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REPORT OF THE 1983 NSAC INSTRUMENTATION SUBCOMMITTEE

DOE/NSF NUCLEAR SCIENCE ADVISORY COMMITTEE

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THE 1983 NSAC INSTRUMENTATION SUBCOMMITTEE

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I. SUMMARY OF FINDINGS AND RECOMMENDATIONS

We find the state of instrumentation in nuclear physics to have greatly improved over the past four years. New physics opportunities in electron and energetic heavy-ion research make it essential to increase our detector capability. Hence, we make the following three highest priority recommendations:

- **Increased support of detector research and development, with vigorous university participation.**
- **Specification, design, and construction of detector systems to exploit the physics potential of relativistic heavy-ion beams.**
- **Support and development of computer systems with multiprocessor architecture especially suited to the task of processing and analyzing event-mode data from nuclear experiments. A gain in analysis speed of the order of 20-100 is required.**

II. 1983 NSAC INSTRUMENTATION REPORT

Physics is a constant search for an underlying unity in the diversity of our experiences. As such, it represents a fascinating confrontation between man's ideas and the physical universe he inhabits. The continued growth and vigor of physical science arise from quantitative confrontation between the calculated predictions of our idealizations of reality and precise measurement of the corresponding physical processes. This tension and synthesis between ideas and experience are the foundation upon which modern science is built. The pursuit of physical reality to the very small ($<10^{-12}$ cm) distances necessary for investigations of the properties of atomic nuclei requires projectiles accelerated to higher and higher energy. These higher energy projectiles produce collision products of ever increasing complexity. To detect, record, and organize the results of these collisions require scientific instrumentation at the limits of present-day technology. The development of scientific instrumentation is obviously an evolutionary process in which achievement of increased capability generates development of even further capability.

The character of nuclear matter plays a central role in the evolution of the universe and the creation of the chemical elements and is a fascinating study in its own right. As a result of previous research we are positioned to examine entirely new aspects of nuclear properties. The meson content of nuclei is becoming quantitatively accessible as are effects arising from the supposedly composite nature of the nucleons.

This report deals with the present state and future opportunities in instrumentation available to nuclear scientists in the United States to further probe the nature of nuclear matter. The report was written by a group convened by DOE/NSF as a subcommittee of the nuclear Science Advisory Committee (NSAC).

The charge to this subcommittee, known as the 1983 NSAC Instrumentation Subcommitte, reads as follows:

> This Subcommittee shall evaluate the present status of instrumentation in basic nuclear research and identify the 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. In particular, the Subcommittee should update its findings annually and formulate recommendations for an appropriate course of action.

To carry out this charge, NSAC in consultation with DOE and NSF appointed a group of expert nuclear scientists from universities and national laboratories. The names and institutional affiliations of the Instrumentation Subcommittee are listed in Appendix A. The Subcommittee held two meetings to select areas to be covered in the report. The areas are listed in Appendix B, with the names of the people assigned to each. A series of working papers were generated and survey information obtained; some as part of the NSAC 1983 Long Range Planning Activity. The Subcommittee then met for two days to discuss individual reports and formulate its recommendations.

As the Subcommittee's task was to build upon the report of a similarly charged subcommittee in 1979, it is useful to look back on the earlier findings and recommendations and briefly indicate the status of issues raised in that earlier report.

The earlier report focussed on the status of instrumentation at nuclear physics laboratories operating accelerators. It was found that as a result of fiscal stringency, several of the university laboratories, particularly those operated by the NSF, were unable to allocate sufficient resources for new instrumentation. The general plight could be put in specific terms by noting that the median age of the real-time data-acquisition systems at all university nuclear physics laboratories was 9.0 years. This represented a very serious problem which severely limited experimental programs and made it impossible to take advantage of the explosion of capability in peripheral devices because of the outmoded CPU's. Thus the 1979 Instrumentation Subcommittee recommended, as its highest priority, that equipment funds be diverted to address this problem, with the aim of bringing the data acquisition systems of these laboratories to an acceptable level. The DOE/NSF's response was excellent: a more recent survey shows the median age has dropped to 3.0 years. Great progress has also been made in addressing the need for increased interaction and communications regarding data acquisition and analysis as well as a more extensive use of standardized systems of hardware and software. Table 1 lists the conferences addressing the progress in real time data acquisition systems. It is clear from the table that the interest in this sector has greatly increased since 1979. The organization initially responsible for the last three conferences is now becoming part of a standing committee of the IEEE. This development should lead to even closer communications between researchers active with real time systems in nuclear physics and those in particle physics. The recent survey also shows that 80% of the university laboratories in nuclear physics now use CAMAC and approximately 50% use data-acquisition systems written at other institutions. Both of these cases represent a twofold gain over the state of affairs in 1979.

Table 1. Conferences on Real-time Computer Applications in Nuclear and Particle Physics

Conference	Date
SKYTOP[a]	Oct 1969
Sante Fe[b]	May 1979
Oak Ridge[c]	May 1981
Berkeley[d]	May 1983

[a]Proceedings for the SKYTOP Conference, USAEC-Div. of Tech. Int. Conf. 690301
[b]IEEE NS-26 4369-4677 (1979)
[c]IEEE NS-28 3673-2927 (1981)
[d]IEEE NS-30 3726-4022 (1983)

Figure 1 shows allocation for capital equipment in nuclear physics at DOE/ERDA/AEC for the past 13 years. This is a useful index in tracking the direct investment in instrumentation in basic nuclear physics research. The information is presented in two different ways. First, in Fig. 1a as a fraction of the operating budget, and in Fig. 1b in constant dollars. Both show that the allocation for instrumentation has been relatively constant over the past 5 years.

The Subcommittee's observations on the state of instrumentation in nuclear physics as well as impressions based on several interviews with research groups (see Appendix C) lead to the conclusion that the available funds are being more effectively utilized than was the case four years ago. The Subcommittee also believes the current expenditure on instrumentation in satisfactory balance with the total funds allocated to the field.

The realization that most of U.S. science had developed a very serious problem with respect to instrumentation has been evident for a decade. In a remarkably forthright report entitled Revitalizing Laboratory Instrumentation a variety of approaches to this problem are discussed.[1] Many of the suggestions and recommendations of that report were appropriate to nuclear physics, particularly in the university sector. The report argued that it is unrealistic and perhaps unwise to seek major new infusions of federal funds for instrumentation. The report stressed more effective and imaginative use of existing resources to address the instrumentation problem. In particular, the notions of balance, future planning, and innovative financing were greatly supported. Additionally, the role of the scientific community in allocating resources for instrumentation was considered most important. Revitalizing Laboratory Instrumentation is an important document that should be read by all charged with the responsibility of the welfare of university research.

The present NSAC Instrumentation Subcommittee supports initiatives that offer to provide new instrumentation to physical science and nuclear physics in particular. However, a very important point we wish to make is that at the current level of total support for nuclear physics, the investment in instrumentation appears in better balance with the rest of the field than was the case four years ago. The nuclear physics community and its federal sponsors have done much to bring about this healthier state of affairs. However, achieving this balance has not been without its costs. The number of university-based accelerator laboratories receiving operating support from the federal government has decreased by 4 between 1979 and 1983.

The 1979 Instrumentation Report focussed on the state of instrumentation at the university-based accelerator facilities. The present study has more emphasis on the state of instrumentation for research carried out by user groups. There are two reasons for this change of emphasis. First, instrumentation at the accelerator laboratories is perceived as

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[1] Revitalizing Laboratory Instrumentation - The report of a Workshop on Scientific Instrumentation, March 12-13, 1982, National Academy Press, Washington, D.C., 1982

