on November 22, 1977.

One of the first actions taken by the Committee was the establishment of a Facility Subpanel. Their immediate task was to evaluate proposals for new construction in FY 1980. The nuclear physics community came forth with several excellent proposals. Those judged to be of highest priority were strongly endorsed by the Committee. Acting on this advice, the DOE and NSF took a significant step toward the goal of providing the facilities needed to keep the nuclear physics effort in the U.S. at the forefront.

It is obvious that in addition to state-of-the-art particle accelerators, appropriate ancillary equipment must also be available. This smaller scale equipment, which includes magnetic spectrometers, detection systems, and data acquisition and analysis systems, is absolutely crucial to make effective use of an accelerator. In late 1977, the Committee set up an internal instrumentation task force to examine this situation and propose a course of action. This task force recommended that a subcommittee with the necessary expertise be set up and charged to come forth with specific recommendations.

The Instrumentation Subcommittee was established in the fall of 1978 and given the following charge:

NAME: 1978 Instrumentation Subcommittee

CHARGE: The Subcommittee shall evaluate the present status of instrumentation in the field of basic nuclear science and evaluate future needs and opportunities in this area. The purview of the Subcommittee is broad. It includes magnetic, solid-state, and electronic devices for detection and measurement of nuclear radiations, ion sources, control systems, data acquisition/analysis systems, and various devices appropriate to particular subfields of nuclear research, but does not include the design and construction of large facilities. The Subcommittee shall pay special attention to areas in which rapidly changing technologies present new, more cost-effective modes for research or present

fundamentally new scientific opportunities. The Subcommittee shall prepare a draft report for modification and approval by the Committee prior to forwarding to DOE and NSF.

The Instrumentation Subcommittee members were selected and appointed by DOE and NSF. The list of Subcommittee members appears in Appendix I. The full Committee membership is shown in Appendix II.

## II. Methodology

At the initial meeting (October 7-8, 1978) of the Instrumentation Subcommittee in Washington, D. C., the charge was examined and discussions were held with Agency personnel.

The Subcommittee Chairman pointed out at this meeting that it was important for the group to keep in mind that the Committee strongly endorsed the recommendations of the Friedlander Panel of the National Academy of Sciences, in particular its Recommendation A.\* Therefore, the Instrumentation Subcommittee should pay particular heed to those aspects of instrumentation that would benefit existing laboratories. It was agreed to set up specific tasks within the Subcommittee to examine each important area of instrumentation in the context of the following questions:

- (1) What is currently in use?
- (2) What is the present state of the art?
- (3) What instrumentation is ripe for development and who should develop it?

The areas delineated for study were determined by consideration of the equipment required to perform a measurement at a facility (from ion source through data analysis). Accelerators and reactors were excluded from the present

\*Recommendation A of the Ad Hoc Panel on the Future of Nuclear Science, NRC, NAS, 1977: To remedy the underutilization of existing facilities, the Panel recommends as its highest priority item an immediate step increase of about 13 per cent in operating support for nuclear science. It further recommends additional increases, as shown in Table 4.2, reaching by fiscal year 1983 a level approximately 60 per cent in real purchasing power above fiscal year 1976. Increased capital equipment budgets, at a level of 12-15 per cent of operating budgets, are also recommended.

study as this subject already attracts the attention of the Facility Subcommittee. The instrumentation requirements for data analysis in terms of specific nuclear models were not considered. The scope of the analysis systems considered was limited to the reduction of data to a model independent format, such as a center of mass differential cross section. The hardware needed for more detailed theoretical analysis of data and the extraction of nuclear structure information was not dealt with. It should be pointed out, however, that the increasing power of the data handling computer systems could prove very useful to nuclear theorists for their calculations.

In the course of the first meeting, the following topics were selected for detailed examination to determine where the greatest advantage for progress in nuclear physics could be had at this time.

1. Ion Sources
2. Beam Transport Systems
3. Targets
4. Electro-Magnetic Spectrometers
5. Detection Systems
6. Electronics
7. Data Acquisition and Control Systems

To more adequately cover these topics, the membership of the Subcommittee was expanded somewhat after the initial meeting. As the list of membership in Appendix I indicates, the Subcommittee was selected from universities, federal laboratories and industry. In addition to specific technical expertise, several of the members possess broad experience in most of the important areas of nuclear science.

One of the pieces of information needed by the Subcommittee was the fraction of the available funds expended on instrumentation. This proved to be difficult to determine because the great bulk of instrumentation development in nuclear physics is carried out within research groups motivated by specific nuclear physics goals. A readily accessible data base from which these expenditures could be reliably extracted does not exist because of the small size of directly funded instrumentation efforts. The tabulation of the annual Capital Equipment Expenditures of AEC/ERDA/DOE is available and useful, but it only serves as a relative indicator of the history of instrumentation expenditures. It does not provide a complete picture, as it need not include the manpower costs involved in development and, for example, certain important classes



of large detectors are not procured with funds from this budget category.

In order to obtain the required data on how funds are allocated to instrumentation, the chairman of the present Subcommittee sent a written inquiry to DOE and NSF laboratories receiving \$350K/year or more. Information was requested on the relative expenditure of manpower and dollars on instrumentation as well as specific information on each laboratory's data acquisition system, large special purpose equipment and their future plans and priorities. The laboratories responded well and a workable picture of the institutional aspects of the instrumentation needs and opportunities was achieved.

Each of the task forces covering the seven topics listed on the previous page generated reports in their respective areas. This information was distributed among the Subcommittee members and extensively discussed at a two-day meeting in Washington, D. C. on May 19-20, 1979. At this meeting the final set of recommendations of the entire Subcommittee were formulated. In addition, the Subcommittee considered procedural changes that could help to deal with the general problem of assuring adequate balance in instrumentation allocations in the future.

Specific recommendations appearing in each of the task force requests were considered with an eye to their overall significance, realizability, and timeliness. In addition to the highest priority recommendations, which are presented in Section IV, there are several important recommendations appearing in each of the task force reports. The reports appear in Appendix III. The recommendations appearing in the texts of the individual reports are supported by the entire Subcommittee.

### III. General Findings

As was mentioned earlier, the AEC/ERDA/DOE Capital Equipment allocation is a readily accessible indicator of the relative investment in instrumentation as a function of time. Figure 1a shows the ratio (expressed as a percentage) of the Capital Equipment allocation to operating budget on a yearly basis. In the four fiscal years prior to 1970, the ratio was 13%, while from 1974 to 1977, it dropped to 8.1%, a reduction of 38% in this potentially crucial index. It should be noted that there has been a slight increase in the relative allocation to capital equipment over the past two years with the two-year average rising to 9.5%. Figure 1b shows those Capital Equipment expenditures in  $10^6$ \$/Y, taking account of inflation via the Consumer Price Index. The shape of this curve is very similar to that of Fig. 1a except that the ratio of the actual expenditure for '74-'77

FIGURE 1a.

### RATIO OF CAPITAL EQUIPMENT ALLOCATION TO OPERATING BUDGET AEC/ERDA/DOE

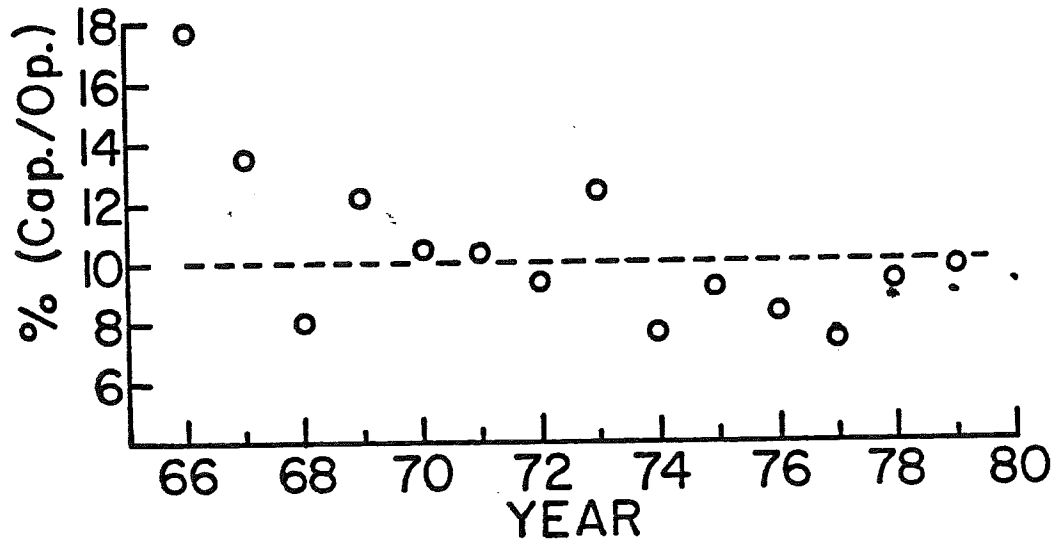
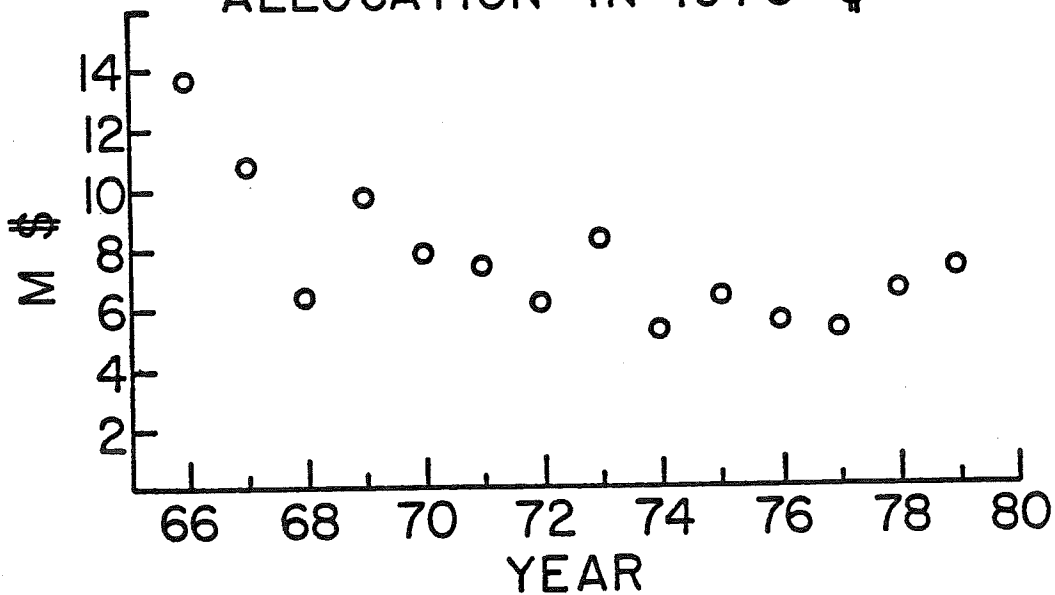


FIGURE 1b.

### AEC/ERDA/DOE CAPITAL EQUIPMENT ALLOCATION IN 1976 \$



to that of '66-'69 shows a reduction of 44%. The relatively larger reduction in this instance reflects the fact that the operating budgets were also lagging inflation during the middle seventies. Taking these results at face value would indicate a substantial reduction in the equipment investment by AEC/ERDA/DOE during the bulk of the '70's.

The situation within the NSF university laboratories is apparently far more serious. It is difficult to produce a simple, well-documented case for this assertion as the NSF does not identify a separate capital equipment budget. Figure 2 shows some results gleaned from the responses to our questionnaire. For each laboratory the ratio of salaries plus purchases directly attributable to instrumentation compared to their total federal operating grant is plotted. One notes seven NSF university laboratories clustered about the 10% level. Of the four NSF laboratories above 20%, one is Indiana University, a new and large cyclotron laboratory. Two of the other three receive strong state support, which substantially supplements their equipment expenditures. The value of these supplements is included and this causes their ratio to be above the 10% level. Recently the NSF initiated a review of 11 of their university-based low energy nuclear physics laboratories. Three laboratories were selected in this review as deserving of especially favored treatment because of their productivity and promise. It is striking to note that the three laboratories selected were the three laboratories (excluding Indiana, which was not in the review) investing more than 20% of their budgets in instrumentation. While there are likely many complicating factors, there appears to be information gained from this exercise. It may be useful to pay more attention to the funds spent on instrumentation as it ought to lead to achieving a better balance of a laboratory's resources and avoid serious damage to an institution's viability.

One of the best documented cases of the impact of inflation on a university laboratory can be found in the recent report of the Ad Hoc NSF laboratory review committee mentioned above. Table 1 was prepared by the Stanford University Tandem Van de Graaff laboratory as part of the review and is reproduced here with their permission. This table shows the combined impact of inflation, increased employee benefits and university overhead rates on the funds available for research over the past decade. One sees more than a two-fold decrease in the funds available for the performance of research. The expenditure on capital equipment at this laboratory over the period '74-'77 was 10.8K/year. This is 2% of their operating budget, a level far too small to be sustained for any period without seriously affecting the health of the laboratory. Indeed, unless strong positive measures are taken to remedy the effects of sustained under-investment, laboratories in this situation will cease to be effective.

### FRACTION OF FEDERAL OPERATING BUDGET SPENT ON INSTRUMENTATION

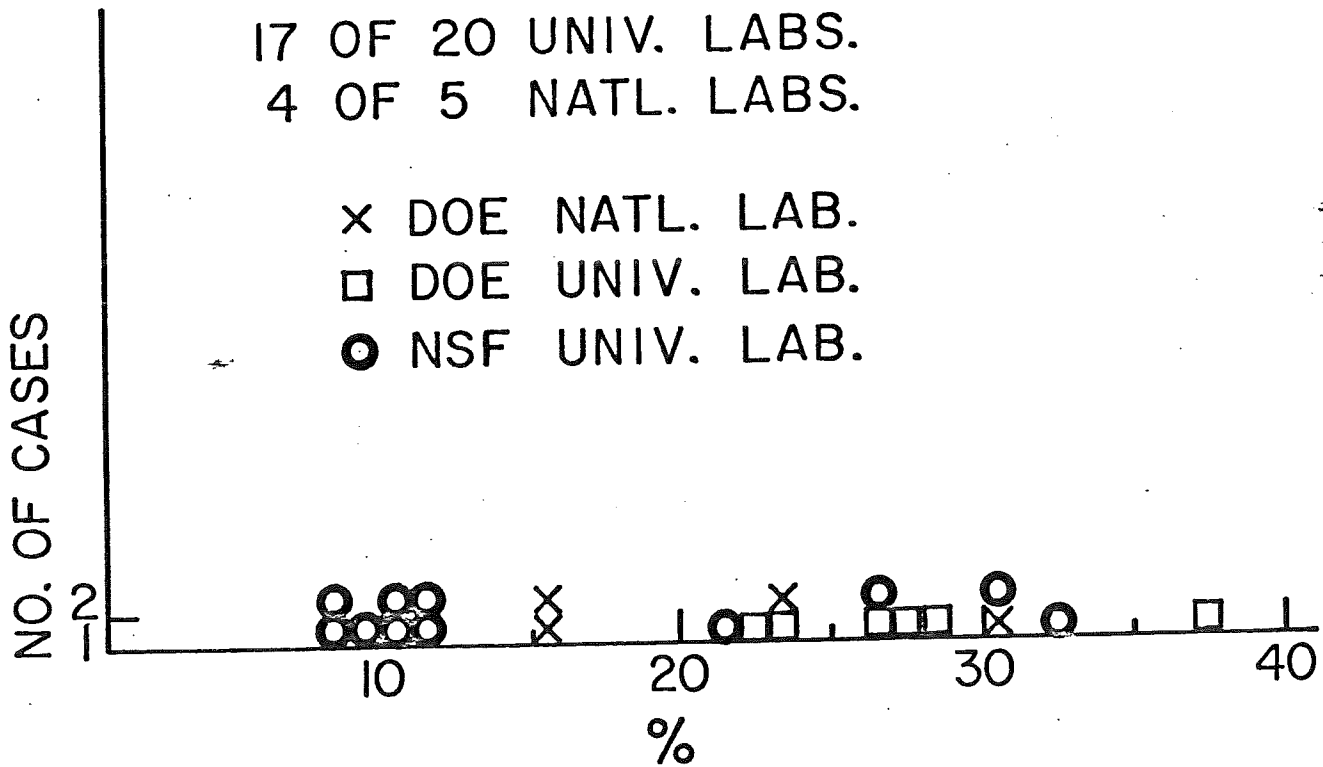


FIGURE 2.

Providing state-of-the-art instrumentation at university laboratories has the additional benefit of making experimental nuclear physics far more attractive to graduate students in the process of selecting an area of study.