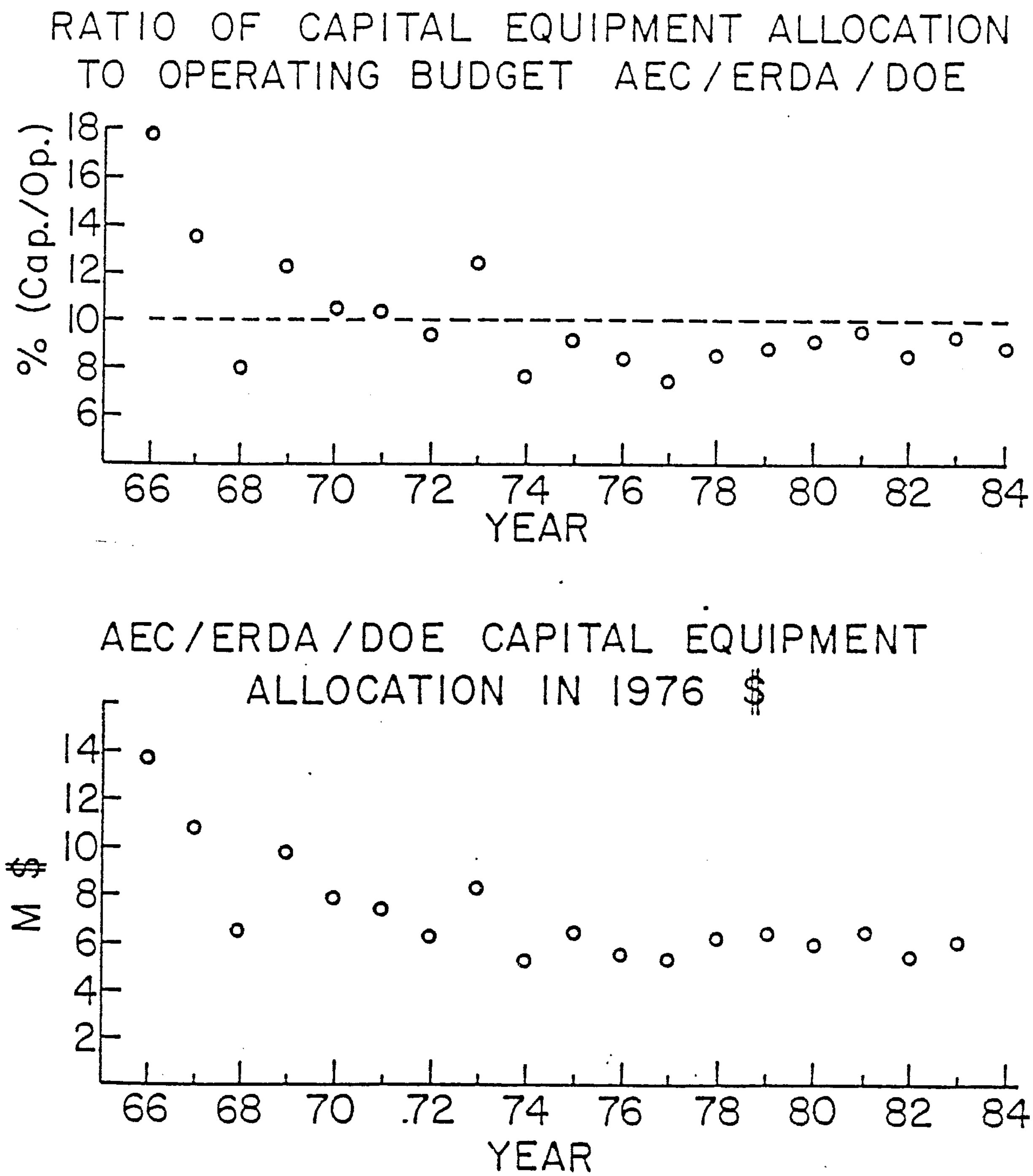

Fig. 1. Allocations for Capital Equipment in Nuclear Physics at DOE/ERDA/AEC from 1966 to 1984.

generally improved, and secondly, user groups are assuming a more important role in nuclear research. Effective user groups must do more than travel to a research facility, employ existing hardware, and perform standard measurements. The scientific health of user groups, their ability to attract outstanding graduate students and their role in the nation's research effort require that they be actively involved in some phase of the development of the tools of basic research. Further, this development activity must have visible presence on campus. Our survey of user groups (Appendix C), revealed no substantial problems at the moment, save the difficulties attendant in their effective participation in large detector development. However, it is just this capability and involvement that must be developed if the U.S. nuclear physics community is to make full use of the research opportunities of the late 1980's.

It appears that a large number (approximately 10) of sizeable detector systems will have to be constructed over the next five to seven years. At least 3 large systems are required at the proposed high energy, 100% duty factor electron accelerator. In addition, 3 to 5 large, fine-grained detector systems must be constructed to fully confront the complexity of energetic heavy-ion reactions. A sensible development of neutrino physics and pursuit of small effects that emerge from the unifications beyond the standard theory of electroweak interactions will involve construction of another 3 to 4 large and complex systems. Each of these detector systems will cost in excess of $3 million with several of them well in excess of $10 million. Moreover, support for the data-acquisition and analysis systems must be provided from the outset.

To produce significant impact, these systems must be built in a timely fashion with detailed attention to prototyping, design, and construction. They must be designed at a level where they can deal with the complexity present in the physics. In the case of relativistic heavy-ion physics, the U.S. nuclear science community has not invested sufficiently in detector construction. At present, the most successful detector at the LBL Bevelac facility is the multiple element Plastic Ball system which drew largely upon West German resources for its implementation. In the absence of powerful detectors of this type with appropriate modes of analysis, the rate at which exciting physics can be separated from the pervasive complexity will be too slow and the pace of research will languish. The timely fashion in which the UA-1 and UA-2 detectors at the CERN SPS facility were able to observe the $W^{\pm}$ and Z^0 mesons and obtain reasonable measurement of their mass serves as benchmarks for what can be achieved by good planning and realistic detector investment. The design and successful operation of a large complex detector is a difficult systems undertaking. The task is made all the more complex because several institutions necessarily participate in the conception, design and construction. Project management techniques now applied only to accelerator projects will need to be applied to the construction of these large detector systems. Our Subcommittee lacks expertise in project management and so can offer little useful advice. We do, however, recognize that project management is an essential component in constructing and successfully operating such systems.

User groups will undoubtedly play a role in the extensive efforts required to produce large detector systems. Adequate interfaces must be provided to fully exploit the capabilities of these groups. Moreover, care must be taken to define the responsibilities between users and the facility where the research is to be carried out.

III. RECOMMENDATIONS

During the course of the Subcommittee's deliberations the NSAC 1983 Long Range Plan was generated. The recommendations presented below reflect the physics priorities of that plan. The Subcommittee's recommendations are the result of a two day meeting in Washington DC in December and represent a unanimous consensus of the subcommittee present at the meeting.

The priority accorded each recommendation is based on its importance to the field. It does not imply that the recommendation be executed in a time-ordered sequence. Indeed, the first recommendation will require some time before the community is able to respond with a sizable number of appropriate proposals. The last two recommendations, on the other hand, do not require extensive resources and there exist extremely able investigators in these areas. Hence these last two recommendations should be dealt with as the opportunity to fund them arises.

New directions are being undertaken in nuclear physics. An effective effort in general detector development will require more involvement from the university community than has been the case in the past.

Therefore, as highest priority, we recommend increased support for detector research and development activity and we invite vigorous university participation.

Searches for the physics arising from the composite nature of the nucleon, its modification in the nuclear interior, and determination of the nuclear equation of state will challenge our intellectual and technical resources as never before. A strongly focussed effort by a large segment of the nuclear research community will be required if we are to be successful. Support in the form of specialized technical facilities such as test beams at user facilities and resources for necessary travel must be accessible to university user groups involved in detector development. It is also likely that the engineering capability of university user groups should be enhanced. Adequately carried out, this recommendation will improve the on campus technical capability of university nuclear physics research groups and provide attractive options for experimentally-inclined graduate students. There are several examples of desirable detector research to be found in the appendices of this report. For example, a clear need exists for research leading to improved energy resolution from large liquid ionization chambers.

The high priority NSAC has accorded new accelerator facilities which produce beams of high-energy continuous wave electrons and relativistic heavy ions places unprecedented demands on detector and spectrometer systems. The specific development problems that each poses are quite different, but the need for large, fine-grained, nearly 4π systems capable of handling high event rates is evident. In particular, appropriate detectors must be constructed for the relativistic heavy-ion beams envisioned to be provided by the AGS in 1986.

Therefore, we recommend high priority be accorded to the specification, design, and construction of detector systems to exploit the physics potential of relativistic heavy ion beams.

Workshops with federal agency support need to be initiated immediately to define the physics more precisely and to establish detector specifications.

As experiments become more complex and data rates increase, our ability to perform these experiments becomes limited by the data-acquisition and analysis systems. The computing resources needed for rapid data analysis are significantly greater than was believed a few years ago. Analysis time can be at least 15 to 20 times longer than the data acquisition time, even for moderately complex experiments. The next generation of detectors will place demands on analysis facilities at least an order of magnitude greater than those now experienced.

Therefore, we recommend support for development of computer systems with multiprocessor architectures especially suited to the task of processing and analyzing event-mode data from nuclear experiments.

A reasonable goal is a factor of 20-100 increase in speed for handling multiparameter data. This is a frontier area for computing in general. There is also a definite need for small-scale systems which could be widely replicated as well as for a smaller number of large systems. The development of a sophisticated microcomputer system that could be used by many laboratories and user groups offers an excellent opportunity for increased productivity. By virtue of the kinds of experiments nuclear physicists do, they have a unique opportunity to be in the forefront of computer systems design.