Data acquisition systems play an essential role in how experiments are designed and executed. After the accelerator proper, the acquisition system is apt to be the most important piece of hardware in a nuclear experiment. Figure 3 is a plot of the age (as of January 3, 1979) of data acquisition systems at university accelerator laboratories. There are several problem teenagers evident in this group. A slash through a check indicates that the laboratory has funds in hand to obtain a new system. The average age of the computers in this group is 7.7 years with a median age of 9.0 years. The standard practice of the federal government is to amortize the cost of a computer over 7.0 years which in equilibrium would produce an average computer age of 3.5 years. However, more important than any statistical argument is the fact that the complexity of nuclear science has increased several fold since these older data acquisition systems were purchased. Heavy ion experiments, which are carried out at most of these laboratories, produce complex final states requiring multiple coincidence measurements to characterize the reaction completely. These experiments are very difficult if not impossible with the older acquisition systems. These systems have limited volume, limited rate capability, and are not easily adapted for the sorting of multiparameter data. It is clear to us that these outdated and inadequate systems must be quickly upgraded if laboratories are to remain competitive. The inventory of the computers in use at the facilities surveyed is shown in Appendix III, pages 67 & 68.

### Recommendations

Based on our professional experience, our survey of the present situation and the reports of the task forces, we believe that serious problem areas exist in the present instrumentation resources in nuclear physics. The following set of recommendations are put forth as a start to correct these problems and to take advantage of opportunities which can produce significant impact on the experimental study of the atomic nucleus.

\* \* \* \* \*

### AGE OF DATA ACQUISITION SYSTEMS AT UNIV. ACC. LABORATORIES

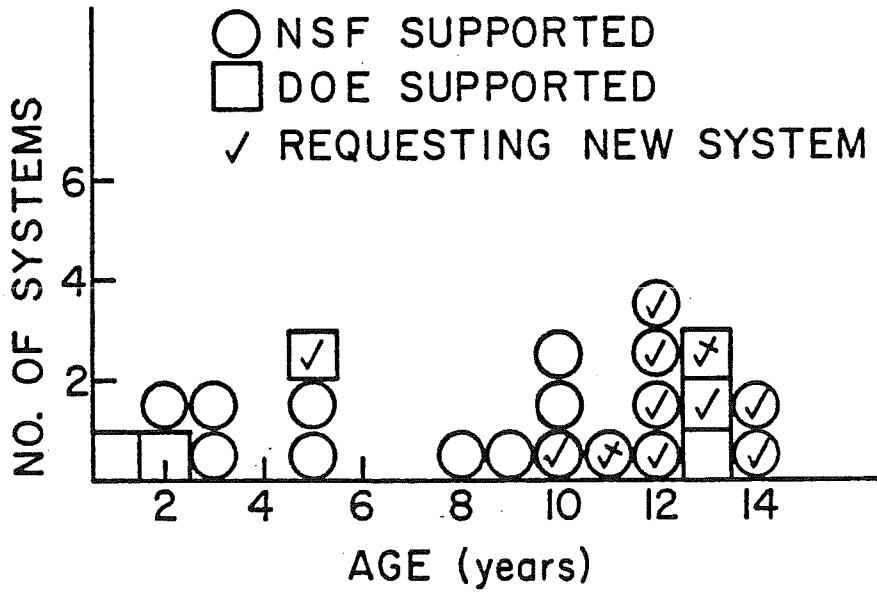


FIGURE 3.

Table 1  
 STANFORD UNIVERSITY  
 TANDEM ACCELERATOR LABORATORY

Year	(Local \$)	NSF Budget (Constant 67 \$) (thousands)	Fringe Benefits %	Overhead Rate* %	(Local \$)	Net Budget (Constant 69 \$) (thousands)
1969	471	471	11.8	57.0 (S&W)	312	312
1970	480	453	12.7	59.0 (S&W)	311	295
1971	470	422	14.6	59.0 (S&W) 46.0 (MTC)	300	275
1972	460	398	16.0	46.0 (MTC)	287	254
1973	485	404	16.7	46.0 (MTC)	300	245
1974	530	405	17.5	47.0 (MTC)	324	235
1975	546	376	17.6	47.0 (MTC)	345	234
1976	550	354	17.4	56.5 (MTC)	318	206
1977	560	335	19.5	58.0 (MTC)	321	195
1978	483	270	20.4	58.0 (MTC)	303	168
1979	500	260	20.4	58.0 (MTC)	280	141

\*Overhead rates given as appropriate to salaries and wages (S & W) or modified total cost (MTC).

In a complex, quantitative subject like nuclear physics, the speed and ease with which large amounts of information can be stored, sorted and manipulated sets the pace for how rapidly progress can be realized. Fortunately, the computer industry has been developing extremely fast, high-volume systems that are potentially well suited to the needs of nuclear research. These systems need to be brought to bear on both data acquisition and data analysis activities. Therefore:

- I. As our highest priority we recommend that a pulse of \$6M be provided over the next two (2) years to bring the hardware of presently outdated data acquisition and analysis systems to an acceptable level.

This recommendation receives highest priority because many subsequent instrumentation choices depend on the capability of the acquisition and analysis systems available. Recommendations made on future instrumentation must assume a digital capability at a laboratory consistent with its size. Given the complexity of the required experimental program and the potential capacity of the new systems, standardization of significant parts of both software and hardware is required. However, to enjoy the benefits of standardization the great bulk of the laboratories will have to be in a position to employ them. For example, standardization via CAMAC will allow the cost effective use of large numbers of ADC's that would be either difficult or expensive to realize with other approaches. The analysis of complex experiments is found to proceed much more rapidly and easily via the use of high level array-oriented languages such as SPEAKEASY. A language of this complexity has requirements on minimum memory size and needs to be adapted to specific operating systems. The \$6M figure allows the university and federal labs whose systems have become outmoded to both catch up and be in a position to enjoy the new developments in this fast-moving area. We recognize that this increased investment in digital hardware and associated peripheral equipment will place severe software demands on the nuclear physics community. This should be used as an opportunity to develop much more interaction throughout nuclear physics and related sciences in a constructive program of software sharing and development. Ten years elapsed between the Sky Top Conference and the recent Santa Fe meeting! This is strong evidence that communication in this very important area of instrumentation is deficient. More visibility, interaction and planning are needed to avoid needless duplication of effort. A set of useful suggestions are set out in the report of the Data Acquisition and Analysis Subgroup found in Appendix III.

\* \* \* \* \*



Ion sources recently developed in Europe show that considerably higher charge states can be produced. The Electron Cyclotron Resonance (ECR) source and the Electron Beam Ion Source (EBIS) represent developments that can increase the useful charge state by a factor of at least 50% above that available with ion sources currently in use. As the beam energy available from a cyclotron varies as the square of the ion charge, the ion beam energy can be more than doubled if these sources can be effectively developed and engineered. As this represents a target of opportunity for development having a potentially large payoff, our next highest priority is as follows:

- II. Two advanced high charge state heavy ion sources have been investigated in Europe, the Electron Cyclotron Resonance (ECR) Source and the Electron Beam Ion Source (EBIS). These sources can significantly increase heavy ion beam energies from existing cyclotrons as well as from future cyclotrons and linear accelerators. We recommend development programs at U.S. laboratories to further develop these sources. The work undertaken should build on the experience gained abroad.

A more complete description of these ion sources is to be found in the section on multiply-charged ion sources in Appendix III.

\* \* \* \* \*

Polarized hydrogen ion sources have undergone rapid development over the past few years. Many high energy physics installations (ZGS, CERN) have taken advantage of these developments which were carried out in nuclear physics laboratories. The use of these ion sources in nuclear physics will advance our understanding of nuclear structure and reactions and will make possible significant tests of time reversal invariance as well as measurements of the weak interactions between hadrons. Thus, our third recommendation is:

- III. Polarized ion sources are now available which can provide a factor of more than 30 increase in intensity over sources presently in use. We therefore recommend that laboratories doing forefront work requiring polarized hydrogen beams should be provided new or suitably upgraded sources.

Further discussion on the background and operating principles of these sources is to be found in the section in Appendix III on polarized ion sources.

\* \* \* \* \*

It is the general feeling of the Subcommittee that the instrumentation needs in nuclear physics are not receiving sufficient attention or an appropriate share of resources. It has however proved extremely difficult to spell out what constitutes the appropriate level of investment. The level of approximately 10% at which several of the NSF laboratories function is clearly too low. This level is limiting what otherwise can be accomplished by intelligent and resourceful scientists in an internationally competitive field like nuclear physics. They must also have the apparatus to carry through their ideas in a reasonable time. The Facilities Subcommittee has done much to regenerate interest in new accelerators and has provided advice on a sound construction plan for FY '80 and more recently for FY '81. We believe that instrumentation would also benefit from similar exposure and discussion. Therefore, we recommend the following procedure be tested for the next three (3) years:

- IV, The optimal balance between operating, new construction and equipment budgets is not clearly understood at present. In order to provide DOE and NSF with useful advice on that balance it is recommended that an Instrumentation Subcommittee be formed. This Subcommittee should provide an annual report with recommendations to the full Committee.

Some members of the Committee feel this task would be difficult to carry out and might unduly interfere with appropriate decision making processes. They caution that it may put too many hurdles in the way of actually carrying out an experiment requiring substantial equipment, particularly in instances where the user mode of operation is involved. In the judgment of the entire Committee, however, it was felt that the potential gains of recommendation IV outweigh the possible difficulties and further that some group must be charged with the responsibility of acquiring a broad view of instrumentation development within the national nuclear physics effort.

\* \* \* \* \*

In the course of carrying out this study, we became acutely aware of the difficulty of obtaining reliable manpower and budgetary data on the annual expenditures on instrumentation maintenance and development. We believe this number to be a significant and possible sensitive indicator of the good health of both individual laboratories and the field as a whole. It is evident that there will be a broad distribution in the relative and absolute investment in instrumentation depending on the specific nature of the research and the style at a given laboratory. However, as pointed out in Section III the results of the NSF Laboratory Review and our Figure 2 indicate that further study would be

potentially useful and possibly a stronger justification of the appropriate level of investment in instrumentation can be developed.

- V. We recommend that the DOE and NSF keep satisfactory estimates of the annual expenditures for instrumentation development at each installation. To provide a clear picture, these estimates must include, in addition to the federal support, other support available to the laboratory.

These estimates should be prepared at the end of a fiscal year. Therefore, effort should be expended to collect the information for FY 1979. In order that the estimates for instrumentation be consistent from lab to lab, we suggest that the entire laboratory budget be divided into appropriate categories. The resulting information would represent a very different cut through expenditures in nuclear physics and should prove useful to other advisory committees in the agencies.

\* \* \* \* \*

#### Concluding Remarks

It goes without saying that there are many specific areas of instrumentation that could prove to be of great benefit to nuclear science if they were pushed more vigorously. However, the Subcommittee was much against generic instrumentation development. In each case where recommendations are made, it is to specific solutions. While detector development is clearly crucial to the advancement of nuclear physics, it has to be tied to the interest and competence of specific individuals who either wish to do development per se or need to develop detectors for specific physics problems. We therefore see detector development as an intrinsic part of nuclear physics and believe that the support provided to this area can readily be judged scientific competition with the other components of the research program.

There were important areas that were not addressed; among them were the appropriate computational facilities for nuclear theory and the role of user groups in instrumentation development.

In response to our charge, we unanimously support the five (5) recommendations presented in the previous section and urge their implementation. They represent a solid first step toward providing the instrumentation needed in nuclear science.

Appendix I

DOE/NSF Nuclear Science Advisory Committee  
Instrumentation Subcommittee 1978-1979

- Gerald T. Garvey - Argonne National Laboratory (Chairman)
- Robert L. Burman - Los Alamos Scientific Laboratory
- Lawrence S. Cardman - University of Illinois
- David J. Clark - Lawrence Berkeley Laboratory
- Ralph M. DeVries - Los Alamos Scientific Laboratory
- Harald A. Enge - Massachusetts Institute of Technology
- Kazuo Gotow - Virginia Polytechnic Institute and State  
University
- Willi Haeberli - University of Wisconsin
- David C. Hensley - Oak Ridge National Laboratory
- Walter LeCroy - LeCroy Research Systems Corporation
- Roy Middleton - University of Pennsylvania
- Veljko Radeka - Brookhaven National Laboratory
- Keith Rich - Stanford Linear Accelerator Center
- R. G. H. Robertson - Michigan State University

Appendix II

DOE/NSF Nuclear Science Advisory Committee 1979

- H. Feshbach - Massachusetts Institute of Technology  
(Chairman)
- F. Ajzenberg-Selove - University of Pennsylvania
- P. D. Barnes - Carnegie-Mellon University
- G. E. Brown - State University of New York at Stony Brook
- R. M. DeVries - Los Alamos Scientific Laboratory
- W. A. Fowler - California Institute of Technology
- G. T. Garvey - Argonne National Laboratory
- W. Haeberli - University of Wisconsin
- I. Halpern - University of Washington
- B. G. Harvey - Lawrence Berkeley Laboratory
- J. R. Huizenga - University of Rochester
- E. A. Knapp - Los Alamos Scientific Laboratory
- R. E. Pollock - Indiana University
- D. Robson - Florida State University
- T. T. Sugihara - Texas A&M University
- J. D. Walecka - Stanford University

### Appendix III

## REPORTS OF INSTRUMENTATION TASK FORCES

### 1. ION SOURCES

#### Introduction

It is difficult to overstate the impact that ion source development has had on the field of nuclear science. The invention of the Penning source and its subsequent development over the years has had a profound effect on the performance of numerous cyclotrons and linear accelerators enabling a wide variety of heavy ions to be accelerated to increasingly higher energies. The past decade has seen enormous strides in negative ion source development and the present-day sputter source is capable of generating microampere beams of almost all elements of the periodic table and allows ion species at tandem accelerators to be charged in a matter of minutes. There has also been a continued development of both negative and positive polarized ion sources which has added new capability for nuclear research.

It is also noteworthy that a major ion source development not only expands and broadens the capabilities of an existing accelerator but might also influence the direction of future accelerator development. For example, if a continuous duty source could be developed capable of producing microampere beams with charge states about a factor of two higher than is presently available from a high-powered Penning source, accelerator engineers would have to re-think the most cost-effective way of proceeding. Such a source coupled to a single cyclotron may be comparable in performance to two coupled cyclotrons and less expensive.

In spite of the importance of ion source development to nuclear science there is relatively little funding for ion source development per se. Much of the ion source research in the USA--particularly that directly related to nuclear science--is carried on in universities and national laboratories as an adjunct to an on-going program of nuclear research and is frequently motivated by a specific nuclear research problem. Whether this is an effective procedure is an open question. On the one hand the U.S. probably leads the world in negative ion source and polarized ion source development but appears to have lost the initiative in developing multiply-charged ion sources. In Europe the extremely promising electron cyclotron resonance source has been developed by Geller at Grenoble and similar sources are being actively developed in at least two other laboratories. Also the electron beam ion source has been demonstrated at Dubna and Orsay.

It is also worthy of comment that ion source development is incredibly fragmented and there are numerous groups engaged in research for reasons unrelated to nuclear science. For example, much ion source development is related to ion implantation, space propulsion, fusion, mass spectrometry, ion microprobes, X-ray lasers, particle physics, weaponry, etc. Since the results of this work are published in an amazing diversity of journals, it is questionable whether there is adequate cross fertilization.

The remainder of this document is devoted to summarizing the present status of development of (1) negative ion sources, (2) polarized ion sources, and (3) multiply-charged ion sources. The desirable features for ion sources include long lifetime, good emittance, a duty factor to match the accelerator (100% for cyclotrons and electrostatic accelerators). In the case of (1) and (3) the availability of the maximum number of atomic species is required.

### Negative Ion Sources

Prior to 1950, negative ions were essentially a scientific curiosity seemingly having no practical application. The arrival of the tandem accelerator in the late 1950's drastically changed the situation and spurred the development of the first negative ion sources. The early sources, which frequently were modified positive ion sources, had poor yields, large emittance and the number of ion species was extremely limited. Since then, tandems have steadily grown in size and several are actively being developed as injectors for cyclotrons and linacs to boost the energy even higher. Needless to say, the availability of increased energy allows the study of nuclear reactions with heavier projectiles and this has prompted the development of "dedicated" negative ion sources capable of generating microampere beams of essentially all elements of the periodic table. Furthermore, sources have had to be developed with improved emittance to minimize accelerator loading and with low energy spread to enable sub-nanosecond bunching.

Although tandem accelerators have prompted most negative ion source development, not very surprisingly other applications of negative ions have emerged and have spurred the development of highly specialized sources. For example, extremely intense negative hydrogen sources are currently being developed in several laboratories for use with linear accelerators, synchrotrons, cyclotrons and a variety of fusion devices. Other growing applications are in negative ion mass spectrometry and microprobe analysis.

## Present Status

One of the major discoveries of the late 1960's was the near resonant process for producing negative helium ions which occur when low velocity ( $\sim 1$  keV) positive helium ions are passed through cesium vapor. Shortly thereafter it was demonstrated that several microamps of  $\text{He}^-$  ions could be generated by charge exchange in lithium vapor at a more convenient energy of about 20 keV. It was also shown that this method could be very profitably used to generate moderately intense beams of other ions such as carbon, nitrogen ( $\text{NH}^-$  or  $\text{NH}_2^-$ ) and oxygen. However, the full potential and generality of the technique were not appreciated until the comparatively recent work of Heinemeer and Tykesson. These scientists have made a systematic study of equilibrium charge state distributions for 10 - 90 keV heavy-ion beams in charge exchange with Na and Mg vapors and have shown that the negative ion fractions are generally in the range 1% to 90%--considerably higher than had previously been thought. When coupled with the many advances that have been made in positive ion source development, particularly for ion implantation, this method of making negative ions remains powerful and in some instances possibly the best method.