Substantial improvements have been made in the intensity of polarized positive and negative ion beams in the past few years. In contrast, relatively little development work is in progress to improve the intensity and polarization of polarized electron beams, although the potential for improvement of photoemissive sources is very good. Measurements of fundamental symmetries and nuclear structure using high-energy electron accelerators will benefit from polarized electron beams of higher intensity and polarization than are currently available.

Therefore, we recommend a few development programs with the objective of providing polarized electron sources of high brightness and polarization.

Polarized nuclear targets will also be required for a number of measurements with electron and ion beams. Particularly interesting targets will be those with high hydrogen content, and low sensitivity to radiation damage. In some cases, special purpose low density targets such as can be obtained with a polarized gas jet may be extremely important. Several new techniques involving cryogenics, atomic beams or optical pumping have showed promise for these applications. These techniques may also be useful in providing more intense polarized ion beams.

Therefore, we recommend a few development programs with the objective of providing polarized nuclear targets with high polarization and low sensitivity to radiation damage.

In the appendices of this report are more detailed discussions of the state of nuclear instrumentation in a number of specialized areas. Several useful suggestions and recommendations are offered, and were considered by the Subcommittee in arriving at its recommendations.

Appendix A

1983 NSAC Instrumentation Subcommittee Membership

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Stanford Linear Accelerator Center

Dr. J. David Bowman
Los Alamos National Laboratory

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University of Illinois

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Dr. David J. Clark
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Professor Robert A. Eisenstein
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Dr. Gerald T. Garvey (Chairman)
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Dr. Douglas Greiner
Lawrence Berkeley Laboratory

Professor Willy Haeberli
University of Wisconsin

Dr. Walter F. Henning
Argonne National Laboratory

Dr. David C. Hensley
Oak Ridge National Laboratory

Dr. Michael LeVine
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Professor Arthur B. McDonald
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Professor Roy Middleton
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Professor N. Russell Roberson
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Dr. R. G. Hamish Robertson
Los Alamos National Laboratory

Professor Kurt A. Snover
University of Washington

Appendix B

Areas Investigated by the Subcommittee*

1. User Group Instrumentation
   R. Arnold, R. Eisenstein, D. Bowman, H. Chen

2. Data Acquisition and Analysis
   L. Cardman, D. Hensley, M. Levine, R. Roberson

3. Detectors
   Photons - D. Bowman, K. Snover
   Gas-filled - W. Henning
   Large Fine-grained - H. Chen, G. Garvey, D. Greiner

4. Polarized Beams and Targets
   W. Haeberli, A. MacDonald, H. Robertson

5. Multiply Charged Ion Sources
   D. Clark

6. Negative Ion Sources
   R. Middleton

7. Accelerator Mass Spectroscopy
   R. Middleton

8. Magnetic Devices
   H. Enge, M. Levine

*The underlined names indicate primary responsibility.

Appendix C

The following reports are included to provide detailed information on the status of particular areas of nuclear instrumentation. They contain numerous recommendations that are important and, in general, are supported by the committee. The recommendations felt to be of highest priority by the committee are included in the body of the report.

Appendix C is arranged as follows:

C-1. INSTRUMENTATION AND USER GROUPS

The goal of any user group is to mount and perform the best possible physics experiments at an appropriate facility. However, experiment design, specialized equipment construction, and data processing and analysis are however often carried out at the home institution. These tasks require high-quality electronic and computing equipment, as well as other sophisticated apparatus, which comes from several sources:

1. Large electronic module pools at the national laboratories, from which general purpose equipment can be borrowed;

2. Individual government (or foundation) grants from which equipment can be purchased;

3. Monies provided for the construction (at both the home site and at national facilities) of specialized equipment;

4. The large-scale dedicated facilities with extensive instrumentation available to users, such as EPICS or HRS at LAMPF.

Adequate levels of financial support for instrumentation plays an especially important role for user groups. Such support is the foundation on which any long-term successful program must be built.

Are the needs of the user community being adequately met? Based on an informal survey, we find that the answer depends significantly on the size of the experiment to be done. Users wishing to use fixed, in-place facilities (e.g., HRS or EPICS) generally encounter few problems, while users wishing to construct large-scale equipment (e.g., large scintillator arrays, new beam lines, or spectrometers) are often strongly limited. Generally, however, it seems that the user program is in balance with the rest of the U.S. nuclear science effort.

NSF grant requests in FY 81 and 82 from large facilities indicate that 20% of capital equipment money is spent for instrumentation; among small grants, about 15% of the total award is so allocated; at university laboratories, about 10% of the total award is used.

Users contacted by our working group Roos, Maryland; Preedom, South Carolina; Segel, Northwestern; Rapaport, Ohio University; Glashausser, Rutgers; Eckhause, William and Mary; and Hichwa, Hope College, generally seem to feel that their instrumentation needs are being adequately addressed from the standpoint of equipment available at host laboratories and through their own grants. However, discussions with Miller, Singh, and Vigdor of IUCF indicated that the IUCF electronics pool becomes seriously depleted when drawn upon by more than one (moderate size) experiment at a time. This fact makes multiple use of beams impractical and renders set-up difficult especially in the case of on-line and data processing computers when another experiment is in place. IUCF spends about 7% ($35 K) of its capital funds each year on electronics, and an additional 8% on computer-related facilities.

Instrumentation awards for a specific piece of hardware are available from the NSF. In FY 81, about $870 K was so granted, 98% of which was allocated to the start-up of the IUCF high resolution magnetic spectrograph. These awards can be extremely important as a way of helping university user groups maintain a larger and more active presence on the campus. It is clear that good visibility of a group on campus helps attract promising students into our field, an obviously essential goal if we are to ensure the future of nuclear science.

A similar picture emerges from an examination of DOE allocations. Equipment money spent by a sample of user groups Igo, UCLA; Peterson, U. Mass.; Denhart, Minnesota; Huizenga, Rochester; Kaplan, C-MU; Prosser, U. Kansas; and McCarthy, Virginia, was rather limited, averaging about 10% of total grant size. The DOE also provides a supplemental grant mechanism for user instrumentation development. This is currently at a level of about $760 K/year. In FY 82, 12 such grants were given.

The user group effort in this country is based in part on the idea that the large host laboratories make available rather large general-purpose equipment pools and support facilities such as staging areas, wire chamber and scintillator shops, machine shops, off-line computing and technical help. While all the large labs provide such services to some extent, there is considerable variation in level of support.

LAMPF, which is the largest user laboratory in the U.S. nuclear science program, has very effective user support services. Its equipment pool is large ($2.9 M total investment) and contains ~ 3500 items. Last year $300 K was spent out of capital equipment funds of $2.9 M to add to this pool. Apparently the pool is able to meet the demand placed on it, even though it must serve many experiments simultaneously. One difficulty encountered by users at LAMPF is high costs associated with the use of the LANL construction shops.

The construction of large-scale equipment, however, does present a problem for user groups, since often they simply do not have the technical capacity (specialized machinery, electronics, staff support) to generate a big project on their own. This situation has led to collaborative efforts between national laboratories and user groups, which have often been quite effective. The high-resolution proton spectrometer at Indiana, the low-energy pion spectrometer for LEP at LAMPF and the MEPS system at Bates are examples of extensive user involvement in the conception, design, and construction of large-scale devices. Historically, users have made major contributions to the user facilities at the national laboratories. The newly established NEAL project is a current example; it appears that user input is being sought on every level.

In summary, the status of instrumentation for users in medium energy and heavy ion physics seems commensurate with the overall effort in nuclear science. We talked with no users who had serious complaints on this issue. However, it seems to us that more users ought to be encouraged (with instrument development grants) to design and construct instrumentation "at home," to maintain as active a stance as possible as a way of attracting good students to our field. It seems that groups who have computing as their only home base activity are at a comparative disadvantage in this regard. This may imply large-scale changes in other areas of user group physics (e.g., personnel), and so present special financial problems.

C-2. DATA-ACQUISITION AND ANALYSIS SYSTEMS

i) Introduction

Data-acquisition systems play a central role in determining the complexity of the reactions that can be studied in a nuclear experiment. The severe limitations of most of the available computing systems in the nation's nuclear laboratories at the end of the 1970's were well documented by the 1979 Instrumentation Subcommittee. The highest priority recommendation of that Subcommittee was that funds be provided to bring the then outdated data acquisition and analysis systems to an acceptable level. With a few exceptions, this recommendation has been carried out by DOE and NSF. It was clear from the 1979 subcommittee report that the ever-growing complexity of nuclear physics experiments requires the continued replacement or upgrading of aging computer systems.

It should be noted that during the latter part of the 70's, when few new computer systems were installed, there was a substantial decrease in the number of students receiving training in the design of data acquisition hardware and software. This lack of qualified manpower has been and continues to be a serious problem.

At the 1983 Conference on Real-Time Computer Applications in Nuclear and Particle Physics held in Berkeley, there was a crystallization of opinion concerning the directions that data acquisition and analysis systems should take in the 1980's. First, higher raw data rates and more complicated event patterns require that one "put more smarts near the detectors." Second, parallel processing with multiprocessor architectures will be needed in order to reduce analysis times. Already, a few systems utilizing one or both of these principles are in operation; several more are being designed and constructed. The widespread acceptance by the nuclear community of CAMAC as the standard hardware interface for data acquisition (a 1979 recommendation) makes it relatively easy and inexpensive to add intelligence near the detectors, thereby permitting higher raw-data rates and less dead time.

The computing resources needed for rapid data analysis appear to be significantly greater than was believed even a few years ago. Reports presented at the 1983 Berkeley conference indicate that even for well-planned and well designed heavy-ion experiments, the CPU analysis time can be from 15 to 20 times longer than the data acquisition time. One can expect similar difficulties in analyzing data obtained with the next generation of accelerators (GeV electron accelerators, upgraded meson factories, relativistic heavy-ion accelerators, etc.). Only parallel processing with multiple CPU's seems to offer an affordable solution to this problem.

ii) Front-end Systems

CAMAC has clearly become the standard interface for nuclear physics data acquisition systems. Over 80% of university based systems now have front ends utilizing CAMAC; those that do not tend to be older systems that have not been upgraded. The situation appears to be similar at the national laboratories. It is clearly possible to expand our capabilities in a cost-effective way by putting more intelligence in or near the CAMAC crates. This will permit higher effective data rates and could reduce the load on the host computer.

A wide variety of microprocessors and bit-slice processors with cycle times as fast as 200 ns is now available in CAMAC, designed either as branch drivers or as auxiliary crate controllers. These processors function as fast trigger filters and provide sparse data scans, local histogramming, and intelligent data processing. Relatively low cost CAMAC memories used either for fast buffer storage or for fast local histogramming, combined with fast (5 μs) ADC/FIFO systems, can provide exceptional performance for data collection at pulsed-beam accelerators. A wide range of other fast digital interface modules is available.

Word transfer rates much higher than 500 kHz will require either using parallel CAMAC crates each controlled by a dedicated processor or changing to the FASTBUS system. The FASTBUS system, which is being developed primarily by the high energy community, will become a specified standard in 1984. It is both faster (10 MHz vs. 1 MHz on the backplane) and wider (32 bits vs. 24 bits) than CAMAC. It uses larger circuit boards which allow for more efficient and more modern circuit design and for large bulk memories (many MB). FASTBUS is also designed to allow multiple autonomous controllers (e.g., intelligent parallel processors). This design feature of FASTBUS could provide, via intelligent processors, for fast and complex trigger systems. While FASTBUS will be used in the front ends of some of the next generation of complex experiments, CAMAC will probably remain the principal data acquisition interface for most of our experiments. The committee encourages the nuclear physics community to follow the development of FASTBUS and take advantage of its power when possible.

iii) Computer Systems

The newer 32 bit super-minicomputers have become the accepted standard for the host machine. The very large address space of the 32-bit machines solves many of the problems associated with the popular 16-bit minicomputers used during the 1970's. The reduced price (2 k$/MB) of computer memory allows megabyte physical memories for even the most modest system. Advances in technology have dramatically increased computer power through floating point accelerators, cache memories, etc. High density tape drives (6250 bpi), while still rather expensive, are routinely available. The price of large disks continue to fall, with 500 megabyte drives now costing around 20 k$. Thus, even though our computer requirements are growing rapidly, there is hope that the continuing relative drop in the cost of computers and memory will help to keep the overall costs manageable.

The super-minicomputers have one aspect that strongly affects the nature of the front-end acquisition system. The operating systems for these computers are designed such that the response to interrupts is slow and the time to perform single-transfer I/O is long. These features limit straightforward interrupt-driven data acquisition to fewer than a thousand words per second. Consequently, the front end system must be smart enough to handle large blocks of data before demanding attention from the host. Host attention is then required only for each block of data; little if any I/O is required, and the interrupt overhead can be spread over many events.

As experiments become more complex and data rates increase, even the super-minicomputers will become inadequate as the real-time analysis computers; the same will be true for the front end systems, even with intelligent branch drivers and auxiliary crate controllers. Multiprocessor architectures allowing parallel processing can provide a cost-effective method of expanding the current systems. Fortunately, the recent explosive development of microprocessors and the development of fast standard data busses have provided the tools for multiprocessor architectures. A typical design may have several processors connected via an asynchronous bus, with each processor handling separate events in parallel. Intelligent event handlers would connect the parallel processor system to the CAMAC (FASTBUS) front end. The host computer could then perform tasks such as tape handling, graphics display, and equipment control, while the time-critical jobs were handled by the parallel processor system.

There is a critical need to reduce the off-line analysis time for experiments where the number of measured parameters per event exceeds several hundred. Since each event is generally independent and can be processed through the same analysis sequence, high speeds can be obtained by parallel processing. One system utilizing multiprocessor architecture has been built and is in the testing stage. The results are encouraging; 8 CPU's showed a performance 8 to 15 times that of a standard computer with 1 CPU. Other systems are being designed at a number of laboratories, and industry has begun providing some parallel processor architecture systems. It is clear that these efforts should be supported by the physics community.

Although the obvious trend is to larger more powerful systems, another very strong trend is to distributed processing. In fact, the increasing complexity of experiments suggests that a modular approach may also be appropriate. The complexity and large scale of the next generation of experimental apparatus are such that fully functional modules will probably be developed and tested by separate parts of the experimental groups, e.g., universities. This modular approach requires that these sub-groups have sufficient data-acquisition capability to test the full range of the apparatus, and it suggests that the data acquisition system be portable, since equipment check-out may be performed at a variety of sites. Consequently, support should be given to the development of microprocessor based systems which could rival much of the capability of the current super-minicomputers, but which would be available at a fraction of the cost.

Most of the parts for such micro systems are currently available commercially, but the appropriate interfacing, software, and packaging for nuclear science need to be developed. When such systems are developed, they will provide a most cost-effective approach for traveling user groups, sub-groups of a large effort, smaller laboratories trying to upgrade their data acquisition systems, and any laboratory attempting to off-load some of the data acquisition and apparatus-testing chores from the heavily utilized super-minicomputer systems.

iv) Networks

The difficult and complicated experiments to be done in the future will require that the nuclear physics community have access to the full range of nationally available computer resources. This resource-sharing will require the implementation of a nuclear physics computer network (NPnet). This network should allow effective and convenient access to existing and planned supercomputers, large data bases, large facilities suited to the task of analyzing event data, and other special computing equipment.

Such a network could be implemented by using the available commercial network offerings (e.g., TELEnet) and/or existing private networks (e.g., ARPAnet). The initial version of NPnet should provide inexpensive communication for interactive service at speeds up to 9600 bps and should be designed to allow expansion and permit the use of new technologies. Of particular interest would be the development of a wideband satellite-based network. It is known that NSF is taking an initiative in this area, and such a high-speed system could augment or replace the access services discussed above.

v) Software

The general situation concerning computer software has not changed significantly since the 1979 subcommittee report. The real-time, multi-user, multi-tasking operating systems available with most computers have proven to be reliable environments for operation of data acquisition software. Most current systems have been written in a high-level language like FORTRAN. A number of laboratories are using the event analysis language EVAL to sort and manipulate data events. We recommend that new systems utilize the existing higher-level languages.

Reduction of programming duplication continues to be an important software priority for the community.

vi) Communication

There is a strong consensus among those involved with nuclear data acquisition and analysis concerning the benefits to be derived from increased communication and interaction within the nuclear and particle physics communities. Part of this problem has been addressed since 1979 by the three conferences on real-time computer applications in nuclear and particle physics. Succeeding conferences were arranged by an executive committee elected at the previous conference. The conferees at the 1983 Berkeley meeting voted to affiliate with the IEEE Nuclear Science Society; this should ensure the continued existence of these biennial conferences.

There are large numbers of both software and hardware modules that could be transported to other facilities, and the cost of everyone developing the same basic system is simply too high. The best way to promote cross fertilization and communication is to have interested individuals travel to key laboratories and remain long enough to become thoroughly acquainted with the apparatus, the software, and the overall effectiveness and deficiencies of the data acquisition and analysis systems. Consequently, the community should encourage and support travel for individuals planning and designing new data acquisition and analysis systems.