Closely related to charge exchange is the method of Gentner and Hortig for producing negative ions. They showed that if a beam of relatively heavy positive ions such as argon is passed through a canal containing, for example, oxygen gas, a relatively intense beam of  $\text{O}^-$  ions can be directly extracted from the canal. The method is commonly used to produce negative ion beams of lithium and it has recently been demonstrated at the University of Pennsylvania that if cesium positive ions are used rather than argon, the  $\text{Li}^-$  output is increased by about an order of magnitude ( $\sim 10$   $\mu\text{A}$ ). The method has considerable promise for all of the alkali metals and possibly also for the group II elements.

During 1973/74 a new type of negative ion source was developed by Middleton and Adams at the University of Pennsylvania that enabled negative ions to be generated directly from a solid surface under the action of cesium ion sputtering. The source has several advantages and has been widely adopted by most tandems as a general "workhorse". These include moderate-to-high intensity for practically all elements of the periodic table, extremely rapid change of ion species, low energy spread and reliability of operation (typically 500 to 1000 hours before a major strip-down). Early versions of the source had undesirably large emittance but improvements by several workers have reduced this to about 6 mm mrad  $\text{MeV}^{-\frac{1}{2}}$  which is well within the acceptance of most tandems.



During 1974/75 a new and important negative ion source was developed at the University of Aarhus. Basically this consisted of a direct radial extraction Penning source, the discharge of which was seeded with cesium vapor. The novel feature of the source was the inclusion of a third sputter cathode facing the extraction aperture. Although the performance of this source is generally comparable to that developed by Middleton and Adams, in some respects it is complementary. For example, it typically produces close to an order of magnitude more current for elements, such as copper, that sputter readily and less current for elements that are difficult to sputter.

Very recently an extremely simple new type of negative ion source has been independently developed at the Universities of Wisconsin and Pennsylvania. This source combines the virtues of the Aarhus and Middleton sources and not only produces significantly more current but appears to have reduced emittance. Figure III-1 shows a sketch of the source developed at Pennsylvania and Table III-1 lists some of the currents that have been obtained.

## Conclusions

Generally speaking, the status of negative ion source development in the USA is healthy and has come close to satisfying the demands of the new generation of large tandems and tandem-booster combinations. However, it should be emphasized that although some of the new breeds of sources are capable of generating intense beams of a wide range of elements, none are truly universal and certain elements require specialized sources--this is particularly true for the alkali and alkaline earth metals. Another outstanding problem is that of producing negative ion beams of rare isotopes such as  $^{48}\text{Ca}$ . There appear to be two approaches to such problems and neither has been satisfactorily solved. One is to design an extremely efficient source requiring an extremely small sputter target and the other is to design an extremely intense source so that the natural element can be used and the isotope separated by the negative ion inflection magnet. For example, a source capable of producing a little over 100  $\mu\text{A}$  of  $^{40}\text{Ca}$  would yield a useful 0.2  $\mu\text{A}$  of  $^{48}\text{Ca}$ .

Finally, it is noteworthy that although the present outlook for double negative ions is bleak (see reference), little, if any, work has been directed at attempting to make double negative molecules. Microampere beams of  $\text{XH}_n^-$  would be extremely useful even for low values of X.

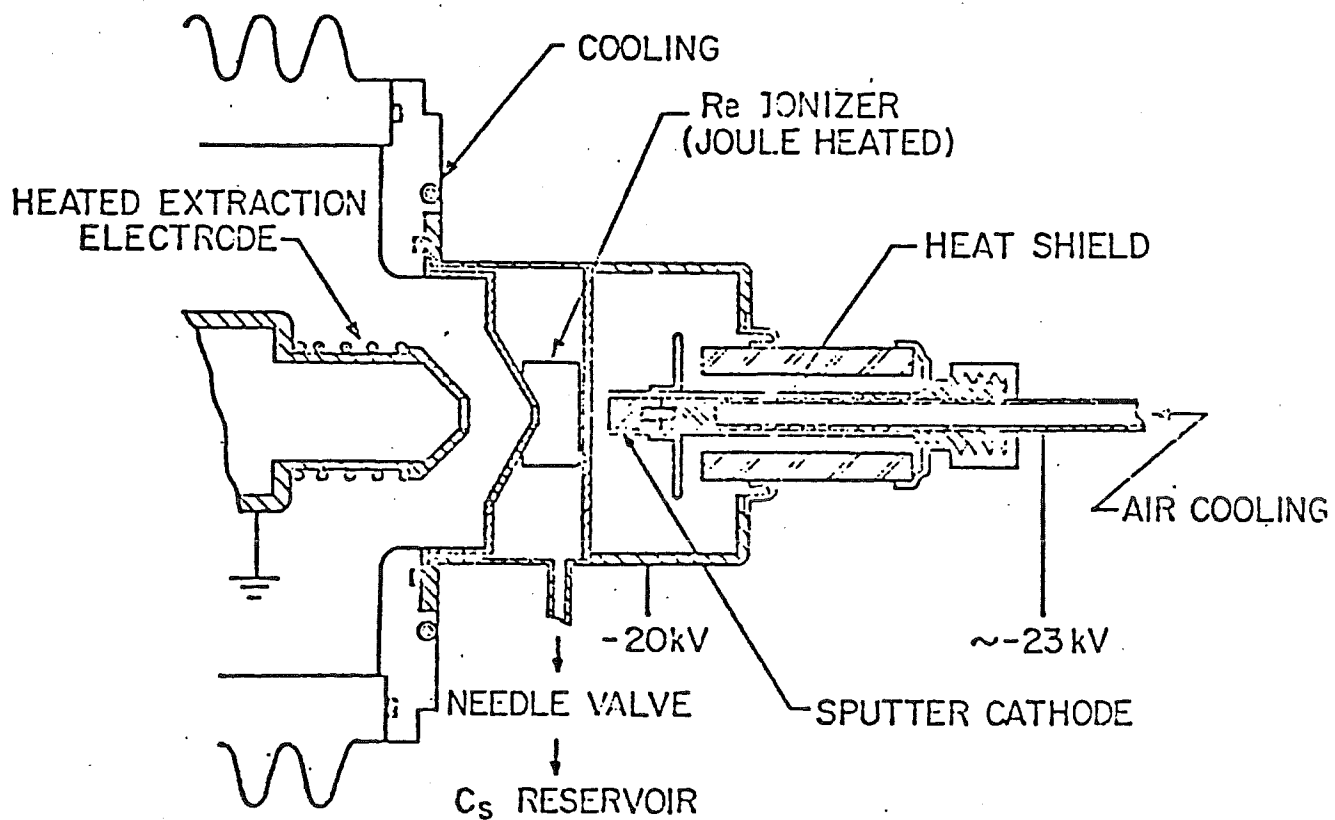


FIGURE III.1

Table III-1

<u>Ion</u>	<u>I<sup>-</sup> (μA)</u>	<u>Cathode</u>
H <sup>-</sup>	40 - 60	1/8" diam. by 1/8" thick titanium pill loaded with H <sub>2</sub> gas
<sup>12</sup> C <sup>-</sup>	60 - 150	1/8" diam. graphite pill
<sup>27</sup> Al <sup>-</sup>	~1.0	1/4" diam. aluminum cathode
Al <sub>2</sub> <sup>-</sup>	~12	
<sup>28</sup> Si <sup>-</sup>	20 - 40	1/8" diam. piece of silicon crystal
<sup>48</sup> TiH <sup>-</sup>	4.1	same cathode as used for H <sup>-</sup>
<sup>59</sup> Co <sup>-</sup>	10 - 23	1/8" diam. pill of cobalt
<sup>56</sup> Fe <sup>-</sup>	2 - 3	
<sup>58</sup> Ni <sup>-</sup>	40 - 60	1/4" diam. nickel cathode
<sup>63</sup> Cu <sup>-</sup>	40 - 70	1/4" diam. copper cathode
<sup>107</sup> Ag <sup>-</sup>	20	1/8" diam. pill of silver
Pt <sup>-</sup>	10 - 35	Small natural platinum nugget mounted in 1/4" diameter aluminum cathode

## Multiply Charged Ion Sources

At nuclear science accelerators, the positive ion sources used for protons and deuterons are usually PIG sources at cyclotrons and duoplasmatrons for injecting linacs such as LAMPF. They produce adequate beams and have been extensively optimized over many years, so the following discussion will concentrate on existing heavy ion sources, used in cyclotrons and linear accelerators, and advanced heavy ion sources which offer opportunities to upgrade accelerator performance.

The requirements for a heavy ion source are the production of beams of all atomic species, with intensities of a few microamps to milliamps, and large duty factor. For cyclotrons the highest possible charge states should be available, because energy is proportional to the square of ion charge. For future linear accelerators, higher charge states can reduce the length, and thus the cost of the accelerator structure needed to reach a given energy.

The production of positive ions is accomplished by electron bombardment. The creation of a required ion charge state requires that the ion be contained for a sufficient time so that the electron flux increases the charge state by successive ionization, Auger processes, and multielectron shake-off. The electron energy spectrum should contain energies of at least several times the highest ionization potential in the process. The background pressure should be low enough to prevent charge exchange ( $10^{-9}$  torr for very high charge states).

The source now used for cyclotrons and heavy ion linear accelerators is the PIG (Penning Ion Gauge) source. It uses metal cathodes to produce a high density electron flux in a uniform magnetic field. The plasma is about 10 cm long by 1 cm in diameter. It produces beams of all ions, dc or pulsed, with 10's of milliamps total intensity for the sum of all charge states. The highest charge states for microamp intensities are, for example,  $N^{5+}$  and  $Ar^{8+}$ . The limitations for high charge state production are the limited containment time (drift time over a few cm) and high background pressure.

One type of advanced heavy ion source which produces higher charge states than the PIG source is the Electron Cyclotron Resonance (ECR) source. This source uses microwave power to heat electrons in a magnetic mirror plasma confinement chamber. The chamber is about one meter long and 30 cm diameter. It produces continuous beams of tens to hundreds of microamps (sum of all charge states), and microamp beams of  $N^{7+}$  and  $Ar^{12+}$ . The ECR source can therefore double the energy of a cyclotron for ions heavier than carbon, with microamp source intensities. Its performance is superior to the PIG for high charge states because the mirror magnetic

field provides electron confinement which in turn gives ion confinement, and the two-stage design provides plasma formation in the first stage and very good vacuum in the second stage where the high charge states are produced. Electron energies can easily be tens of keV. The development of this source had taken place mainly at CEN, Grenoble, France, using an existing plasma machine. This source has now been shut down because it consumes 3 megawatts of power. It can however be duplicated using superconducting coils. Uranium beams have been run for a day in the first stage as a test, without problems. Laboratories at Karlsruhe and Darmstadt, Germany, and Louvain, Belgium, are developing sources of this type. Optimization of source geometry, increase of the magnetic field, and improved pumping are expected to produce even higher charge states. An R&D program would require about \$2M and duplication of the optimized source \$1-2M.

Another promising type of advanced heavy ion source is the Electron Beam Ion Source (EBIS) developed at Dubna, USSR, and elsewhere. This source uses an electron beam of 5-10 kV, in a solenoid magnet to produce successive ionization. The solenoid is about one meter long, and is superconducting in the high performance versions. The EBIS uses a batch process, in which a group of ions is created during some milliseconds of confinement and then extracted. High charge states have been demonstrated at Dubna and Orsay, France, such as  $C^{6+}$  and  $Ar^{16-18+}$ . Intensities are typically  $10^8-10^{10}$  particles/pulse. Dubna has built a source for synchrotron injection. Orsay is constructing a source for a synchrotron, has done experiments at high repetition rate, and has recent data on high charge states in a very short confinement time, indicating an unusually high density electron beam. More development work is expected to produce the fast repetition rates of 10-100 Hz and duty factors up to 50% useful for cyclotrons, and production of beams from solid materials. The cost of an R&D program and duplication of an optimized source are each estimated at \$1-2M.

The ECR and EBIS sources both offer potential for further development. The ECR source has the advantage of dc beams while the EBIS has higher charge states at high masses. The costs are similar. Their application is that of at least doubling cyclotron energies for external beam intensities of  $10^{10}-10^{11}$ /sec by installation on axial injection systems at 10-50 kV.

There is some work in progress on developing laser sources for high charge state production. This uses the high peak power density of a laser pulse hitting a solid surface. High charge states such as  $Ti^{20+}$  have been observed for power densities of  $10^{15}$  watts/cm<sup>2</sup>. A portion of the ablation plume can be accelerated by an extraction system. Some research of this type is in progress at the University of Arkansas, where a power density of  $10^{11}$  watts/cm<sup>2</sup> is producing 6 mA

peak ( $5\mu\text{A}$  average) of ions such as  $\text{Al}^{3+}$  at 50 Hz repetition rate. The highest charge states seen are  $\text{C}^{4+}$  and  $\text{Al}^{6+}$ , for example, similar to those of a PIG source. The repetition rate can be increased to 400 pulses/sec. The laser is capable of high charge state production, but its duty factor is low. It lacks the fast repetition rate of the EBIS for the highest charge states, or the continuous beams of the PIG or ECR source.

Several other ideas for high charge state production are in the early study phase. These include the PROBIS which would use proton beams for ionization in a system similar to the EBIS, and the MIGMA concept which would use colliding beams of protons and heavy ions in a mirror-type magnet.

### Polarized Sources

There are two established ways to produce polarized beams of protons or deuterons: (1) Atomic-beam sources in which separation of spin states is accomplished with inhomogeneous magnetic fields (Stern-Gerlach separation), with subsequent ionization of the atoms by electron bombardment; and (2) Lamb-shift sources, in which polarized H-atoms in the metastable ( $2S$ ) excited state are produced by selective quenching, with subsequent ionization by charge exchange in a gas or vapor. In the U.S. Lamb-shift sources are used exclusively to produce negative hydrogen ions by charge exchange in Ar. In the U.S. five tandems and LAMPF are equipped with such sources to provide polarized beams of protons and deuterons, while atomic-beam sources are used to provide positive polarized ions for acceleration in three cyclotrons and one single-ended electrostatic accelerator. In addition, atomic beam sources are used in two tandem laboratories in which case the required negative polarized ions are obtained from the primary positive ion beam by charge exchange in alkali vapor.

The Lamb-shift sources installed on five tandems were all built in-house. Some of these have continually been improved step by step over the last few years (e.g., University of Washington). At the University of North Carolina a project has been funded to improve the beam intensity of the TUNL source. The goal is to obtain  $1\mu\text{A}$  source output. This is to be compared to less than  $0.1\mu\text{A}$  on some of the sources now in use.

The most intense beam of polarized negative ions ( $3\mu\text{A}$ ) was recently obtained from a test device at the University of Wisconsin. This device employs a new principle and the University of Wisconsin has been provided funds to build in-house an ion source for installation on their EN Tandem. The device uses a colliding-beam method; collision of polarized thermal H atoms with fast  $\text{Cs}^0$  atoms to produce polarized  $\text{H}^-$ .

The patent is owned by the U.S. government and a license to produce the device commercially has been granted to ANAC, a company which produced most of the atomic-beam polarized sources in use.

Upgrading to a colliding-beam source would be particularly cost effective for tandems which now use atomic-beam sources, because in this case a substantial part of the equipment is already available. In addition, compared to the present beam intensity from these sources (of the order 0.1  $\mu$ A or less) the expected improvement is large. At LAMPF an increase in beam intensity by a factor  $\sim 20$  should be obtained if the current source were replaced by a colliding-beam source. Replacement of tandem Lamb-shift sources by sources yielding higher intensity should be supported in cases where this will permit aggressive research programs in new directions (parity, triple-scattering parameters, polarized neutrons). The cost of the ANAC commercial colliding-beam source is substantial (\$363,000) but not unreasonable. For comparison, the in-house construction of the colliding-beam source at the University of Wisconsin required \$300,000 in equipment and machine shop costs alone. Polarized-ion sources supplied by ANAC to Indiana, Texas A&M and Argonne ZGS have an excellent performance record.

In cyclotrons, polarized protons and deuterons are accelerated by axial injection of polarized  $H^+$  and  $D^+$ . At SIN (Switzerland) the beam intensity of the 70 MeV injector cyclotron was increased by more than an order of magnitude in January 1979 by installation of a new ionizer. This ionizer was originally developed by a commercial company (ANAC) for a joint project with CERN. The cost of the commercially obtained SIN ionizer was about \$120,000, while an entire source, guaranteed to produce 80  $\mu$ A polarized  $H^+$ , DC, costs  $\sim 0.3$ M\$. A new ionizer of this type should be considered for the Berkeley 88-inch and for Texas A&M. Indiana has a rather new polarized source. In this case, the gain to be expected from a "super ionizer" is only about a factor of 4. Upgrading may be justified at a later time.

### Polarized Neutrons

Work at LASL and TUNL has established polarization transfer as a powerful method to produce beams of fast, highly-polarized neutrons. The neutron polarization is reversed by reversing the polarization of the charged-particle beam initiating the reaction. The increased beam intensity available with the new generation of polarized ion sources should make it possible to study in some detail the scattering and reactions induced by polarized neutrons. It may also be interesting to study the usefulness of a dedicated 14 MeV

polarized neutron facility using the 80  $\mu$ A polarized  $D^+$  beam from a modern atomic-beam source to initiate the  $T(d,n)$  reaction.

### Polarized Heavy Ions

No work has been done in the U.S. with beams of polarized heavy ions. Indeed it is not clear that exciting insights would result from the use of polarized beams in heavy ion reactions. However, work with polarized  ${}^6\text{Li}$  and  ${}^7\text{Li}$  at the Heidelberg EN tandem suggests that there are interesting effects, but there are at the present no facilities to study the phenomena at higher energies.

### Polarized Electrons

The use of a GaAs surface as a photoemitter of polarized electrons was proposed and developed at ETH, Switzerland. This type of source has been perfected at SLAC where it now produces pulsed beams of electrons of some 80  $\mu$ A with a polarization in excess of 30%. Polarized electron beams at much lower energies would be of interest to extend the SLAC study of parity violation in electron scattering. Also, installation of a polarized electron source has been under discussion at Bates.

### Development Opportunities

There are exciting opportunities to further develop sources of polarized ions. Further, possibly quite large increases in intensity are possible by using the colliding beam method using collision between unpolarized  $H^-$  and polarized  $H^0$  to produce polarized  $H^-$  ions as discussed by Haeberli at the Symposium on Polarized Beams in High Energy Physics.

Important benefits of such increases would result, for instance, in experiments at LAMPF, and also for multiturn injection into high energy accelerators. No doubt other new ideas will offer interesting research opportunities in the future. Much of the ion source development has been done at university laboratories, but because of the decreasing funding (in real dollars) the technical support at most laboratories has suffered to the point that extensive (and uncertain) development projects cannot be carried out. Even injection of special funds for a specific project does not solve the problem entirely, because a high-technology group cannot be assembled quickly and released again after a year or two. The solution would require raising the overall level of



permanent technical support staff which is very expensive. The type of innovative development work which ANL has carried out on the superconducting linac is likely in a laboratory where there remains a degree of flexibility in funding new projects on a trial basis and where there is sufficient level of support staff to free the physicists from having to struggle to keep, e.g., the accelerator operating. The university programs are smaller to start with and recent funding patterns make it even more difficult for university laboratories to contribute significantly to instrumentative development. This is regrettable because university laboratories can and have made extremely significant contributions.

## 2. BEAM TRANSPORT SYSTEMS

### Introduction

This report summarizes the present status and future developments and needs of beam transport systems at nuclear science accelerators supported by DOE or NSF.

### Components and Techniques

The field of beam transport is well developed. Well-known techniques exist for calculating or measuring electric and magnetic fields due to given configurations of electrodes or magnets. The computer codes, however, are usually two dimensional, and a need exists for three dimensional codes which are not too costly or difficult to use. The parameters of the beam as it passes through various electromagnetic elements and drift lengths can be calculated with high accuracy by standard computer codes such as TRANSPORT.

The principal components used for bending and focusing of full energy accelerator beams in the 10-1,000 MeV range are magnetic dipole, quadrupole, and sometimes sextupole and solenoid magnets. This is a well-established technology, and most labs obtain these components from industry. In cases requiring low aberration magnets, computer codes such as TRIM are used to calculate two-dimensional magnetic field profiles in the magnet gap and at the edges. Usually the coil conductor is hollow water-cooled copper. But a few groups use tape-wound coils for a more compact design. For example, the LBL SuperHILAC has developed compact tape-wound quadrupoles, bending magnets and solenoids with an 80-90% packing factor (space occupied by conductor). Two-hundred fifty quadrupoles are in use in linac drift tubes and beam transport, and 16 bending magnets have been built.

At low energies of 10-100 keV, typical for accelerator injectors, electrostatic components are often used because they are simpler, cheaper, and adequate for low energies. These elements include einzel lenses, electrostatic quadrupoles and bending channels. For beam intensities over .1-1 mA, magnetic elements are usually chosen to allow space charge neutralization.

A development which may be cost-effective for higher energy beam lines is the use of superconducting magnets. Some superconducting dipoles and quadrupoles have been designed or built by the high energy physics groups at national labs such as ANL, BNL and LBL for high energy beam lines or accelerator rings. Several nuclear science labs are planning to use superconducting elements for new beam lines. Argonne National Laboratory is building a superconducting 90° bending magnet in three sections for the ATLAS superconducting linac experimental area. Michigan State University is planning to build superconducting quadrupoles for a new beam line for the K = 500 superconducting cyclotron experimental area. Superconducting transport magnet technology saves power, and is an attractive option if there is already a large refrigerator in the laboratory for an accelerator, as in the cases mentioned above.

A special technique of beam transport which is used for neutron time-of-flight experiments is a "beam swinger". Here a set of bending magnets can direct the beam at any selected angle upon a target. The scattering angle can thus be varied while leaving the outgoing beam path fixed. This is convenient where the time-of-flight line is 10's of meters long, and impractical to move or duplicate along other paths. The University of Colorado uses this type of system, both for neutron time-of-flight experiments and for angular variation of the beam into a target for a high resolution charged particle spectrometer.

Another special application of beam transport magnets is the use of solenoids or dipoles for spin rotation of polarized beams. At LAMPF a special opportunity exists for faster rotation by using the large magnetic moment of an  $H^0$  beam which is formed by stripping of the  $H^-$  beam. This method may be more desirable than using the  $H^-$  or  $H^+$  beam.

### Vacuum Systems

The vacuum required in beam lines ranges from the  $10^{-5}$  torr for light ions to the  $10^{-8}$  torr for some heavy ion beam lines. For heavy ions the better vacuum is needed to prevent stripping of partially stripped ions, resulting in loss of beam at the next bending or focusing element, or in beam halo at the target. Various conventional pumping systems are used, including diffusion pumps, turbomolecular pumps, ion pumps,

and cryopumps. Preferred beam pipe materials are stainless steel for good vacuum, or aluminum for low residual radio-activity.

A new pumping arrangement will be tested by the Michigan State cyclotron group. This is a cold bore beam pipe with liquid nitrogen near the wall and cold helium cryopumping tubing inside running parallel to the beam. This forms a distributed pumping system which eliminates conventional pumps and valves, and should produce an excellent vacuum.

### Beam Diagnostics

The function of a beam diagnostics system is to provide information about beam intensity, spatial distribution, emittance, time structure, energy and energy spread. The ideal diagnostics system is rapid and does not interfere with the beam. A great deal of development work has been done on diagnostics systems, and some components are available commercially. The kinds of devices used include Faraday cups or beam stops, slit systems, phosphors, scanning wires, inductive or capacitive pickups, solid state detectors, ionization and proportional counters, secondary emission monitors, foil activation, film exposures and analyzing magnets.

There are still needs which have not been met by present systems. More development needs to be done on devices for non-destructive and rapid measurements of beam profile, especially for high intensity beams such as at LAMPF or Bates. Possible systems include residual gas or gas jet ionization chambers. A signal from such a device could be used in a feedback loop to stabilize the prior beam transport elements and the accelerator. A device for measuring the energy-phase correlations (longitudinal emittance) would be a valuable tool for tuning accelerators. Development work in this area is in progress at the LBL Super HILAC and the ANL Superconducting Booster.

### Beam Sharing

At multi-particle nuclear science accelerators, there is a wide range of particles and energies, and a small overlap of experimental requests for ion and energy. So the opportunity for beam sharing is limited to sharing with test runs or experiments requiring only a small fraction of the beam. For electrostatic accelerators and cyclotrons, the particle and energy change time is at least a few minutes, so beam sharing with small loss of time for the principal experimenter is limited to switching the beam periodically for a few minutes

to the secondary experiment, or splitting off a small fraction of the beam with fast time pulsing or spatial beam splitting with a septum. In most of these accelerators this kind of operation offers only small benefits, so a low priority has been given to its implementation.

A more flexible kind of beam sharing for a multiparticle accelerator is used at the LBL SuperHILAC. Here fast switching (milliseconds) is used to feed one or two pulses per second from one injector into the accelerator for use at the Bevatron. The remaining 35 pulses per second are fed from the other injector to the accelerator for use at the SuperHILAC experimental area. Separate particles and energies can be chosen for the two beams with very little loss of duty factor for the SuperHILAC experiment. This "time sharing" mode of operation is also used to serve a secondary experiment at the SuperHILAC. An additional splitting system which preserves duty factor is planned at the SuperHILAC, using two septum magnets facing each other. This system, in use at GSI for several years, will give three beams of the same particle and energy.

At the LAMPF proton linac positive and negative hydrogen ions are accelerated simultaneously on opposite phases of the rf wave. They are then separated in the beam transport system and sent to separate experiments. This mode of beam sharing costs nothing in duty factor of either beam, but both beams must have the same energy. The beams are further shared by typically 10 experiments at the same time by splitting off part of the  $H^-$  beam and by traversal of several targets in the  $H^+$  beam. A technique is under development to accelerate different energies of  $H^+$  and  $H^-$  by inducing longitudinal oscillations to put the  $H^-$  beam out of phase part way down the accelerator.

At the Bates electron linear accelerator an electrostatic beam splitter is planned. This will be a kicker at 1 kHz repetition rate which will provide beam sharing between two experimental halls, without preservation of duty factor.

### Secondary Beams

Secondary beams are available at some accelerators. For primary beams of energies less than 100 MeV/nucleon, the principal secondary beam is neutrons. Several groups generate neutron beams from targets hit by primary proton or deuteron beams. Polarized neutron beams can be produced from polarized deuteron primary beams or by  $d + t$  reactions. In early experiments, polarized protons were produced by  $\alpha + p$  scattering, but high intensity polarized ion sources have replaced these systems. Neutron beams are used for cancer therapy trials at several cyclotron laboratories.

At installations having beam energies of over several hundred MeV/nucleon  $\pi$  and  $\mu$  meson secondary beams are frequently used. LAMPF has  $\pi$  and  $\mu$  channels. LAMPF is considering a combined low energy muon beam and pion channel, with a design based upon the successful surface muon beam (Arizona type) at LAMPF.

### Computer Control

Computer control of the beam transport or diagnostic elements has been implemented at some of the larger installations. This kind of program is usually an extension of computer control of the accelerator. It is cost effective for complex transport systems which are time consuming to set up, and where setting errors are likely to occur. The computer may handle any of a number of tasks including set-up, tuning, monitoring, safety and logging. At larger installations, these tasks become very time consuming for operators, making computer control desirable.

### Summary and Recommendations

The construction of magnets is well developed. An area of possible future development for cost effectiveness is the use of superconducting dipoles and quadrupoles for higher energy beam lines because of their low operating cost. Another construction technique which should be considered for cost effectiveness by laboratories making a large investment in beam lines is the use of tape-wound dipoles and quadrupoles, as used by the LBL SuperHILAC. Magnets of this type are compact, low power, and have good field quality. A practical three-dimensional magnetic field code would also be useful.

In the area of beam diagnostics, many devices have been developed for determining the spatial, time and energy structure of the beam. There are continuing needs for faster and more convenient monitoring systems. For example, non-intercepting beam profile monitors are needed for high intensity beams at Bates and LAMPF for better accelerator tuning and reliability.

Beam sharing offers the possibility of increasing the research output of an accelerator. This has been utilized effectively at the LBL SuperHILAC by fast pulsing and at LAMPF by  $H^+$  and  $H^-$  acceleration and by multiple target traversal. It is not as effective for electrostatic accelerators and cyclotrons to share beams, because of the longer time constants for energy changes and the small overlap in beam ion and energy requests. But continuing efforts should be made

to utilize beam sharing in all accelerators and particularly in future facilities where the beamline layout has not been frozen.

The continuing development of diagnostics, beam sharing and secondary beam facilities is being competently carried out by the accelerator development groups at each laboratory to meet their special requirements. This specialized technology is shared at conferences and interlab visits, so no special additional funding appears necessary.

Computer control of beam lines offers the advantages of automatic set-up of beam magnet currents, and storage and monitoring of the parameters. This is desirable in large installations to save set-up and trouble-shooting time, where the investment in the computer system capital cost will pay for itself in the saving of operating time over a period of years.

This report has made a brief survey of the status and future needs and opportunities in the beam transport field. It was not able to evaluate detailed design questions such as the vacuum requirement for heavy ion transport or detailed comparison of beam line costs in various laboratories.

We recommend to the funding agencies that for large proposed facilities, where beam transport system costs can be in the \$1 million range, the group reviewing the proposal include members experienced in beam transport technology and cost estimating, to be sure that the design is adequate and cost effective. An alternative would be to have a panel of experts in certain fields who could be consulted by the agencies on beam transport questions. For the discussion of some technical areas among specialists, informal meetings or workshops could be organized by interested people or by the agencies.

### 3. TARGET PREPARATION

#### Introduction

Every nuclear physics laboratory in the world is involved in target preparation at some level. The level of activity ranges from a staff of 21 making use of equipment valued at \$3.5M at ORNL to a graduate student using a laboratory evaporator. The fact that every lab possesses some sort of target-making apparatus is a clear statement that a centralized facility apparently cannot meet all the needs. We shall discuss the reasons for this.

Target making is a key element in experimental nuclear research, but is viewed with a certain amount of alarm or disdain by some physicists. This attitude is not difficult to fathom--target-making is not susceptible to precise predictions. Instead, it requires experimentation, luck, a flair for the technique, and frequently the background of a chemist. We shall offer a suggestion in this matter.

Much ingenuity is devoted to finding new methods for target production. We include a list of recent achievements to illustrate the vigorous activity in the field, and we mention some outstanding unsolved problems.

Finally, the state of target-making equipment in the U.S. is considered, and a recommendation made.

#### Central or Localized Facilities?

A few commercial enterprises and ORNL fabricate targets on request for a price. One might ask why nuclear labs do not avail themselves of this service as a matter of course, dispensing entirely with costly evaporators, technicians, etc. Indeed as E. H. Kobisk of ORNL points out:

"Centralization of isotope target and research materials preparation is of significant benefit to the researcher:

- (a) Lower materials consumption because of the possibility of centralized reprocessing, purification, and the availability of larger quantities of material.
- (b) More diversified preparative technology.
- (c) Concentration of dedicated personnel whose sole function is sample preparation.
- (d) Capability of drawing on expertise at ORNL other than that of IRML.
- (e) Concentration of costly equipment assembled only for sample preparation.
- (f) Availability of facilities for handling of and operating with noxious materials and hazardous radioisotopes.

"At ORNL, cost of sample preparation is strictly a function of time and material consumption. No profit is charged. Therefore, minimization of cost to the research simply arises from finding sample parameters which reduce preparative effort to a minimum. Of course,

the lower enrichment which can be tolerated for any specific isotope reduces the cost. The smaller the target size (area) and (usually) the thicker the sample, the lower is the cost. Vapor-deposited samples are generally 2x to 10x more expensive than rolled samples.

"It is interesting to note that almost every research accelerator has associated with it a target fabricator --an expense 'hidden' in the overall funding. Because sample preparation costs are thus locally hidden (except for purchase of materials), the individual researcher does not see the direct cost and usually views our preparative charges as being "outrageous".

"Hopefully I'm not being prejudiced, but it would seem that a central target preparation facility (such as the Isotope Research Materials Laboratory (IRML) at ORNL) is the only feasible way to provide services at a reasonable cost and over a broad spectrum of preparative methods encompassing both stable and radioisotope materials. Similar thinking resulted in EURATOM setting up the Central Bureau of Nuclear Measurements at Geel, Belgium. The single biggest deterrent to complete success in such centralization is the problem of shipping fragile materials, i.e., thin self-supported films. However, for the most part, this problem has been circumvented by shipping vapor deposited targets on substrates from which the isotope film can be removed in the customer's laboratory and appropriately mounted."

Notwithstanding these persuasive arguments, one cannot foresee a time when complete centralization will occur. The reasons are: (a) Cost of centrally-prepared targets. However justified their prices, ORNL and commercial targets seem very expensive to the average researcher. For difficult targets, only ORNL and a few other labs may possess the necessary equipment--such targets are expected to be expensive. For trivial targets, however, the sophisticated equipment and highly skilled technical personnel represent unneeded overhead.

(b) Difficulty of transporting fragile self-supporting targets. Frequently one of the most difficult phases of target making is the releasing of the target from the substrate and picking it up on a frame. Breakage is common, and the prospect of having to perform this operation on an (apparently) expensive foil from a central facility is daunting.

(c) Convenience. The ability to fabricate a target on short notice is an important element in a forefront research effort.

(d) "Over-performance" of centrally-produced targets. ORNL and commercial concerns maintain extremely high standards.



Frequently a poorer quality target is entirely adequate for a particular experiment. The unnecessarily high quality adds to the cost of a target.

In summary, while the need for a high technology target-production center such as ORNL is obvious, we cannot recommend the complete disbanding of local target preparation laboratories in favor of correspondingly increased funding for purchase of targets from a centralized facility. On the contrary, we feel that a minimal target lab is an important part of a nuclear physics laboratory, and should be supported as such. The model of Stony Brook is exemplary--target-making equipment was considered by the State of New York to be as fundamental a part of the laboratory as tables and chairs, and was funded appropriately.