In addition, the development of a nuclear physics computer network (NPnet) would substantially improve communications within the community. The existence of NPnet would facilitate the exchange of programs, software libraries, and data or text files and would encourage collaboration among researchers. It should be noted that BITnet, an existing network operated primarily by colleges and universities, allows users to share information via electronic mail and file transfer at speeds of 9600 bps. Currently, the nodes in the network are IBM mainframes operating under the VM or MVS system, but a program is being developed that will enable VAX/UNIX and VAX/VMS systems to be part of the network. The committee encourages the nuclear physics community to make use of such existing networks; the benefits are convenience and time savings.

vii) We recommend the following:

1. Continued upgrading and timely replacement of data-acquisition and analysis computer systems in nuclear science. Past experience indicates that this replacement should take place about every 7 to 8 years to remain competitive.

2. Support for development of computer systems with multiprocessor architectures especially suited to the task of analyzing event data from nuclear experiments. There is a definite need for small-scale systems which could be widely replicated as well as for a smaller number of large systems. This is a frontier area for computing in general. By virtue of the kinds of experiments we do, we have a unique opportunity to be in the forefront of computer systems design.

3. Implementation (within the next 3 years) of a network to allow all the members of the nuclear science community to access the computer resources they require. This network should support transmission of data at 9600 baud or faster. The cost of accessing this network should be reasonable.

While FASTBUS is emerging as a solution to the problems posed by some highly complex experiments, we view CAMAC as the principal data acquisition interface of the nuclear science community for the foreseeable future.

C-3. DETECTORS

a. Photon Detectors

i) Introduction

Our ability to detect photons is crude compared to the efficiency and precision of techniques available for charged particles. This makes each advance in detector technology important; a factor of two improvement in resolution, timing, or efficiency may make it possible to study a new class of phenomena or to find a new aspect of a familiar phenomenon. We discuss the properties of several types of instruments for the detection of photons of energy between several MeV and one GeV. Some of the instruments seem to be fully developed while others, though very interesting, are yet to be demonstrated.

ii) Large Single-Crystal NaI(Tl) Spectrometers

For $E_\gamma \sim 10$–50 MeV (and perhaps higher) the best resolution is offered by large single-crystal NaI spectrometers. These spectrometers are commonly used for nuclear resonance spectroscopy, including giant resonance studies in charge particle capture. A number of these devices exist in various laboratories, and consist typically of a cylindrical NaI crystal with a diameter of 10 in and a depth of 10 in or more, with an active outer shield (usually made from plastic scintillator) for suppressing cosmic-ray background as well as for improving the response by rejecting partial absorption events in the tail. Several larger NaI detectors (usually without active shields) are in use in applications involving higher E_γ; in general, they have substantially inferior uniformity and light collection and correspondingly poorer resolution. These spectrometers have relatively high overall efficiency $\varepsilon\Omega$ where the intrinsic full-energy peak efficiency ε is about 0.4 and the solid angle $\Omega \sim 100$ msr or larger. State-of-the-art resolution for these spectrometers with NaI crystals in the size range 10 in x 10 in to 10 in x 14 in of about 2% FWHM for $E_\gamma \sim 20$ MeV. To achieve this resolution requires a good crystal uniformity (usually achieved with a single crystal) and good surface reflectivity compensation adjusted to optimize the response uniformity for events at different locations. The response uniformity is usually measured with a Cesium (660 keV) source; however, further improvement is apparently obtained by also requiring a uniform response for 6.1 MeV γ-rays (from, e.g., an Am-^{13}C or Pu-^{13}C source).

For most such detectors the percentage resolution improves with increasing E_γ, indicating the importance of photoelectron statistics. For one of the best detectors, at Brookhaven National Laboratory ($\Delta E/E = 2.2\%$ at E_γ = 20 MeV), the resolution is found to vary approximately as $E_\gamma^{-1/2}$ for $E_\gamma = 6$ to 25 MeV when one accounts for the fact that the photopeak consists of a doublet made up of the full-energy peak and a weak unresolved single escape peak. Thus, for a very good crystal, the resolution at these energies is dominated by photoelectron statistics at the first dynode. Hence any improvement either in the amount of light delivered to the photocathode of the PM tubes viewing the NaI, or in the quantum efficiency of the PM tubes, will directly contribute to improved resolution. The much higher quantum efficiency (~60%) and better gain stability of photodiodes make them attractive as a possible alternative to PM tubes for NaI readout (see Section iv.).

Historically, advances in NaI technology have come about through cooperation between the supplier and the user, often at the instigation of the user. It has been quite beneficial to have more than one domestic supplier of NaI crystals and it is in the best interests of the nuclear physics community for this situation to continue.

iii) Multi Crystal Arrays

Two types of arrays are in use in nuclear physics: 1) the crystal box detector at LAMPF which will be used to search for forbidden μ and π decay modes; and 2) several NaI segmented ball detectors which are being used in heavy ion research.

The crystal box consists of 396 commonly encapsulated NaI(Tl) crystals. The solid angle for single photons is 60% of 4π. The energy resolution is about 6% at 50 MeV. The position resolution of 4 cm is comparable to the crystal size. This detector is well suited to kinematically complete measurements of few-body final states and will allow searches for the decays $\mu \to e\gamma$, $\mu \to e\gamma\gamma$ and $\pi \to \gamma\gamma\gamma$ at between 10^{-9} - 10^{-11}.

Crystal ball NaI(Tl) arrays for photon spectroscopy following heavy ion collisions are in use at Oak Ridge and Heidelberg. The crystals are individually encapsulated, which facilitates reconfiguration of the NaI to accommodate various auxiliary detectors but which unfortunately implies unobserved energy. The detector crystals are large enough to have a substantial probability of a few MeV photons being absorbed in a single crystal. The resolution of the individual segments is moderately good at low energy, $\lesssim 7\%$ at 1 MeV. These detectors measure the photon multiplicity, spatial and time correlations between photons, and total energy. At energies that are appropriate to the study of the decay of giant resonances (10-30 MeV) the inert material that encapsulated the crystals may be a real disadvantage for their energy resolution.

A large planar array of NaI crystals would serve many useful functions in electron and pion physics laboratories. The scale of the detector might be an 8 × 8 array of 10 cm × 10 cm × 35 cm NaI crystals. At 1 meter the solid angle would be 0.6 steradians. The position resolution would be 5 cm FWHM, the energy resolution would be 4% and the time resolution would be <1 nsec at 50 MeV. Such a device would be well-suited for the detection of photons and electrons with large, known efficiency and moderate energy resolution. The reaction $\pi \to e\upsilon$, $\pi^- p \to n\nu$, radiative π and μ capture, $\mu \to e\nu\upsilon\upsilon$, $(\pi^{\pm},\pi^0)$ π^0 production, electron scattering involving coincidence and proton bremstrallung would be natural candidates for study.

iv) Bismuth Germinate

The use of bismuth germinate BGO ($Bi_4Ge_3O_{12}$) as a photon detector is just beginning. Its physical properties make it more desirable than NaI in some situations and less so in others. Table C-3-a-1 lists several properties of BGO and NaI.

Table C-3-a-1. BGO-NaI(Tl) Comparison

	BGO	NaI
Mechanical		
Hardness	like soft glass	like rock salt
Specific Gravity	7.13	3.67
Stability	rugged	cleaves
Chemical		
Stability	stable	poor
Solubility (H_2O)	none	hydroscopic
Optical		
Refractive index	2.13	1.85
Scintillation		
λ_{max} Emission, nm	500	420
Decay time, ns	300	250
Photon electrons, MeV (Bialkali photocathode)	~500	~2500
Temp coeff. of light output, %/C°	1.7	0.8
Nuclear		
Relative thermal neutron cross section	0.25	1
Nucleon absorption length (E>1 GeV), cm	23	41
Electromagnetic		
Radiation length, cm	1.12	2.59
Critical energy, MeV	10.5	12.5
Moliére radius, cm	2.2	4.4
dE/dx (min), MeV/cm	~9	4.8

BGO will find applications where physical compactness and large total absorption fraction are important. Its small radiation length and Molière radius make it well suited for multicellular detectors where photon (or electron) interaction position is measured. Its chemical and mechanical properties facilitate the packaging and fabrication of such arrays. If very dense, large arrays of BGO are developed, it may be desirable to use photodiodes rather than the traditional photon multipliers to convert the scintillation light to electrical signals (see below). Since BGO detectors are more compact than corresponding NaI detectors, they can be more effectively shielded from background radiation.

Sodium iodide produces six times more light than BGO. In applications where energy resolution is dominated by photoelectron statistics and is critical, NaI is superior. At high energies and in multicellular arrays where factors other than photoelectron statistics (e.g., gain matching, inhomogenities in scintillation output, and light collection variations) determine energy resolution, BGO may have energy resolution comparable to NaI.