#### Communication of Techniques

It would be difficult to identify an area of nuclear research which causes more frustration and more duplication of effort than target making. Because it is more an art than a science, a great deal of detailed trial and error is often needed before a satisfactory target is obtained. Frequently the same painstaking work is repeated in laboratory after laboratory, each person unaware of the work that has already been done elsewhere. Even successful preparative methods are not often published, and the unsuccessful ones never are.

To alleviate this problem, we recommend that a compilation along the lines of "Nuclear Data Tables" of target preparation techniques be assembled, and that the agencies should make available funds for attractive postdoctoral fellowships (similar to the Nuclear Information Research Associateships) in order to carry out this unenviable task. In this connection, the International Nuclear Target Development Society's work on disseminating target information could serve as a foundation, and we hope their expertise could be drawn upon in the compilation.

#### Some Examples of New Instrumentation

##### (a) Focused Ion Beam Sputtering

Potentially new, powerful tool. Ions of argon or krypton produced in duoplasmatron or Penning ion source and accelerated and focused at 10-20 keV. Small beam spot diameter makes possible sputtering of milligram quantities of rare and expensive isotopes. Can sputter high melting, low vapor pressure, chemically active materials. Can ion implant. Can also in situ reduce oxides of isotopes.

(b) Deposition Monitoring Devices

The thickness monitor has become a routine tool for more accurate target thickness measurements. In addition, some of the new digital devices make use of the period and not the frequency of a quartz crystal. These linear devices can measure up to 2 mgs/cm<sup>2</sup> before becoming unstable. Also, recently a much smaller monitor has been developed in Germany which permits placing it in more confined areas. Microprocessor controlled monitors can now provide more reproducible vacuum depositions.

Future Development in Thin Films

(a) Stripper Foil Research

At present the primary mechanism severely limiting the lifetime of amorphous carbon thin films is understood (structure change due to beam radiation). It would be most desirable to develop a self-supporting stripper which will be resistant to these effects and thereby have a greatly increased useful lifetime.

(b) Ratio of Starting Materials to Finished Targets

The increased cost and reduced availability of target materials, especially stable isotopes, is forcing development of more efficient procedures. Design changes in crucibles for vacuum evaporation, improved rolling methods, and higher conversion/recovery yields in reactions.

(c) Thin Film Structure

Increased nuclear research using both thick and thin single crystal targets requires the fabrication of high purity targets of specific structure and orientation.

State of Target-Making Equipment in the U.S.

Virtually every laboratory in the U.S. has outmoded or inadequate target-making equipment. Even at ORNL serious equipment problems are arising. According to Dr. Kobisk,

"For some years we (IRML) were sufficiently funded for equipment purchase; in the last five years, however, the availability of capital funds has been nearly zero. Because of this, we frequently are forced to fund small equipment items through customer revenues for technical services which, of course, significantly increases cost to the consumer. Large equipment items (> \$5,000) are either funded in the same manner or not purchased. Most of our equipment is now 10-15 years old and requires

large maintenance expenditures, again increasing the charge to the customer. Incidentally, costs of sample preparation are billed at full cost recovery (no profit). Development funding has been constant over the past five years."

This situation appears to be typical. For example, the new vacuum equipment and evaporation methods are capable of producing targets essentially free of oxygen, hydrogen, and carbon contamination, but they are beyond the reach of all but a few fortunate labs.

We are convinced of the value of reasonably modern local target preparation facilities, and we recommend that capital equipment funding be provided to upgrade and augment target-making facilities in productive nuclear physics laboratories.

### Separated Isotopes for Nuclear Physics

There is a growing awareness of a serious problem in the availability of separated isotopes. Electromagnetically separated isotopes are produced in two facilities in the world, one in Oak Ridge in the USA, the other in the Soviet Union. (There is no problem in the supply of the light isotopes  $^2\text{H}$ ,  $^3,^4\text{He}$ ,  $^{12,13}\text{C}$ ,  $^{15,15}\text{N}$ ,  $^{16,17,18}\text{O}$ , and the inert gases, which are separated generally by diffusion, fractional distillation, or related techniques.) The Soviet Union is evidently interested in building up a clientele for isotope sales. They can provide a wide variety of isotopes at reasonably short notice, and at prices typically 70% of Oak Ridge prices, but they are not able at present to supply large quantities or high enrichments (for example, the maximum available  $^{48}\text{Ca}$  enrichment is 70% compared to 98% from Oak Ridge). Thus for many applications, Oak Ridge is the sole supplier.

### The Oak Ridge Facility

Oak Ridge possesses 30 electromagnetic separators ("calutrons") which are arranged into three groups of eight and one group of six for operating purposes. When the decision is made to restock the inventory of a certain element, a "campaign" is begun in which a track of calutrons is charged with that element and functions for a continuous period (five days a week, 24 hours per day) of 2-10 months. Generally that campaign is not repeated for four to five years. At one time all 30 calutrons were in continuous operation, but now only one track can be run at a time owing to budget and manpower limitations. The decision on which elements to run is made on the basis of the estimated demand over the next four to five years, and is therefore a difficult one. Because of the

nature of basic research, the nuclear physics community is unwilling and unable to predict its needs beyond six months to a year. Industry and medicine are both better able to make the predictions and more aggressive in pressing their cases.

Initially it was the intent of the AEC, the governmental branch then responsible for isotope separation at Oak Ridge, that a considerable inventory of separated isotopes be accumulated and that the operation would then revert to a steady-state condition in which sales would provide most of the money required to replenish depleted stocks. This desirable state was achieved in part--Oak Ridge now has an inventory of separated stable isotopes valued at \$26M. However, it is DOE policy that isotopes be sold at production cost (without even a correction for inflation between the time of production and the time of sale), and this figure is always far below replacement cost. Initially in the late 1950's when the isotope facility was new, a campaign cost \$7 per hour; now it is \$40 per hour. Thus, some isotopic material is being sold at prices that are almost six times less than its real value.

Compounding the problem is the real decline in funding. In 1974 the electromagnetic separation budget was \$3M; in 1979 it will fall to \$1.2M. Actual sales of isotopes amounted to \$2.4M in 1976 and \$1.5M in 1977 (much of this difference arises from a \$0.5M sales of  $^{56}\text{Fe}$  in 1976 to an unidentified customer).

#### Problems and Recommendations

When separated isotopes first became available, they were (with the exception of bomb ingredients and reactor fuel) exclusively used for basic research, most of which was nuclear physics. Now, however, basic research accounts for only one-third of isotope sales, with industry accounting for another quarter and medicine the remainder. The growth of nuclear medicine and its financial strength will undoubtedly drive this trend still further, even in the face of rising consumption by research and industry. Almost 50% of ORNL's isotope customers are foreign:

If one assumes that isotopes are presently being sold for an average price one-half of their replacement cost (probably an optimistic estimate), and that annual sales continue at their 1977 \$1.5M pace, then the value of material sold is at least \$3.0M per year. DOE funding permits \$1.2M worth of replacement, leading to a shortfall of only about \$0.3M. Our estimates are sufficiently crude that one may wonder if there is any cause for alarm at all. The disturbing aspect of these figures is that DOE is in effect supporting industry, medicine, and foreign research to the tune of about

\$1.3M per year (in isotope sales alone). The picture of basic research financially supporting industry and medicine, rather than the other way around, is at the very least unesthetic.

It would seem that the solution is:

- (a) to reduce DOE funding for regular isotope production at ORNL to zero;
- (b) to raise the sale prices for isotopes to their replacement cost (figures to be determined annually by an impartial committee to prevent any possibility of empire-building);
- (c) to neutralize the impact of these higher prices on the U.S. basic research community by the appropriate direct allocations of funds (made available through (a));
- (d) to strengthen the research and development program at IRML through a regular allocation of funds (made available through (a));
- (e) to provide a "capital" allocation for immediate replacement of depleted stock.

In our opinion, this approach will halt the decline in isotope inventories, support IRML's efforts to increase the efficiency of isotope separation, and protect U.S. research units, large and small, from a serious research crisis, all at no net cost to the responsible agency. One possible difficulty is that IRML will no longer be insulated from the fluctuations in demand that affect any business. No doubt some mechanism could be devised to smooth out the effect of these fluctuations.

#### Gas Targets

Three general types of gas targets can be distinguished: (a) gas cells with thin windows, (b) differentially pumped windowless cells, and, (c) gas jets.

(a) Gas Cells with Windows: We shall not consider such targets in much detail here. Most laboratories have used gas cells at one time or another, and the problems involved include window technique, slit scattering by the necessary exit slit, and gas recovery for re-use.

(b) Differentially Pumped Gas Targets: In this type of target gas is fed into a reaction volume from which it escapes through a series of constrictions. Because considerable pumping speed is required to hold a good vacuum in regions

remote from the target, such targets are expensive and uncommon. Nevertheless, the principles are well understood and the technology straightforward. Several laboratories have constructed such targets, and we shall mention only a few novel devices. A unique combination is the gas target installed in the University of Pennsylvania Multigap spectrograph. This target is a hybrid arrangement, having no entrance window but a thin exit window. Highly efficient differential pumping has permitted operation with gases as costly as  $^{21}\text{Ne}$  and  $^{36}\text{Ar}$ . From another point of view, the Oxford University gas target is one of the most sophisticated. Specifically designed for radiative capture studies, it uses all-metal construction and cryopumping to achieve a uniquely low level of impurities, particularly the troublesome  $^{13}\text{C}$ . To our knowledge, no target as advanced as the Oxford one has been constructed in the U.S.

(c) Gas Jet Targets: In recent years a new type of target has been developed in which gas escapes freely from an aperture or nozzle, emerging into the vacuum at sonic or supersonic velocity. The high speed gas jet then enters a port where it is slowed, recompressed and pumped away. Usually other pumps are added to scavenge any gas escaping from the main stream.

Jets offer some interesting advantages over other types of gas targets:

1. There can be unrestricted access to the full range of reaction angles from  $0^\circ$  to  $180^\circ$ .
2. The target is confined to a small region, and one can often dispense with collimating slits (and the attendant slit scattering) both for the beam and the reaction products.
3. The expanding gas cools substantially below ambient temperature, reducing the Doppler broadening which affects certain resonance experiments.
4. The small target size offers improved performance in some experiments sensitive to kinematic effects.

The first suggestion to use a dynamic gas target is contained in a 1959 patent of R. J. Van de Graaff. His basic design, in which the gas flow is parallel to the incident particle beam, is a type still favored in intense neutron sources where a rather thick target is required, and where the flowing gas provides a natural means for heat dissipation. Modern versions of this target are under development for the Canadian Intense Neutron Generator and the Los Alamos INS facility.

Development of a "transverse" jet target (i.e., one in which the jet intersects the beam at right angles) first received serious attention at Los Alamos with the work of J. F. Brolley. The scale of Brolley's work was impressive and may have led to the exaggerated reputation for complexity that jet targets have. The nozzles made by Brolley have been transferred to Fermilab where they are incorporated into the main-ring jet targets.

The first Fermilab jet target was constructed by a Soviet group and employs cryopumping. The target has performed satisfactorily for several years, but the complexity of the liquid helium supply, the need to regenerate the cryopump periodically, and a high consumption of cryogen led to development of a room temperature target conventionally pumped by oil diffusion pumps and ion pumps. The pulsed nature of the Fermilab beam suggested the use of a pulsed target and a large buffer volume, which allowed a reduction in pump size.

There are no jet targets in use for low and medium energy physics in the U.S. On the other hand, Germany has devoted a great deal of effort to developing this type of target for nuclear physics use. There are three now in operation, two at Erlangen, one of which can achieve the remarkable density of  $0.25 \text{ mg/cm}^2$  for  $\text{H}_2$ , and the other at GSI (built by the Frankfurt group). A jet target is now under construction at Argonne for use in a specific experiment, but, especially with the commissioning of new heavy-ion accelerators in the U.S., there is a need for general-purpose jet targets.

#### Recommendation

Development of a jet target as part of a U.S. national heavy ion laboratory seems to be a most important item. High priority should be given to the development and construction of at least one jet target. It would be very useful if such a target or targets were generally available. The actual hardware costs for jet targets are in the vicinity of \$25-50K, but there is a real need to study and optimize the design. An instrumentation R&D expenditure of \$150-200K would be rewarded by new and interesting nuclear physics capability.

### 4. MAGNETIC SPECTROGRAPHS

#### Introduction

Magnetic spectrographs are used in nuclear physics for measuring the energies of charged particles, mostly particles emitted from the target in a nuclear reaction. Other, simpler instruments can be used for the same purpose, e.g., the gas

ionization chamber, the solid ionization chamber (solid state counter), and scintillation detectors. Typical energy resolving power for these other detectors is about 1%. A notable exception is the solid state counter when used for light ions. Its resolving power may then be of the order of 0.3%. If a better resolving power is needed, a magnetic spectrograph is called for. The spectrograph also has other advantages, such as better background rejection, less "tail" on intense peaks, possibility for blocking out intense elastic peaks or the beam itself, possibility for making kinematic corrections, etc.

In this report we will distinguish between the various spectrographs according to their usage and divide them into the following four categories:

Electron spectrographs

Spectrographs for nuclear fragments  
(protons and heavier)

Recoil spectrographs

On-line separators

#### Existing Spectrographs

Magnetic spectrographs have been used for analyzing protons and heavier charged particles emitted in nuclear reactions since about 1947. Table III-2 is taken from a forthcoming review in Nuclear Instruments and Methods and shows the most common types of single gap magnetic spectrographs in roughly chronological order. (The "QSP Design" and the "Rochester QD" represent paper studies only.) The last column in Table III-2 gives a parameter  $Q$  which is a measure of the data-taking power of the instrument. It is defined as the solid angle  $\Omega$  divided by the number of exposures needed to cover a momentum range of a factor of two. The trend in spectrograph design has been to increase the parameter  $Q$  as well as the resolving power.

A very popular spectrograph for charged particle nuclear reactions has been the Browne-Buechner spectrograph. Both this instrument and some of the later instruments--for instance, the Elbek spectrograph and the Split Pole-- were all designed to be used with nuclear track plates as recorders. Since the detector resolution is then only determined by the width of the strip counted under the microscope, a fairly low dispersion was adequate and indeed desired. With the advent of the multiwire or single wire proportional counters with about 1 mm resolution came a demand for magnetic spectrographs with higher dispersion. The Q3D family of spectrographs was developed as a result of this demand. The solid angle of accep-



Table III.2  
Single gap spectrographs

MAGNETIC SPECTROGRAPHS

Spectrograph	Mean radius R (cm)	Altgap d (cm)	Range P <sub>max</sub> /P <sub>min</sub>	Solid angle Ω (mrad)	Dispersion D = Δx/Δp	Magnif. M <sub>x</sub>	M <sub>y</sub>	D/M <sub>x</sub>	Res. pow. Δ (approx. eV)	Focal φ (degrees)	Surface shape	Kinematic correction	Q (mrad)
Annular magnet	35	1.3	1.04	0.5	2.0	1.0	-	2.0	2000	0	Straight	None	0.03
Nichigan n-1/2	133	1.3	1.06	0.4	4.0	1.0	1.0	4.0	8000	55	Straight	Det. displ.	0.03
Ronne-Buechner	51	1.3	1.5	0.4	2.0	1.0	-	2.0	3000	63.5	Curved	None	0.23
Elbek	62	2.8	2.1	1.0	2.4	0.8	-	3.0	4500	45.2	Curved	Det. displ.	1.1
Split-pole	60	3.8	2.8	2.0	1.9	0.3	4.0	5.7	4500	41.5	Curved	Det. displ.	3.0
Berkeley	178	10.0	1.15	1.0	2.1	0.4	5.0	5.3	5000	0	Curved	Det. displ.	0.20
Q3DI	100	8.0	1.10	14.7	14.0	1.5	4.0	9.5	10000	43.0	Curved	Multipole	2.0
Q3DI	90	7.2	1.22	14.7	10.2	1.1	3.0	9.0	10000	43.0	Curved	Multipole	4.2
QTR	90	7.2	1.28	10.0	7.8	1.1	4.3	7.3	10000	45.0	Straight	Multipole	3.6
Qm2	120	9.6	1.10	10.0	6.7	0.9	5.8	7.1	10000	45.0	Straight	Multipole	1.4
Indiana QPQ	135	8.0	1.03	3.2	7.7	1.0	1.0	7.7	6000	46.0	Curved	Multipole	0.14
Osaka QDDQ	150	8.0	1.06	13	11.1	1.1	4.0	10.0	10000	52	Curved	Multipole	1.1
CSI QPQ	200	10.8	1.08-1.29	3.0	2.6-0.7	1.8-0.26	2-7	2.9-5.5	370	Variable	Curved	Quadrupole	0.7
Julich QPQ	172	6.0	1.10	10.0	9.8	0.9	7.2	11.5	7	0	Curved	Multipole	3.3
QSP design	100	8.0	1.86	8.8	2.1	0.38	3.3	7.1	2500	38.3	Straight	Det. displ.	7.9
Tokyo QDP	140	10.0	1.15	6.4	2.8	0.38	4.4	7.4	7	55.0	Curved	Det. displ.	1.3
IKO QPQ	180	14.4	1.10	17.2	4.6	1.2	2.5	3.9	4000 <sup>b</sup>	38.7	Straight	Computer	2.4
Indiana QQSP	38	5.8	1.63	<35.0	2.3	0.3	3.3	7.4	1000 <sup>b</sup>	40.5	Straight	Computer	20.0
Bates QQSP	50	5.0	1.22	35.0	2.5	0.4	4.2	6.5	2000	46.1	Curved	Computer	10.0
Rochester QP	75	35	1.5	<400	-	-	-	-	3000	-	-	Computer	<200

<sup>a</sup>An approximate measure of the theoretical aberration-limited resolving power at the solid-angle listed.  
<sup>b</sup>With data corrected for (x/θ<sup>3</sup>).

tance was also increased from the order of 1 milliradian (msr) to 10 or 15 msr.

Parallel to the development of spectrographs for protons and heavier particles has been the development of spectrographs for the study of elastic and inelastic electron scattering. The most modern instrumentation of this kind involves the utilization of the so-called energy loss principle. Instead of selecting a small part of the electron beam with an energy window commensurate with the desired resolution, the entire electron beam is dispersed on the target and the dispersion is matched to the dispersion of the spectrometer in such a way that electrons scattered from a given level in the target nucleus fall on the same place in the detector. The electron spectrometer at Bates Linear Accelerator at MIT operates on this principle. The split-pole spectrograph at Michigan State and the proton spectrometer at LAMPF also utilize the energy loss principle.

In order to study angular distributions of charged particles emitted in a nuclear reaction, it is, of course, necessary with a single gap spectrograph to take multiple exposures at different reaction angles. The multigap spectrographs were designed to simplify this procedure and increase the data-taking power. Altogether eight multigap spectrographs have been put into operation; Table III-3 lists these instruments and their major features.

In heavy ion physics it is important to measure not only the momentum of a particle but also its mass and element number. In particular, heavy evaporation residues from a fusion reaction are difficult to identify by other means than an electromagnetic spectrograph. The energy-mass spectrograph (EMS), constructed and operated by MIT at Brookhaven National Laboratory, was designed to meet this need. The instrument has a mass resolving power of approximately 1 part in 400 and an energy resolving power of about 1 part in 2000. It utilizes a crossed-field velocity selector deflecting vertically followed by a momentum spectrograph deflecting horizontally. The only similar instrument in operation for heavy ions is a velocity filter called the SHIP at Gesellschaft für Schwerionenforschung, Darmstadt, Germany. However, there are several instruments of this kind being planned for use at the new heavy ion research facilities. At the high-energy accelerators multiparameter separation has been in use for many years. In particular, velocity selectors have been developed to hold electric fields of about 60 kV/cm over a 10 cm gap.

The majority of nucleon-stable nuclides have half-lives shorter than one minute. In order to study their decay properties it is necessary to transport them from the place of production to the detector or detectors as quickly as

MAGNETIC SPECTROGRAPHS

Table III.3  
Multigap spectrographs

Location	Type	Pole piece radius (cm)	Maximum orbit radius (cm)	Alger (cm)	No. of active gaps	Angular separation (degrees)	No. of beam ports	Smallest angular interval (degrees)	Exposures per load
MIT	B-B	50	57	1.0	24	7.5	1	7.5	3
Aldermaston	B-B	50.8	58	1.3	24	7.5	1	7.5	1
Mexico	B-B	60	68	1.0	18	10	1	10	3
Oxford	B-B	61.0	69	1.3	24	7.5	2	3.75	3
U. of Penn.	B-B	61.0	69	1.3	24	7.5	2	3.75	2
Yale	B-B	78.7	90	1.6	23	7.5	3	3.75	3
Heidelberg	B-B	78.7	90	1.6	29	7.5	3	3.75	3
Niels Bohr Inst.	Elbek	-	100	2.0	26	10	1	5	2

possible. On-line isotope separators operating in conjunction with an accelerator or nuclear reactor have been in use for many years. For very short lived nuclei ( $10^{-7}$  sec to  $10^{-1}$  sec) the recoil mass spectrographs or velocity filters mentioned above will prove useful.

Table III-4 is a list of existing conventional on-line separators.

### State of the Art and New Developments

To what extent do the instruments mentioned above represent the state of the art, and what is on the horizon in the U.S. and abroad? We shall look at the four areas one by one.

The electron spectrograph at Bates, combined with its sophisticated beam-handling system producing dispersion matching, represented a giant step forward in instrumentation for electron scattering processes. The instrument has a resolving power of about 1 part in  $10^4$  with a beam-energy spread of about 3 parts in  $10^3$ . The solid angle is 3.4 msr and the momentum range is  $\pm 10\%$ .

A new electron spectrograph being constructed for the Instituut Voor Kernfysisch Onderzoek in Amsterdam is somewhat more advanced than the Bates spectrograph. It has a solid angle of 10 msr and a larger dispersion than the Bates instrument  $D=4.9$  vs. 3.3 for the Bates instrument. The IKO spectrograph can also be operated in conjunction with a hadron spectrometer for coincidence measurements. It is expected that the Amsterdam facility will be in operation in 1980.

Another energy-loss spectrograph, operating with a proton linear accelerator, is the high-resolution spectrograph (HRS) at Los Alamos. It has a capability of bending 800 MeV protons and has demonstrated a momentum resolving power of better than 1 part in 10,000 with a beam-spread of 4 parts in 1,000. The solid angle is 2.5 msr.

For nuclear reaction studies with light particles the various version of the QDDD spectrograph represent the state of the art. The differences between the earlier instruments (Heidelberg, Munchen, Princeton, Brookhaven, Los Alamos, Chalk River and Saclay), and the latest version is partly that the newer instruments (Groningen and Strasbourg) have less dispersion and also that the focal plane is straight. By lowering the dispersion it was possible to increase the range of the instrument and resolving power was not sacrificed because of the newest developments in focal plane detectors. A Groningen type of spectrograph has also been built for the Hahn Meitner Institute in Berlin, where it will

EXISTING ISOL FACILITIES

Table III.4

ISOL Installation	Mean Radius m.	Magnet Characteristics		Focusing Double or Single	Type	Name	Accelerator Beams	Energy	Location
		Deflection Angle deg.	Radius m.						
<b>Heavy-Ion Accelerators</b>									
IMISOR	1.50	90		D or S	Cyclotron	ORIC	HI	100 Q <sup>2</sup> /A	ORNL, USA
GI ISOL	1.50	55		D	Linear	UNILAC	HI	2-8 MeV/A	GSI, West Germany
FINGIS	2.00	90		S	Cyclotron	225 cm U-300	$\alpha$ , HI	43 Q <sup>2</sup> /A	Stockholm, Sweden
KMS-II	.80	60		D	Cyclotron	Cyclone	HI	4-8 MeV/A	Dubna, USSR
LI SOL	1.50	55		D	Cyclotron	88 inch	P, d, <sup>3</sup> He, $\alpha$ , HI	110 Q <sup>2</sup> /A	Leuven, Belgium
RMMA	.67	60		S	Cyclotron		P, d, <sup>3</sup> He, $\alpha$ , HI	140 Q <sup>2</sup> /A	Berkeley, USA
<b>Light-Ion Accelerators</b>									
ISJIDE	1.50	55		D	Synchrocyclotron		P, <sup>3</sup> He	600 MeV	Cern, Switzerland
ISCELE	.80	75		Inhomogeneous Field n=1/2	Synchrocyclotron		P, <sup>3</sup> He	200 MeV <sup>3</sup> He	Orsay, France
TOKYO ISOL	.60	45		D	FM Cyclotron		P	53 MeV	Tokyo, Japan
PRINCETON ISOL	1.50	90		S	Cyclotron		P, d, <sup>3</sup> He, $\alpha$	60 Q <sup>2</sup> /A	Princeton, USA
JYASKYIA ISOL	1.50	55		D	Cyclotron		P, d, <sup>3</sup> He, $\alpha$	20 Q <sup>2</sup> /A	Jyväskylä, Finland
EMOMIB	1.50	55		D	Synchrocyclotron		P	2 GeV	Dubna, USSR
<b>Reactors</b>									
TALSTAN	1.50	90		S	Reactor		n	thermal	BNL, USA
OSTIS	.215	77.5		S	Reactor		n	thermal	Grenoble, France
STAIUS	.60	90		S	Reactor		n	thermal	Strasbourg, France
OSIRIS	1.50	55		D	Reactor		n	thermal	Studsavik, Sweden
SCAR	.305	60		S	Reactor		n	thermal	Battelle, USA
LALE	1.50	90		D	Reactor		n	thermal	Buenos Aires, Argentina
JOSEF	1.25	312		?	Reactor		n	thermal	Julich, West Germany
SOLIS	1.50	55		D	Reactor		n	thermal	Soreq, Israel

(cm<sup>2</sup>sec<sup>-1</sup>)  
flux

be used in conjunction with a heavy-ion cyclotron. The vacuum system is all metal so that the best possible vacuum can be obtained, minimizing charge exchange for heavy ions. A third and similar Groningen-type spectrograph has been contracted for by the English heavy-ion facility at Daresbury, and a fourth one has been ordered by a nuclear physics laboratory in Peking.

Heavy-ion spectroscopy is in many respects different from proton and alpha-particle spectroscopy. It is more difficult to identify the particle ( $Z$  and  $A$ ), angular distributions vary more rapidly, the energy resolution is often severely limited by target and beam parameters, etc. Recognizing that superb resolution (one part in  $10^4$ ), is normally not attainable for heavy ions, DeVries and Elmore have proposed a superconducting instrument with primary emphasis on solid angle or "data-collecting power" in general. The momentum and the reaction angle are both determined by "raytracing" techniques which have long been used in high-energy physics. The particle orbits are traced with the aid of three large two-dimensional multiwire detectors--one between the two magnetic elements, and two following the dipole. According to the plans, the latter two detector planes can be separated by as much as 10 meters to provide a relatively long flight path for time-of-flight measurements. Energy loss information from the detectors also aids in identifying the particle.

A Heavy-Ion Spectrometer System (HISS) is being designed for operation in conjunction with the Bevalac Accelerator at Berkeley. The spectrometer is intended to be used for particles with energies of the order of 1 GeV/nucleon or more, and the detectors will be required to determine  $Z$ ,  $M$  and  $\vec{p}$  simultaneously for many particles from an individual interaction. The central component of HISS is a superconducting magnet with circular pole faces, 2 meters in diameter and a pole gap adjustable up to 1 meter. The maximum field strength at 1 meter pole separation will be 3 Tesla. By adding pole pieces and reducing the gap to 0.2 meters, it will be possible to attain a field strength of 3.6 Tesla.

Another less ambitious project, but with a new twist, has been proposed by the Physics Department at the University of Washington. This spectrograph is designed specifically for zero-degree or small angle operation. It has a relatively low momentum dispersion at an intermediate focal plane and zero momentum dispersion at the final detector. It is intended for time-of-flight measurements (to determine the mass) where the beam or elastically scattered particles must be separated out before the final detector. This particular instrument is a result of a dilemma that exists in heavy-ion spectroscopy. The dilemma is that it is very difficult to measure the time of flight through a standard magnetic spectrograph to a high accuracy at the same time as a reasonable

solid angle and decent resolution is maintained. A very simple theorem states that the uncertainty of the length of the flight path through the instrument is given by the expression  $\Delta L/L = \Delta\theta RD/ML$ , where  $\Delta\theta$  is the uncertainty in reaction angle,  $R$  is the orbit radius,  $D$  is the non-dimensional dispersion,  $M$  is the magnification and  $L$  is the length of the flight path. The first order momentum resolution is given by  $\Delta p/p = X_t M/RD$  where  $X_t$  is the target spot size. The product of the attainable time resolution and the momentum resolution is therefore  $(\Delta p/p)(\Delta L/L) = \Delta\theta X_t/L$ . In most modern instruments  $RD/ML$  is approximately equal to unity. Therefore, to determine the velocity to, for instance, 0.2 per cent, one needs to know the angle  $\theta$  to about 2 milliradians.

The electro-magnetic isotope separator on-line (ISOL) to a nuclear reactor or accelerator is an almost classical tool for nuclear structure studies first used in Denmark in 1950. Essentially unusable then for lack of data acquisition technologies, ISOL systems strongly increased in interest in the mid-1960's with the advent of semiconductor detectors, particularly Ge(Li), and of "large" data acquisition systems. Beginning with several pioneering projects (Princeton with an internal fission source, ISOLDE at the CERN proton synchrotron, TRISTAN at the Ames reactor), there are now a number of ISOL systems in existence or planned at accelerators and reactors throughout the world, with an overwhelming majority in the European countries. Although the parameters (current capabilities, resolution, dispersion, angle-of-bending, etc.) vary somewhat, all ISOL systems employ relatively simple dipole magnets and mostly use electrostatic lenses. Mass resolutions are of the order of  $2 \times 10^{-4}$ , dispersions are in the vicinity of 150 cm/A, and total system efficiencies are in the range  $\ll 1\%$  to 30%, dependent primarily on the element being separated. The major differences in such ISOL systems, and the areas in which developmental work is taking place, are in the coupling of the production device to the isotope separator and in the post-separator portion of the system--separated-beam transport, experiment capabilities, data acquisition capabilities.

### Spectrographs of the Future

For light ions the Q3D type of spectrograph seems to meet most needs, both for resolving power and solid angles. Instruments of this kind represent a total investment of close to \$1 million and it is, of course, wise to utilize them as efficiently as possible. Considerable efforts have been put into developing good electronic detectors and readout systems, and these efforts should certainly continue. The various detectors in use in existing spectrographs are enumerated in the following section.

For heavy ions produced in nuclear reactions one needs to measure the energy, the mass, and the element number. Very often one also needs to determine the reaction angle to a higher precision than is generally acceptable for light ions. The cross-sections are often small, which means that a large solid angle of acceptance is called for. Magnetic fields can only help in determining the momentum of the particle and produce focusing. Therefore, all of the other tasks must be handled by the detector and/or by the use of the time-of-flight technique. What is needed is a large solid-angle instrument matched to a detector that can determine the position in two dimensions; the energy loss  $\Delta E$  with the highest possible accuracy and the total energy  $E$ , also with high accuracy. The arrival time must be measured with an accuracy of better than one nanosecond. The detector or detectors must also be capable of determining the angle of incidence of the particle (for flight-path correction) to a few milliradians. The state of the art of both spectrograph design and detector design is now at the stage where intelligent choices can be made for such a complete heavy-ion spectroscopy system.

One of the authors of the present report has made some very preliminary ray-tracing work on the ion optics of QQDD instrument for heavy ions. The instrument is intended to be mounted vertically and the optics is such that the reaction angle can be determined by the y position on the detector, whereas the x position measures the momentum. It is expected that the instrument can have a solid angle of up to 35 msr.

Recoil mass instruments such as the EMS at Brookhaven National Laboratory and the SHIP at GSI represent a new area of instrumentation. It is expected that many of these types of spectrographs will be built in the future, specifically for collecting evaporation residues in fusion reactions and spallation products in high energy reactions. The heavy ions in these reactions are emitted in a relatively narrow cone in the forward direction and therefore need to be separated from the main beam, as well as from the low energy components of the beam which may be too intense for the detector. This can only be done efficiently with a combination of electric and magnetic fields.

In a fusion reaction the momentum/charge ratio of the recoiling evaporation residues is typically very close to that of the beam (momentum is conserved and the mean charge states are similar). Therefore, a magnetic spectrograph alone is not the right instrument for these reactions. The velocity of the evaporation residues is typically 1/3 to 1/2 of the velocity of the main beam. Therefore, an ExB velocity selector is more useful and can easily separate out the full-energy beam. Heavy-ion beams, however, have low energy tails, some of which have the same velocity as the evaporation residues.



It turns out that a separate-function velocity selector consisting of three units with E, B, and E fields, respectively, can be used to effectively get rid of the beam and the tail.

The design of a recoil mass spectrograph for heavy ions (evaporation residues, etc.) is further complicated by the fact that we are dealing with two characteristics (velocity and mass/charge) that produce dispersion in electromagnetic fields. The most convenient parameters to use are  $\delta_v = \Delta v/v$  and  $\delta_m = \Delta m/m$ . (In momentum spectrographs we use  $\delta = \Delta p/p$ .) Corrections of the chromatic aberrations are further complicated by the fact that the dispersion produced by available E-fields are small. There are, altogether, eight important second-order terms that need to be eliminated if an instrument of this kind produces good mass resolution at solid angles of the order of 1 msr or larger. The new heavy-ion facilities require instruments of this kind, and more effort should be put into their development and design at this stage.

With regard to ISOL instruments, the design of isotope separators themselves satisfactorily meets the needs for virtually any conceivable on-line system. The primary deficiencies in all on-line systems are beam/target/ion-source combinations to produce isotopes of interest in usable quantities. Although there have been a number of advances in recent years, it is generally true that a given design is usable only for a specific element at a specific facility. For example, ISOLDE target/ion-sources are not usable at an ISOL facility employing a heavy-ion accelerator. Continued development for such specific cases is certainly required. However, it would be extremely useful if more general ion-source development efforts could take place. For example, the possibility of r.f.- and laser-induced ionization could be investigated. Two additional areas for development are the continued reduction of energy dispersion in order to make use of new laser techniques to study hyperfine interactions, and development of techniques for fast, on-line Z-separation.