Large, high-quality crystals of NaI are commercially available at a cost of roughly $2/cc. The cost of BGO is about $20/cc and the quality of the material is unreliable. Two problems of crystals growth need to be solved: 1) What kinds and levels of impurities impair detector performance? and 2) How can BGO be grown so that the growth process does not introduce impurities?

v) Photodiode Light Readout for NaI and BGO

Traditionally, photomultipliers have been used to convert the light from NaI into electrical signals. The high number and density of contemplated BGO detectors have stimulated high-energy physicists to consider the uses of Si photodiodes for BGO light readout. The index of refraction of Si is well matched to that of BGO and the quantum efficiency is high, which mitigates the effects of the poor light yield of BGO. Photodiodes are more compact than photomultipliers and do not require multiple high voltages but do require good, low-noise amplifiers. In principal, photodiodes can be inexpensively made using semi-conductor fabrication technologies. Photomultipliers are hand made and will remain expensive. Photodiodes are more stable than photomultipliers. Photodiodes have larger noise than photomultipliers, which provide nearly noiseless gain. With BGO, FWHM energy resolutions of about 1 MeV are the best so far obtained with photodiodes. Shortcomings of photodiodes are their sensitivity to direct interactions with ionizing radiation and the long integration times (several μsec) required. Nuclear physicists have considerable experience with this type of detector and may be able to exploit it.

vi) Lead Glass

The principal virtue of lead glass is that it is the least expensive photon detector: the cost is approximately $0.2/cc. When coupled to a bialkali photocathode, the lead glass yields 1-2 photoelectrons/MeV and gives energy resolution of ~30% at 100 MeV (which scales like $E^{-1/2}$). Several lead glass detectors that give position information have been built using either segmentation with resolution of a few centimeters or conversion in an active or passive converter backed by tracking detectors (with position resolutions of a few millimeters).

Two aspects of the performance of lead glass might be improved. First, the types of lead glass with a high lead content and a short radiation length tend to be yellow and have a poor light transmission. The degree of yellowness can be controlled to some extent by the purity of starting components and by melting procedures. Second, the production of light by the Cerenkov process is instantaneous, there is also a significant slow component of light from lead glass (~30% with a decay time of ~400 ns). It would be useful to find a way of eliminating this slow component in order to improve the performance of lead glass in very high-rate applications.

vi) Pair Spectrometers

For $E_\gamma \sim 100$ MeV the best resolution (better than 1 MeV FWHM at E_γ = 130 MeV) is obtainable with a pair spectrometer, at the expense of efficiency (typically $\varepsilon\Omega/4\pi \sim 2 \times 10^{-5}$). Electrons and positrons produced when the incident photon strikes a converter foil are tracked through a 180° bend in a magnetic field. Good resolution requires the converter foil to be thin to minimize multiple scattering; the corresponding conversion efficiency, ~2%, is thus rather low. Once the pair is produced, it is detected with a fairly large geometrical detection efficiency (~30%). A modest gain in efficiency (less than a factor of 2) at the expense of resolution is possible by using two converter foils.

vii) Hybrid Ge-NaI for $E_\gamma < 20$ MeV

For $E_\gamma < 20$ MeV a hybrid spectrometer consisting of a central germanium (Ge) detector surrounded by a NaI(Tl) shell offers the possibility of substantially improved resolution (relative to single-crystal NaI) while at the same time retaining a reasonable efficiency. At these energies, even very large Ge crystals (~3 in dia. by 8 in - 10 in length) have insufficient volume to contain the total photon energy. Moreover, the response function is dominated by radiation leakage, although the intrinsic resolution is excellent (10's of keV). However, most (~90%) of the energy of a collimated photon beam could be contained in the Ge crystal (which could be segmented). Then if the (low-energy) escape radiation is detected with good resolution (~5%) in the NaI shell, one could generate a sum-energy spectrum with a factor of two to three better resolution than is possible with a single-crystal NaI spectrometer.

viii) Hybrid Detectors for Spectroscopy and High-Spin Studies

Many interesting hybrid detector systems combining Ge with BGO and/or NaI are being planned or developed at various laboratories including LBL, Argonne, Stony Brook, Oak Ridge and MSU/Pittsburgh. Compact BGO shielded or BGO/NaI shielded Ge detectors yield high resolution and efficiency for $E_\gamma \lesssim$ a few MeV, along with excellent Compton suppression resulting in a peak/total ratio $\gtrsim 0.5$, particularly important for double and triple coincidence discrete-line spectroscopy studies. Arrays of such detectors operated in coincidence with a core array of NaI or BGO (the latter offering the important advantage of compactness and good peak/total ratio) for sum energy and multiplicity information will be particularly powerful tools for the study of nuclear properties at high spin.

ix) Liquid Xenon Ionization Detector

In principle, a liquid xenon (LXe) ionization chamber should make a very good spectrometer for energetic gamma rays. Its low ω-value (energy per ion pair) and theoretical Fano factor imply an excellent intrinsic resolution (FWHM) of ≈2 keV • $\sqrt{E_\gamma (\text{MeV})}$, which approaches that of germanium. The high Z and relatively high density of LXe imply a radiation length and hence efficiency similar to that of NaI. A large-volume detector of this sort would revolutionize the field of nuclear spectroscopy with continuum gamma rays, including hadron and pion radiative capture, pion single charge exchange, hadron inelastic scattering (h,h'γ), decay studies, etc.

Several groups have studied the performance of small-volume gridded LXe ion chambers, obtaining photon resolution of ~60 keV FWHM at 1 MeV, a factor of 30 worse than the theoretical limit. A similar degradation (factor of 10) is observed for liquid argon. Fluctuations in electronegative impurity trapping (at impurity levels as low as parts per billion), and/or ion recombination are suspected as the major contributors to the degradation; the relative importance of each is not yet known. Additional problems at higher photon energies and larger volumes are to be expected, including shower containment, incomplete charge collection due to dead spaces, and long drift times. Because of the enormous impact that would result if such a detector were available, further research to characterize the problems of LXe should be carried out. These problems are very difficult, and their solution will require the efforts of a dedicated and professional team.

x) BGO—Hybrid π° Detector

Active converters of BGO approximately one radiation length thick, backed by tracking detectors and a total absorption BGO or NaI detector, could determine the interaction vertex of photons to better than 1 mm. This excellent position resolution, together with the fair energy resolution of BGO (or BGO plus NaI), makes possible the construction of an opening angle type of π° spectrometer with an energy resolution varying between 0.1 and 1.0 MeV and a solid angle of up to 10 millisteradians. Such a π° detector would advance the field of pion charge from the study of a handful of transitions to a spectroscopic tool. It would be useful for the study of discrete states as well as of broad isovector resonances.

b. Gas-filled Detectors

i) Introduction

Gas detectors have become widely used both in medium-energy and heavy-ion nuclear physics. They are used as stand-alone detectors and, quite often, in combination with magnetic-(electric-) spectrometers. The detectors are insensitive to radiation damage. Moreover, they can be optimized with respect to physical parameters (energy, energy loss, timing, position, size and shape). This flexibility results in a multitude of detector designs and applications. Thus the characteristics of these devices are difficult to summarize in general terms. Some of the characteristics are listed in Table C-3-b-1. Below we discuss categories of gas detectors in use, and then present some more general aspects of future developments.

ii) Gas Detectors in Heavy-Ion Physics

Gas counters are now the dominant detectors in heavy-ion physics, both in stand-alone mode and as track-imaging devices in magnetic (electric) spectrometers. They measure total energy, differential energy loss, position and angle, and timing, with large solid angles sometimes approaching 4π. Recent developments include: i) large, single-volume ionization chambers (~ 0.2 m^3 active volume) with angular wire grids or saw-bladed electrode structure for position measurements; ii) multiple-sampling ionization chambers of large (up to ~ 3 m^3) active volume; iii) Bragg-curve ionization chambers with particle tracks parallel to the electric field, yielding ΔE, total energy, and particle range from one single signal; iv) parallel-plate avalanche counters with position wire grids and segmented cathodes, with increased dynamical range through self-quenching operation at increased pressures; with current research directed towards the use of cathode materials (e.g. LiF) with high secondary-electron production; v) double-gridded large-area avalanche counters at very low pressures with only 300 $\mu g/cm^2$ total mass for the transversing particle, which provide position in two coordinates, timing and some energy loss information; vi) low-pressure multiwire proportional counters providing excellent timing because of an entirely different amplification mechanism at low pressures, plus position and good energy-loss information, vii) gas scintillation with total energy resolution comparable to ionization chambers and fast timing; viii) gas-scintillation drift chambers where position information is obtained from timing between scintillation in the detector gas and delayed secondary scintillation in a high-field gap transversed by the drifting electrons; ix) streamer chamber for multi-fragment detection in relativistic heavy-ion reactions; x) time-projection chambers, in 4π tracking range and energy mode; xi) large wire drift chambers (projected to areas of up to 2×5 m^2) in relativistic heavy-ion reactions. Quite generally, a large number of detector systems used in medium-energy (and high-energy) physics have features that are attractive for future relativistic heavy ion physics.