### Focal Plane Detectors for Magnetic Spectrographs

Table III-5 reviews the present status in the United States. Twenty low- and medium-energy laboratories possess reasonably modern spectrographs equipped with live focal-plane particle detectors.

The first columns give relevant properties of the magnet. The abbreviations are as follows: ESP - Enge Split-Pole, Q - Quadrupole, D - Dipole, M - Multipole, S - Sextupole, Det. motion - Detector motion, Kin, Corr. - Kinematic Correction.

The column labelled " $\Delta p/p, \text{mm}^{-1}$ " gives the inverse of momentum dispersion along the focal plane. This quantity

is deemed the most valuable in a review of detector properties because it can be used directly to translate a given detector position resolution into momentum resolution.

The column  $\theta_i$  gives the angle of incidence of particles on the focal plane, measured to the normal. Large values of  $\theta_i$  pose special problems for detectors.

The shape of the focal plane qualitatively influences detector design. However, except for devices which reconstruct the focus by ray-tracing, no detector is in use in the U.S. which conforms exactly to a curved focal plane (nor is that considered a serious defect).

The last columns in the table list detector properties: PC - Proportional Counter, MWPC - Multiwire Proportional Counter, IC - Ion Chamber, MWDC - Multiwire Drift Chamber, Si - Silicon Position-Sensitive Detector, BK - Borkowski-Kopp technique, DL - Delay Line, CD - Charge Division.

We have indicated which detectors are capable of angle readout in at least one plane. We have also specified LI (light ion) or HI (heavy ion) when a detector is almost exclusively confined to one or the other, but no entry has been made in that column if the detector is used for both. Finally, the column labelled FWHM indicates the best position resolution, in mm full width at half maximum, recorded under conditions reasonably approaching realism.

Table III-6 lists similar data for 22 non-U.S. laboratories. We have not been successful in obtaining complete data for all foreign laboratories. As in Table III-5, the entries are confined to spectrometer systems already in existence, or at least in the final states of construction.

We may make the following remarks on the present state of the art:

1. The performance of focal plane detectors has strongly influenced the design of magnetic spectrographs. Table III-7 lists the dispersions of the family of Q3D spectrographs as manufactured by Scanditronix AB according to the design of H. A. Enge. The list is in chronological order, and shows the steady reduction in dispersion. Low dispersion usually results in significant advantages in other areas (lower cost, larger momentum acceptance, etc.) but places demands on detector performance. The first Q3D was to some extent a response to the primitive state of focal plane detector development at the time, and resulted in a magnet with an excessively long focal plane and limited momentum "bite". Nowadays more compact magnets can give equivalent performance at lower

Table III.5  
U.S. Laboratories with magnetic spectrographs and focal-plane detectors

Laboratory	Magnet	$\frac{\Delta p}{p}$	$\Delta p$ mm <sup>-1</sup>	$\theta$	Surface Shape	Kin. Corr.	Det. Type	Length	x Readout	y Readout	Angle	L1/HI	FWHM
1. Argonne	ESP	6.6 x 10 <sup>-4</sup>		45	= Straight	Det. motion	PC-IC PC	50 14,25 50,90	BK BK	IC	X	HI	0.8 1
2. Bates - MIT	QOSP	5.5 x 10 <sup>-4</sup>		46	Curved	ray tracing	MWDC		DL	DL	X	LI	0.14
3. Berkeley	QSD	2.6 x 10 <sup>-4</sup>		0	Curved	Det. motion	PC-IC	45	BK	Drift	X		
4. Brookhaven	Q3DI	0.8 x 10 <sup>-4</sup>		43	Curved	Multipole	MPPC	50,70	DL				0.2
5. Colorado	Zoom lens	1.6 x 10 <sup>-4</sup>		20	Straight	None	PC PC-IC	62 66	DL DL		X		0.5
6. Indiana	QDDH	0.7 x 10 <sup>-4</sup>		46	Curved	Multipole	PC PC-IC	45	DL BK		X	HI	0.5
7. Los Alamos	Q3DI	0.8 x 10 <sup>-4</sup>		43	Curved	Multipole	PC	25	DL				0.33
8. LANP (HRS) (EPICS)	QDD QQDD	0.55 x 10 <sup>-4</sup> 2.2 x 10 <sup>-4</sup>		-- 0	Curved	ray tracing ray tracing	MWDC MWDC-MPPC	60x10 54	DL	DL	X X	LI LI	0.25
9. Maryland	QDS	2.5 x 10 <sup>-4</sup>		0	Curved	Multipole, Det. motion	PC		CD				
10. Michigan State	ESP	6.6 x 10 <sup>-4</sup>		45	= Straight	Det. motion	PC PC PC	25,50 20,50 10	DL CD DL	Drift		LI HI	0.22 0.6 1.0
11. Notre Dame	QDD	1.5 x 10 <sup>-4</sup>		55	Curved	None	PC	4	CD	Drift			0.5
12. Oak Ridge	Q-Elbek ESP	4 x 10 <sup>-4</sup> 6.6 x 10 <sup>-4</sup>		54 45	Straight = Straight	Det. motion Det. motion	PC	20	BK				0.7
13. Pennsylvania	QD	4.4 x 10 <sup>-4</sup>		64	Curved	None	S1	5	CD				0.5
14. Pittsburgh	ESP	6.6 x 10 <sup>-4</sup>		45	= Straight	Det. motion	PC	50	DL				
15. Princeton	Q3DI	0.6 x 10 <sup>-4</sup>		43	Curved	Multipole	PC	23	CD				
16. Rochester	ESP	6.6 x 10 <sup>-4</sup>		45	= Straight	Det. motion	PC-IC Spark PC	25 61 30,60	CD Acoustic CD		X	HI	1.2 0.7 1.1
17. Rutgers	ESP	6.6 x 10 <sup>-4</sup>		45	= Straight	Det. motion	PC	20	CD		X	HI	1
18. Seattle	QD	4.4 x 10 <sup>-4</sup>		64	Curved	None	PC-IC	57	CD		X	HI	1.2
19. Texas A&M	ESP	6.6 x 10 <sup>-4</sup>		45	= Straight	Det. motion	PC PC-IC	16	CD CD		X	HI	1
20. Yale	Multigap	2.4 x 10 <sup>-4</sup>		64	Straight	None	PC	45	CD				

Table III.6  
Foreign Laboratories with magnetic spectrographs and focal plane detectors

Laboratory	Magnet	$\Delta p$ p	$\theta$	Surface Shape	Kin. Corr.	Det. Type	Length	x Readout	y Readout	Angle	L1/HI	FWHM
1. Auckland	ESP	$9.9 \times 10^{-4}$	45	= Straight	Det. motion	S1	5	CD		X	LI	0.5
2. Bonn	ESP	$6.6 \times 10^{-4}$	45	= Straight	Det. motion	PC	25	DL		X	LI	0.22
3. Cambridge	ESP	$6.6 \times 10^{-4}$	45	= Straight	Det. motion	PC-IC	50	BK		X	LI	1.0
4. Chalk River	Q3DII	$0.8 \times 10^{-4}$	37	Curved	Multipole	MMP	70	Direct			LI	1.0
5. GSI, Darmstadt	SQDDSQ	$(1.6-6.6) \times 10^{-4}$	0		Multipole	PC-IC	50			X	HI	1.7
6. Grenoble	QD					PC	25 x 5	DL	DL			0.5
7. Groningen	QMG2	$0.9 \times 10^{-4}$	45	Straight	Multipole	PC	52 + 52	CD	Drift	X	LI	1.0
8. HFI, Berlin	Q3DII			Curved	Multipole	PC-IC	56	DL				
9. KFA, Jülich	QQDDQ	$0.6 \times 10^{-4}$	0	Curved	Multipole	MMP	30	DL	DL			0.4
10. KFI, Heidelberg	Q3DI	$0.5 \times 10^{-4}$	43	Curved	Multipole	PC	60	CD	Drift	X	HI	0.6
	Multigap			Straight	None	PC	60	DL				1.2
						PC	110	CD				
11. McMaster	ESP	$6.6 \times 10^{-4}$	45	= Straight	Det. motion	PC	25	DL			LI	0.5
12. Munich	Q3DI	$0.5 \times 10^{-4}$	43	Curved	Multipole	MMP	200	Direct		X	LI	1.0
						PC-IC	20	CD			HI	2.0
13. Orsay	ESP	$6.6 \times 10^{-4}$	45	= Straight	Det. motion	PC	43	CD			HI	1.0
						PC-IC	40	CD		X	HI	0.7
14. Osaka	QDDQ	$2.0 \times 10^{-4}$	55	= Straight	Det. motion	PC	50 + 50	CD			LI	1.0
15. Saclay	Q3DII	$0.6 \times 10^{-4}$	52	Curved	Multipole	PC		CD			LI	1.5
	SPESI(QDD)	$0.8 \times 10^{-4}$	37	Curved	Multipole	MMP	60	CD	CD		HI	1.5
	SPESI(QD)	$1.8 \times 10^{-4}$	55	Straight	Ray tracing	PC-DC	170	CD	CD		LI	0.4
16. Sao Paolo	ESP	$6.6 \times 10^{-4}$	45	= Straight	Det. motion	PC	40	BK			LI	0.4
17. SIN, SUSI	QDD	$1.8 \times 10^{-4}$	55	= Straight	Ray tracing	MMP	102.4	DL	DL	X	LI	2.0
18. Strasbourg	Q3DII	$1.0 \times 10^{-4}$	45	Curved	Multipole	PC						
19. Tokyo	QDD	$2.6 \times 10^{-4}$	55	Curved	Det. motion	PC						
20. TRIUMF	QD					MMP				X	LI	
21. Tsukuba	ESP	$6.6 \times 10^{-4}$	45	= Straight	Det. motion	PC						
22. Vrije Universiteit	ESP	$6.6 \times 10^{-4}$	45	= Straight	Det. motion	S1	5	CD				0.5

Table III.7  
Dispersions (along focal plane) of Q3D spectrographs

Scanditronix Type	Lab	Dispersion <sup>-1</sup> (mm <sup>-1</sup> )
E100	MPI, TUM	5.3 x 10 <sup>-5</sup>
E90L	Princeton	5.8 x 10 <sup>-5</sup>
F90L	ORNL, BNL, LASL, CEN	7.8 x 10 <sup>-5</sup>
G120L	KVI	8.8 x 10 <sup>-5</sup>
H88	Strasbourg	10.4 x 10 <sup>-5</sup>

cost, largely thanks to improvements in focal plane detector design. This is a clear instance of the economic benefits of a concerted program of instrument development.

2. We see little cause for panic of the "we-are-falling-behind-the-Europeans" variety in the area of focal plane detector development. Many of the novel features of detectors being adopted world-wide originated in the U.S. Among these are the original Borkowski-Kopp readout technique (now largely superseded), the use of distributed delay lines, and the highly successful Argonne-Rochester heavy-ion detector.
3. The progress of focal plane detector development seems limited more by ingenuity than by funding or policy. They are not expensive devices, even the most sophisticated, especially when measured against the cost of the magnets they serve, and we therefore see little to be gained from a large increase in funding in this area. On the other hand, steady support for investigators trying new techniques (e.g., liquid media, secondary emission, avalanche detectors, etc.) is clearly in order, not only in the context of improving the capabilities of existing spectrometers, but even more in the profound influence it may have on the design of future magnetic devices.

## 5. DETECTORS

### Introduction

The following summarizes the current status, the future possibilities, and our recommendations about the use and development of detector systems in low and medium energy nuclear physics. It covers those detectors undergoing rapid development at the present time: Liquid-ionization chambers, NaI detectors, proportional and drift chambers, and plastic flash chambers.

The report is based on information supplied by physicists involved in laboratory or research management, in design, construction and use of the detectors, or in research and development of such detectors. The continuous spectrum of research groups and laboratories can be subdivided into the following four levels: (a) User groups (for example: a university group using LAMPF); (b) Small accelerator laboratories with users primarily from a single institute (for example: a university tandem Van de Graaff laboratory);

(c) Accelerator laboratories with regional user groups (for example: ORIC); and (d) Accelerator laboratories with national user groups (for example: LAMPF, Bevelac). The funding of detector development at these institutions is complicated, but a rough level of current effort is about 15 physicists and technicians per year, corresponding to about \$800,000 per year.

#### Current Status and Future Outlook

Ionization chambers of liquid Ar are under intensive development at institutions in categories (a) and (d) above. Particles ranging from electrons to heavy ions are detectable with excellent spatial and energy resolution. By collecting ionization over a wire grid, it is possible to get  $dE/dx$  information with sufficient accuracy and redundancy to give good particle identification. If present efforts to increase the drift distance for electrons are successful, chambers up to one meter in depth, with a single readout grid, are feasible. Liquid Xe detectors, which have the promise of excellent ( $\sim 1\%$ ) gamma ray energy resolution, are being looked at in level (d) institutions. At present there are only a few active projects in each type of detector. The low temperature technological problems are severe enough that collaboration with low temperature groups should be encouraged.

Large NaI detectors are a common detector for gamma rays of tens of MeV energy. A new version of such a detector, in the form of an extensive array of blocks of NaI, is in operation at SLAC (the "crystal ball") and is planned at LAMPF (a "crystal box"). These NaI systems provide moderate spatial resolution (a few cm) as well as good energy resolution, and approach  $4\pi$  geometrical coverage. There is close collaboration between these two groups. The cost of the proposed LAMPF version is high, approximately \$350,000, but justified by the much greater efficiency afforded by the  $4\pi$  geometry.

Proportional and drift chamber systems have been used primarily as focal plane detectors in levels (a) through (c), while in (c) and (d) much more use has been made of them as track finding devices. At all levels satisfactory arrangements have been set up to cope with the current need in design and construction of conventional proportional and drift chambers. Good communication and transfer of knowledge and expertise seem to exist among nuclear physics and high energy physics laboratories concerning the detector technology.

There is considerable activity in continuous improvement of focal plane detectors. Current interest is in position-sensitive avalanche counters, vertical drift chambers and other proportional chambers which are slight modifications from conventional designs. For each institution, the manpower

devoted to such activities is roughly one man-year of physicists plus one man-year of technician time. This is a typical situation at level (c). The activities are motivated by requirements either for specific experiments or for specific experimental facilities such as a magnetic spectrometer. Their budgets, therefore, are derived from the physics research or facility budgets.

It is expected that in the near future much more complex detector systems having multiple arrays of large column wire or drift chambers will be used in nuclear physics. This is especially so with new medium energy accelerators, including those using heavy ions. The trend is already apparent for the Bevalac; at which a large drift chamber system for a multiparticle spectrometer and a Xe-filled long drift chamber for ionization measurements are being considered for construction. There is great interest amongst nuclear physicists in the development of the Time Projection Chamber. The initial version is being built at LBL for use at PEP. Other versions are under construction at TRIUMPF and, for heavy ions, at Saclay; there are two proposals for such devices at LAMPF.

Thus, within several years, usage and complexity of proportional and drift chambers in nuclear physics is expected to increase dramatically. Construction of such detector systems requires collaboration of the laboratory and users involved, but it is also highly desirable for such a group to be able to draw technical expertise, experience, and necessary experimental results and knowledge from individuals and national centers which sustain systematic research and development on physics and electronics related to proportional and drift chambers. It should be noted that a serious problem exists in the amount of off-line computation needed for event reconstruction and selection. It is recommended that attempts be made to design smart trigger logic, perhaps super-fast microprocessors, at the computer input to limit the amount of data to be handled off-line.

A new type of inexpensive, large area, position sensitive device--the plastic flash chamber--is being developed at laboratories in the (a) and (d) levels. This chamber is based upon the availability of "corrugated" plastic panels operating as a large set of pulsed discharge tubes. Present research is concentrating upon reliable, but inexpensive, electronic readout systems. These detectors are presently proposed for neutrino experiments, and have applications to other large mass experiments, such as those in cosmic ray physics and astrophysics. Again, there is good transfer of knowledge between the nuclear and the high energy laboratories engaged in these developments.



## Proposed Research and Development

Most research and development of detector systems is for a specific use. There are only a few groups in the U.S., mostly in level (d), which have any systematic research and development program in the physics and electronics problems of detector systems. Generally, these groups do research and development applicable not only to nuclear physics but also to other areas including applied fields, such as X-ray detection for synchrotron radiation, plasma diagnostics, medical applications, etc. The sizes of the groups range from 1 to 5 physicists plus 1 to 4 technicians, and a good fraction of their funds come from areas other than nuclear physics.

These groups appear to work in a climate which is less favorable to their continued existence than that of their European counterparts. They are usually subsections of instrumentation divisions or of larger research groups, and have the danger of falling apart under the pressure of higher priority projects.

The existing research and development groups appear to be well utilized, both within their own laboratories and also by outside groups in various fields of discipline. The principal function to outside groups is in consultation, and transfer of technology and experience, but in a few instances detector fabrication has also been carried out. However, in order to be truly effective, these groups should have a well-balanced mixture of research directed toward specific short-range goals, and directed toward qualitatively different uses of physical processes in detectors.

It is recognized that a healthy detector development program depends both on "mission-oriented" research intended to produce a detector for a specific application, and research into detection systems and processes per se. At present there appears to be no serious difficulty about funding the first type of research, inasmuch as the regular peer review system ranks it against other demands for the available funds, with due consideration of the physics that can be learned. The second type of research, in common with many other forms of instrumentation development, depends heavily on the proclivities of individual researchers. We urge the continued support of the latter type of research, and suggest that it should compete for funds on an equal footing with other forms of basic research, rather than being relegated to the status of a technical service.

## 6. ELECTRONICS

### Introduction

All developments in electronic aspects of instrumentation for nuclear science are dependent on and closely related to developments in detectors and detection techniques. By "electronics" we define here a broad range of functions dealing with extraction of information from detector signals. The functions required are low noise amplification, signal processing (i.e., filtering), amplitude and time measurement, particle position encoding and fast preprocessing, or data reduction specific to a particular experiment and not including the data acquisition (computer) systems. There have been recent detector developments with well developed applications in nuclear science, and some new detector developments in high energy physics which are of interest, if further developed, for medium and high energy heavy ion physics. The former are mainly gas position-sensitive detectors. The latter include  $4\pi$  detectors for multi-particle events providing information on position, energy and particle type. While some spectacular detector-electronics systems have been built and used, this field of work is a fertile ground for new developments to be expected in the next several years. The electronic problems are related to the physical mechanism and limitations in the detection process. The most important ones are fast low noise amplification, high resolution position encoding techniques, fast analog-to-digital conversion techniques for amplitude and time, and to a certain extent, fast decision-making. To make significant advances in these areas requires, in some cases, development of new or improved semiconductor devices and monolithic circuits. A significant advance in fast low noise amplification can be made through the development of better field-effect transistors. The development of fast digital monolithic circuits should be left to the semiconductor industry, where there are many large efforts. To our knowledge, no industry is involved in the development of low noise field-effect transistors suitable for nuclear detectors, and special effort would be necessary to bring about such a development.

There is a new aspect to the development of electronics for nuclear particle detectors. While the developments of detectors and electronics have always been closely related, they have become inseparable with the advent of complex position-sensitive detectors or very large detector arrays involved in a " $4\pi$  system". Thus separation of efforts in electronic and detector developments should be avoided.

## Recommendations

R&D in electronics for nuclear detectors should be supported on a continuing basis, subject to an appropriate review procedure to determine its direction. Such research is best performed in parallel with an ongoing research and development program on detectors or as a part of such a program at institutions where there is a strong nuclear science program. The groups pursuing such a research and development program should always have a dual role: (1) to be involved in development and implementation of a practical detector system for a particular experiment in close collaboration with a group primarily interested in nuclear science research, and (2) to be involved in research and development of instrument techniques with considerable freedom in the choice of problems.

Considerable benefit could be derived from parallel activities in the development of detectors for other areas of science where many similarities exist. Examples of these are high energy physics, research with synchrotron radiation and research based on neutron scattering. Supporting such a broad program as outlined above is probably most efficient. Well defined significant, special and recognized problems may be supported separately. One such problem is the development of low noise devices. Problems such as fast timing and good resolution at high rates are many-component problems best attacked as a part of a broader program of detector and electronics development.

It would be best to support such a program at more than one institution for obvious reasons.

## 7. DATA ACQUISITION AND ANALYSIS

### Introduction

Data acquisition hardware, together with all other aspects of computing, has evolved dramatically in the past decade. While the cost of computer hardware has continued to fall rapidly, at a rate of about 16%/year, this effect has been overshadowed by the increasing sophistication of the experiment performed. Higher and higher raw data rates and the growing complexity of the reactions studied have placed ever-increasing demands on data acquisition systems. It has become clear, however, that balance is more important in data acquisition than raw speed. There is a complex interplay between trigger systems, hardware readouts, computer data interfaces, computer storage devices, operating system software, and on-line and off-line analysis software. System engineering techniques can identify weak areas where more

performance is needed and strong areas where greater economy is possible. Finally, it must be noted that human engineering becomes increasingly important as more complex research is attempted. The systems that are developed should be understandable and easy to use. Simplicity is to be praised and otherwise encouraged.

In the sections that follow, we first outline the current "state of the art" in data acquisition, and then examine the level of instrumentation presently in use in nuclear science, making recommendations for improvement where appropriate. As detector technology, analog signal processing, and fast trigger logic are discussed in other sections of this report, we begin our considerations at the analog to digital conversion and interface section of a general data acquisition system.

### Frontend Systems

Modern interface hardware frequently makes extensive use of integrated circuits, including LSI technology. Microprocessors and microprogrammed bit-slice processors can provide intelligent "pre-processing" of data prior to transmission of the data to a computer. Low cost MOS and bipolar memories can also be employed at this stage for fast buffer storage. The use of these frontend processors and buffer memories permit significantly higher data rates and shorter dead times while decreasing the computing and response time requirements on the data acquisition computer.

CAMAC has clearly emerged as a useful hardware standard interface for data acquisition systems. In addition to the broad range of digital interface modules, which have been available for many years in CAMAC, we now find state-of-the-art spectroscopy ADC's with conversion times of approximately 5  $\mu$ sec are available. Low cost, high density conversion systems, originally developed for high energy physics, will also be applicable to large nuclear detector systems currently in the design stage. While the initial cost of adopting the CAMAC standard is typically higher than the cost of a small, more specialized, dedicated interface, this cost is amply offset by the well-known benefits of standardization, and the incremental cost of additional interface devices is significantly lower. A variety of microprocessors and microprogrammed bit-slice processors are now available in CAMAC, both at the branch driver level and as auxiliary crate controllers, providing a rate capability and flexibility rarely achieved in dedicated interface systems.

CAMAC was originally developed in the 1960's and has enjoyed widespread acceptance in the high energy physics community and a growing acceptance in the nuclear physics

community. To take advantage of the dramatic increases in device complexity since that time, the high energy community is currently working on the definition of a new interface standard called FASTBUS. FASTBUS is likely to become a firmly specified standard in 1980, although it will take a considerable amount of time before the variety of standard modules available will rival those currently obtainable "off the shelf" from manufacturers of CAMAC hardware. FASTBUS is, however, a standard that should be carefully watched and encouraged, as it promises to be considerably faster and more flexible than CAMAC. It is expected to provide a significantly more powerful framework for the application of distributed intelligence to data acquisition, and represents the most probable direction for future large systems.

### Computer Systems

Modern 16-bit minicomputers, typically costing between \$50K and \$150K, are currently well suited for data acquisition, while the newer, 32-bit midicomputers, costing \$150K - \$500K, offer dramatically increased computing power for modest cost. The 16-bit minicomputers have a restrictive address space which precludes running large tasks in them easily even if their physical memory is large. However, they respond well to real-time interrupts, typically requiring between 50 and 100 microseconds. The 32-bit midicomputers have a very large address space which eases the development and operation of acquisition and analysis software considerably, but their more elaborate operating systems, as supplied by the manufacturer, tend to incur interrupt latencies of 500 to 1000 microseconds, limiting their direct applicability to real-time data acquisition. The evolution of low-cost, high density memory technology has reduced the price of computer memory drastically in recent years, bringing megabyte storage capacity within the reach of most budgets. Advances in LSI technology have similarly reduced the price of devices such as floating point processors, providing significant improvements in the computing power of minicomputers. The availability of high speed memory devices has led to the use of control stores for the implementation of microcoded instruction sets, and to the development of writable control stores which permit the knowledgeable user to tailor the computer instruction set to his particular needs. Mass storage technology is also advancing, and 100 megabyte disk drives and high density (6250 bpi) tape drives are now available permitting improvements in data rate capability. Finally, the evolution of microprocessors has led to the development of "intelligent" peripherals such as graphics display terminals whose capabilities have significantly improved the man-machine interface. Microprocessors are also providing powerful, cost-effective solutions for dedicated, modest-speed computer applications such as experiment and beam line control and monitoring.

## Software

Computer software has also improved considerably over the last decade. Real-time, multi-user, multi-tasking operating systems are now available for most minicomputers, greatly reducing the effort required for the generation of complex data acquisition software. Higher level languages, such as Pascal, which have the power and efficiency to accomplish data acquisition reliably and effectively, are also available for general use. As computer hardware costs have continued to drop, the expense of generating the requisite software has come to dominate overall data acquisition system costs. Software maintenance on a large mini or midicomputer can easily absorb 1-5 man-years of effort per year. This is particularly true during hardware or software conversion periods. To reduce these costs in the future, efforts must be made to develop general purpose software packages that are significantly more "portable" or hardware-independent. Higher level languages, such as Pascal (and also FORTRAN), offer a possible aid in this effort. Furthermore, a general transition from simple spectrum accumulation experiments to event mode recording, together with the availability of larger disks and denser tapes, is causing data analysis needs to rise rapidly. Data analysis now frequently requires as much as five times the computing resources used for data acquisition. Interpretive, array-oriented languages such as SPEAKEASY, which allow greater abstraction for accomplishing data reduction and analysis tasks, can reduce the programming effort required for data analysis at the expense of increased computer usage. Finally, it should be noted that there is a clear need for improved software development tools which will permit the writing, debugging, and testing of software without requiring the data acquisition frontend hardware, an accelerator, or any other scarce resource.

## Data Acquisition Systems Currently in Use, and Recommendations for Improvement

The attached table is a census (taken in January, 1979) of all computers currently used for data acquisition in nuclear science at laboratories whose annual operating budget exceeds \$350K. The average age of data acquisition systems in use at university laboratories is now 7.7 years, and the average age of systems at the national laboratories is 4.8 years (3.9 years if ORELA is omitted from the list). Over one third of the university laboratories are currently using computers over 10 years old, placing them sadly behind the state of the art. (At least two identifiable generations of new minicomputers have evolved over the last decade.) The age of these computers has several serious implications for the research effort in nuclear science. The raw computing capacity of these older systems is frequently over two orders

DATA ACQUISITION COMPUTER CENSUS  
(January 3, 1979)  
University Laboratories

Table III.8a

Laboratory	Support	Computer(s)	Approximate Age	Experiment Interface
Caltech	NSF	Nuclear Data 820	10	Dedicated ADC
Univ. of Colorado	DOE	DEC PDP-9	>10	Dedicated ADC
		DEC PDP-11/34	1	CAMAC + Dedicated ADC
Duke University	DOE	2 x DDP-224	13	Dedicated ADC
Florida State	NSF	EMR 6130	10	CAMAC
		Harris/4	5	
Univ. of Illinois	NSF	DEC PDP-15	10	Local standard - similar to CAMAC
Indiana Univ.	NSF	3 x Harris/4	5	CAMAC
Univ. of Maryland	NSF	IBM 360/44	12	Local standard
M.I.T. (Bates)	DOE	2 x DEC PDP-11/45	4	CAMAC
		DEX VAX	0	
Michigan State	NSF	XDS $\Sigma$ 7	10	CAMAC + Dedicated ADC
		DEC PDP-11/45	4	
		2 x DEC PDP-11/20	6	
Notre Dame	NSF	DEC PDP-9	>10	Dedicated ADC
Univ. of Pennsylvania	NSF	DEC PDP-11/55	3	CAMAC
Univ. of Pittsburg	NSF	2 x DEC PDP-15	5-9	Dedicated ADC
Princeton	NSF	DG Eclipse S/230	2	Dedicated ADC
Univ. of Rochester	NSF	DEC PDP-6	14	Dedicated ADC
		2 x DEC PDP-8	14	
Rutgers	NSF	XDS $\Sigma$ 2	11	Dedicated ADC
		DEC PDP-11/55	2	
Stanford-HEPL	NSF	DEC PDP-11/45	3	CAMAC
Stanford-Tandem	NSF	DEC PDP11/34	0	Dedicated ADC
SUNY - Stony Brook	NSF	2 x DEC PDP-9	10	Dedicated ADC
Texas A & M	NSF	IBM 7094	17	CAMAC + Dedicated ADC
		DEC PDP-15	8	
Univ. of Washington	DOE	DEC PDP-11/60	1	Dedicated ADC IEEE 488
Univ. of Wisconsin	DOE	Honeywell DDP-124	13	Dedicated ADC
Yale	DOE	IBM 360/44	12	Dedicated special

DATA ACQUISITION COMPUTER CENSUS  
(January 3, 1979)  
National Laboratories

Table III.8b

Laboratory	Computer(s)	Approximate Age	Experiment Interface		
ANL	4 x DEC PDP-11/45	6	CAMAC		
	1 DEC PDP-11/34	3			
BNL	Tandem XDS $\Sigma$ 7	9	Local Design		
	Hyper-nuclear Spect DEC PDP-11	4	CAMAC		
	HFBR DEC PDP-11/20	3			
		-11/34		3	
		-11/40		5	
LBL	SCC 660	11	CAMAC and dedicated ADC's		
	4 x Modcomp IV	4			
	DEC PDP-11/34	2			
		-11/45		3	
		-11/50		2	
	DEC VAX	1			
LASL	Tandem 3 x Modcomp 4/25	4	CAMAC		
	LAMPF* 9 x DEC PDP-11/45	4 (avg.)	CAMAC		
	3 x DEC PDP-11/34	2 (avg.)			
	1 DEC PDP-11/60	0			
	2 x DEC PDP-11/70	1 (avg.)			
	1 DEC VAX-11/780	0			
ORNL-ORELA	1 DEC PDP-10	9		CAMAC	
	4 x DEC PDP-15	9			
	3 x SEL 810B	10			
	1 DEC PDP-7	10			
	1 DEC PDP-9	10			
	1 DEC PDP-11/34	1			
	-Hollifield	2 SEL840A	10		(dedicated MCA) CAMAC
		4 DEC PDP-11	4		
		2 Interdata 8/32	0		

\*Not including computers currently at LAMPF which are owned by users groups.



of magnitude smaller than the capacity of modern minicomputers, implying limitations on the complexity of the experiments which can be performed. The smaller memory size supported by older computers is also a serious limitation to both data complexity and the sophistication of the on-line analysis and control available to the experimenter. Older computers will not support modern multi-user, multi-tasking operating systems, implying significantly increased software development time, and frequently restricting off-line analysis and program development to only those periods when the computer is not being utilized for data acquisition. Finally, maintenance and spare parts for many of these computers are becoming increasingly difficult to provide due to their obsolescence. It is clear that the evolving technology of data acquisition and processing systems requires either that these systems be replaced or undergo an equivalent upgrading to the current state of the art about every 7 years, resulting in an average age of 3.5 years. Systematic and continuing support is necessary to avoid the present situation in which the average age of data acquisition and processing systems in use at universities is close to 8 years. The demands of this evolving technology have left many nuclear science facilities woefully far behind. We strongly recommend a 6 million dollar impulse, in addition to the continuing support for all systems, to bring out-dated and out-moded data acquisition and processing hardware systems in nuclear science to an acceptable level.

It must also be recognized that the evolution of computer systems requires a similar upgrading of both support hardware and software, a cost which is often ignored when discussing new systems. This accompanying engineering and software effort exceeds the expense of the original computer hardware. To this end we feel that proposals for data acquisition systems should include a fairly detailed discussion of plans for the accompanying engineering and software. Since data acquisition also implies data analysis, how and where the data analysis will be performed should also be described.

While the lack of modern data acquisition hardware is an obvious problem, the mere accumulation of hardware may not provide an adequate solution. System integration is not a trivial problem, and, since system compatibility with other labs is unfortunately rare, we recommend that the use of CAMAC, a valuable, general purpose interface standard for nuclear science, be strongly supported and encouraged. Fewer than half of the university laboratories currently utilize the CAMAC standard. The benefits to be gained from the general use of this standard far outweigh the modest start-up expense for labs not yet employing CAMAC interfacing. User groups, in particular, should find that the implementation of CAMAC

will enhance the quality and flexibility of their participating in experiments in remote labs. It appears that FASTBUS will be a most useful standard for future systems, especially those employing distributed intelligence and very fast pre-processing frontends. It represents the most probable direction for future implementation of large detection systems, in particular, and should be generally implemented as soon as feasible.

Innovations by various research groups in data acquisition hardware is most probable and most productive in the frontend interface, and this is one place where careful optimization generally results in significantly better thruput and quality. Current innovations center on the use of microprocessors, bit/slice devices, and bulk memories, especially as implemented through CAMAC (and FASTBUS). We recommend that such innovations receive explicit support from the nuclear science community and that the communication of these innovations be promoted.

The problems associated with software development are certainly better appreciated today when so much of the livelihood of nuclear science depends on computers. But, whatever the solution, the problems generally return quickly because greater data acquisition capability simply invites increased amounts of more complex data. The most appropriate response of the nuclear science community should be to increase both the amount and the generality of the communication between different groups. The major difficulties with this approach arise from the use of different detection systems, of different frontend systems, of different computers, and of different software approaches. The development and use of higher level languages such as Pascal (and also FORTRAN) for data acquisition and the development and use of array-oriented languages such as SPEAKEASY for data processing and analysis should be promoted. In the long run, the use of these languages will make it easier to develop good software, and their use should also enhance the ability to transport and share the final programs. This is in analogy with the implementation of CAMAC, which has clearly promoted the sharing of hardware advances.

Finally, the nuclear science community should promote communications concerning developments in hardware, firmware, and software. We feel strongly that a yearly meeting devoted specifically to data acquisition and processing systems should be arranged which would allow a detailed exposure and sharing of innovative ideas, recent developments, and on-going improvements. Proposals for new computer systems, detection systems and software could be presented for general information and criticism.