iii) Gas Detectors in Medium-Energy Physics

In medium-energy nuclear physics, gas detectors are generally not used in stand-alone mode, but rather as triggers, filters, as track imaging and focal-plane detectors in some form of magnetic spectrometers. They are sometimes used for timing and differential energy loss, but are infrequently used for calorimetric measurements because of the long range of light particles in gases (although multi-sandwich, analogue-sampling calorimeters in high-energy physics show good performance characteristics when wire chamber proportional counters are used for the active detector slices; also see the discussion below on photo-ionizable vapors and systems consisting of proportional counters and UV photocathodes). The most widely used mode is that of proportional counters, either as multi-wire proportional counters or as drift chambers. Energy loss is measured in some instances, but mostly particle positions either by simple direct wire readout or by determination of the particle coordinate along a wire (by R-C or charge division readout of a resistive wire or through induced cathode pulses and various forms of delay lines). The latter has recently been shown to provide better resolution in small prototype detectors. Averaging over cathode strips and alternate-bussing schemes of delay lines have shown improved resolution and removal of left-right ambiguities. Vertical drift chambers provide excellent resolution both in angle and position from only one wire plane. Time projection chambers, now operational in high-energy physics, show good promise for medium energy applications. Some current investigations aim for reduced multiple scattering through use of light mass gas mixtures and preformed beryllium windows. Recent exciting developments of gas detectors include systems of multistep drift-avalanche combinations that permit selection of events by electrical gating of the drifting electrons; the use of such systems in time projection chambers; and systems where the detection of light from dense scintillators (BaF_2) is achieved with low pressure wire chambers by using either photo-ionizable vapors [preferentially TMAE: tetrakis-(dimethylamine) ethylene] in the gas mixture or by combining UV photocathodes of condensed vapor (TMAE) with wire-chamber proportional counters.

iv) Future Directions

Most of the surveyed improvements in gas detector design originate from research intended to produce a detector for a specific application. The large variety of applications makes this a sensible approach for a large part of the development. On the other hand, some recent advances result from more long-range research into detection systems and processes per se, mostly outside the United States (examples: gas scintillation; low-pressure fast proportional counters (Breskin counters); scintillation — photo-ionization — wire counter combinations; calorimeters with gas detectors as active elements). The 1979 NSAC Instrumentation Report urged support of this type of research on equal footing with other forms of basis research. This is not reflected in the lists provided by NSF and DOE on Nuclear Physics Instrumentation in FY 1980-82, except for some "mission-oriented" research of the type discussed above in connection with large spectrometer projects at major facilities. Gas detector research per se can be effectively pursued at universities, since expensive highly specialized equipment is not necessary, as for example in semiconductor-detector or scintillation-crystal production. Centralized technological support for gas detector production (grid winding, thin foil production, electronic modules, etc.) could be established at a reasonable level at major facilities, together with a mechanism that provides easy access to such services for university researchers.

Table C-3-b-1. Some Characteristics of Gas Detectors

Type	$\Delta E/E$, %	$\Delta(dE/dx)/(dE/dx)$, %	Δt, ns	Δx, μm
Large single-volume ionization chamber	0.3	1.5	2	200
Multi-sampling ionization chamber	0.3	1.0	2	–
Bragg curve spectrometer	0.3	1.1	5	500
Parallel plate avalanche counter	–	20	0.14	2000
Double gridded avalanche counter	–	20	0.20	1500
Low-pressure multi-wire proportional counters	–	10	0.10	100
Gas scintillation counters	0.7	3	0.25	–
Streamer chamber	5	10	–	2000
Time projection chamber	15	20	–	200
Wire chamber proportional counters (multi-wire p.c.'s or drift chambers)	–	20	0.5	100
Vertical drift chambers	–	20	0.5	80
Multi-sandwich, analogue sampling calorimeters (with p.c. components)	5	20	–	–
Low pressure drift chambers with photo-sensitivity (photo-ionizable vapor or UV photo cathodes)	–	–	0.5	5000
Multi-step drift-avalanche system	–	–	fast gating	2000

c. Large Fine-grained Detectors

i) Neutrinos

Neutrino detectors in the low/medium energy regime have contributed to significant discoveries in physics. The pioneering detectors did not have a substantial capability for position sensitivity, and the techniques which were developed and successfully used testify to the ingenuity of these designs. More recently, fine-grained detectors with detailed spatial information have been built. Thus, events may be better localized (for background rejection), tracked (for kinematic reconstruction), and identified (for particle selection). These added capabilities offer new possibilities for experimentation and discovery.

Recent neutrino detectors in this energy range are listed in Table C-3-c-1. Included are detectors of neutrinos from the sun, from stellar collapse, from reactors, and from LAMPF. Table C-3-c-2 shows detectors for experiments on proton decay[1-4] that share many of the same essential attributes as neutrino detectors. Only a few of the existing neutrino detectors, but many of the recently approved proton decay detectors, are fine grained. The higher cost per unit mass of fine-grained detectors constrains their use to critical experiments that would not be possible otherwise.

ii) Sandwich Detectors

All of the existing fine-grained neutrino (and proton decay) detectors, are of the sandwich type. This approach alternates layer(s) of target material with layer(s) of position sensitive detectors. This "separated function" approach is attractive because of the many possible options for the sandwich. The target layer(s) may be inert (e.g., aluminium, iron, lead, marble, concrete) or live (e.g., plastic and/or liquid scintillation counter, water Cerenkov counter). The position sensitive layer(s) also span an enormous range (e.g., spark chambers, flash chambers, MWPC's, proportional drift tubes, limited streamer tubes). This variety is evident in Tables C-3-c-1 and C-3-c-2.

The sandwich approach is particularly cost effective at higher energies. The early sandwich type neutrino detectors at high energy accelerators sampled events at quite coarse intervals. Recent detectors have much finer sampling to provide more detailed information but they have also become more expensive. Thus, the trend at high energy accelerators is also toward fine-grained and correspondingly more expensive detectors.

At lower energies where the sandwich layers must be very thin, the technical and financial problems associated with using many such layers of large area for massive neutrino detectors are severe. As layer thicknesses approach about 1 g/cm^2, such difficulties become much less tractable, and may be insurmountable for large detectors.

iii) Homogeneous Detectors

None of the existing homogeneous neutrino detectors in the low/medium energy range is fine-grained. The classic fine-grained detector at high energy accelerators is the bubble chamber. The unsurpassed spatial resolution of bubble chambers more than compensates for their many liabilities, some of which can be minimized with the use of auxiliary detectors. Bubble chambers, especially the hybridized systems, are expensive per unit detector mass. Nevertheless, such detector systems may become useful with further development, at future very high flux neutrino facilities and elsewhere.

An alternative approach which shows great potential is the liquid time projection chamber (TPC). Two coordinates are determined by the use of an orthogonal set of readout electrodes in a plane; the third coordinate is determined by measuring drift time of ionization electrons to the readout plane. The availability of scintillation light from most liquid TPC media also provides much additional useful information. A liquid argon TPC has been demonstrated on a small scale,(5) and much remains to be done.

iv) Summary

Table C-3-c-3 shows a comparison of the capabilities of fine-grained neutrino detectors mentioned above. Sandwich detectors are versatile and cost effective until sampling intervals approach about 1 g/cm^2. Bubble chambers are unsurpassed in spatial resolution, and hybridized versions, though relatively small and expensive, may be used where no other alternative exists. The liquid TPC offers the potential of massive detectors at moderate cost with finer sampling than sandwich detectors.

With further development, the homogeneous fine-grained detectors will allow experiments not now feasible with sandwich detectors, thus opening new possibilities for experimentation and discovery.

Table C-3-c-1. Recent Low/Medium Energy Neutrino Detectors

Neutrino	Reaction	Detector	Mass	Reference
Solar	$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}A$	C_2Cl_4 Radio-Chemical	400 tons	6
Stellar Collapse	$\nu_e^- \rightarrow \nu_e^-$ $\bar{\nu}_e + p \rightarrow e^+ + n$	H_2O Cerenkov	300 tons	7
Reactor	$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$	Plastic Scint + NaI(Tl)	18 kg	8
	$\bar{\nu}_e + {}^2H \rightarrow \bar{\nu}_e + n + p$	D_2O	200 kg	9
	$\rightarrow e^+ + n + n$	+ ${}^3He$ Prop Tube		
	$\bar{\nu}_e + p \rightarrow e^+ + n$	Liquid Scint	268 kg	10
		Liquid Scint + ${}^3He$ Prop Chamber	325 kg	11
LAMPF	$\nu_e + {}^2H \rightarrow e^- + p + p$	D_2O Cerenkov	6 tons	12
	$\bar{\nu}_e + {}^2H \rightarrow e^+ + n + n$	H_2O Cerenkov		
	$\nu_e + e^- \rightarrow \nu_e + e^-$ $\bar{\nu}_e + p \rightarrow e^+ + n$ $\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$	Plastic Scint + Flash Chamber (sandwich)	14 tons	13
	$\bar{\nu}_e + p \rightarrow e^+ + n$	Liquid Scint + Prop Drift Tube (sandwich)	20 tons	14
	$\nu_\mu + {}^{12}C \rightarrow \mu^- + {}^{12}N$	Liquid Scint	6 tons	15

Table C-3-c-2. Proton Decay Detectors

Location	Detector	Mass	Reference
Gold Mine India	Prop Tube +34 mm Fe (sandwich)	140 tons	KGF
Iron Mine Minnesota	Prop Tube + 41 mm Taconite Concrete (sandwich)	31 tons	Soudan 1
Mount Blanc Tunnel	Limited Streamer Tube + 10 mm Fe (sandwich)	150 tons	NUSEX
Salt Mine Ohio	H_2O Cerenkov 2,048 5" PMT	8,000 tons	IMB
Silver Mine Utah	H_2O Cerenkov 1,000 5" PMT	2,000 tons	HPW
Zinc Mine Japan	H_2O Cerenkov 1,000 20" PMT	2,900 tons	Kamioka
Frejus Tunnel France	Flash Chamber + Geiger Tubes + 3 mm Fe (sandwich)	1,500 tons	Frejus
Gran Sasso Italy	Flash Chamber + Resistive Plate Chamber + 3 mm Fe (sandwich)	10,000 tons	GUD

Table C-3-c-3. Comparison of Detector Performance

Detector Parameter	Sandwich Detector	Bubble Chamber	Liquid TPC
Spatial Resolution			
transverse	very good/excellent	excellent	good/very good
longitudinal	poor	excellent	good/very good
Energy Resolution	poor/good	good	very good (excellent)
Time Resolution	good/excellent	poor	good
Scintillation	excellent	(excellent)	(excellent)
Particle Identification	good	good	(good)
Sensitive Time Duty Factor %	100	0.1 (50) (rapid cycling)	100
Relative Cost	low/medium/high	high	medium

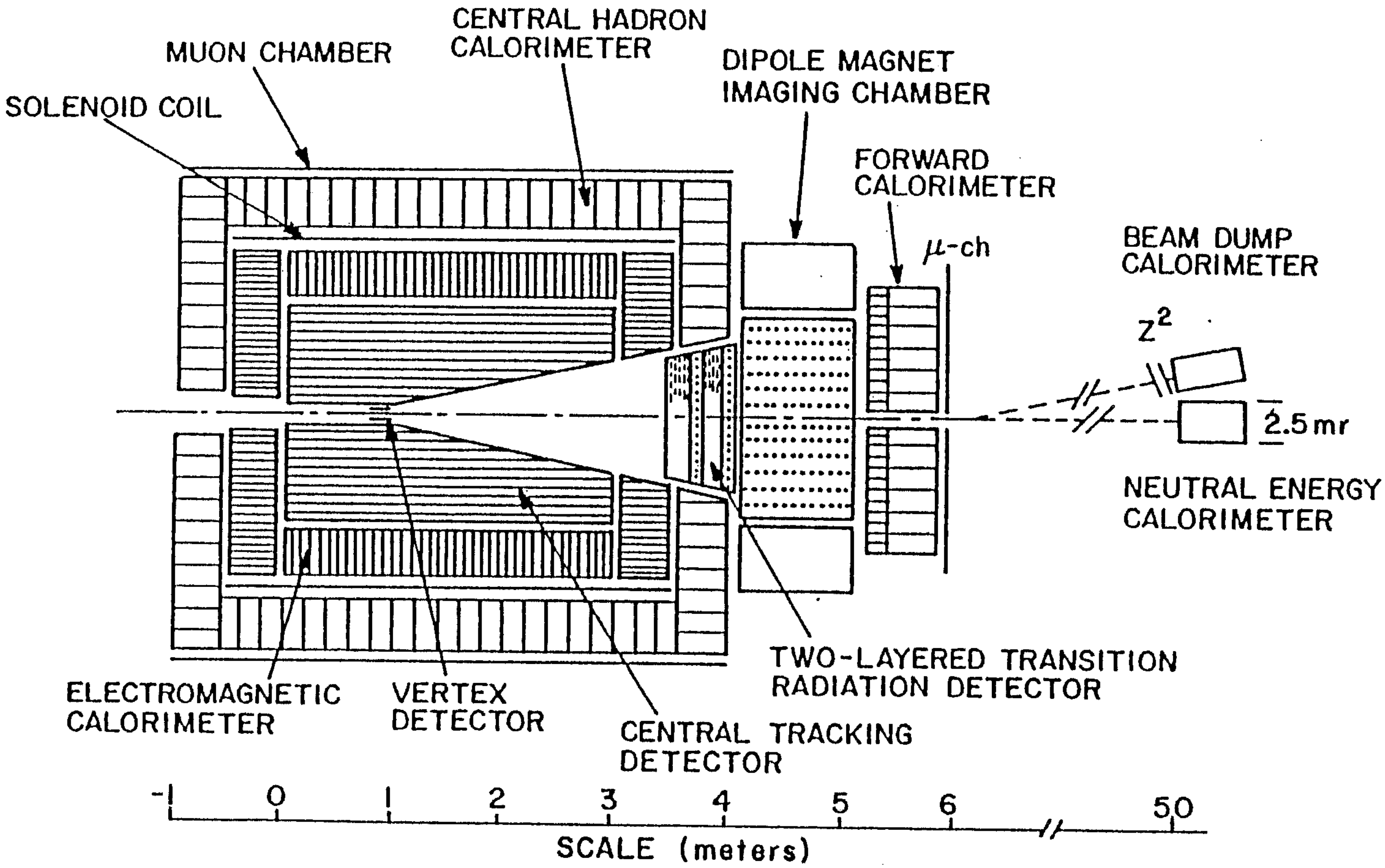

Fig. C-3-c-1. General Purpose Heavy Ion Detector System from Bielefeld Workshop.

v) Fine-grained Heavy Ion Detectors

Establishing the existence of quark matter is more difficult than detecting a new particle like the "W" because it is a macroscopic, many-body state. This is not the place to describe the proposed signatures in detail. References 16-18 provide a good starting place for future discussions. The generally accepted view is that it will take a systematic study of multiplicity, energy flow, and particle production in a global sense to attack the problem. This means that large solid angle detectors with high segmentation and good particle ID are needed. Figure C-3-c-1 shows a general purpose spectrometer from the Bielefeld Workshop (Ref. 19). This detector is typical of the approach to fixed-target experimental designs from several of the studies. The expense of such detector systems is large by the standards of nuclear physics; costs of the order of tens of M$ are not unreasonable estimates.

The task of operating relativistic heavy ion detectors is made easier by the fact that high-energy physicists are dealing with a subset of the problems to be encountered, namely, high segmentation, complex triggering, and high multiplicities (Ref. 20). Thus, normal feedback can be expected when there are several groups working on the same problem. The problems unique to heavy ions, such as dynamic range and very high multiplicities, must be handled by nuclear physicists.

Several actions would help to lay the groundwork for a sound plan for developing the necessary heavy ion detector systems.

1. The Nuclear Physics Division of the APS could sponsor a series of workshops on general heavy ion spectrometers along the lines of the 1983 Division of Particles and Fields workshop on collider detectors (Ref. 20).

2. Proposals for detector development in the following areas should be supported:

   - Large dynamic range, large area tracking detectors. Candidates are drift chambers with gas mixtures that eliminate the cross talk caused by the large avalanche photon production, multi-layer chambers using readout via the gas-scintillation signal, silicon strip detectors, and high pressure microjet drift chambers.

   - Large area charge and time-of-flight detectors for particle identification in the $z>1$ region. Again, there are major problems with conventional approaches because of the dynamic range required. Candidates are total reflection Cerenkov detectors, aerogel radiators, and multiple sampling proportional chambers.

   - Triggering and data handling for experiments of this size. We can count on lots of help from the high-energy community here. However, our trigger problem is more subtle and our multiplicities range up to two orders of magnitude above those expected from the next high-energy machine in the 400 on 400 GeV range. Nuclear physics groups should be provided funds to begin to catch up in the development and use of fastbus related equipment.

These development efforts should be funded at 10-20% of the cost of the detector to be developed. For the detector cost mentioned above, this means the order of 1M$/year assuming a five-year development period. An approach of this kind is required if we are to create the environment necessary for nuclear physicists to vigorously pursue relativistic heavy ion physics.

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d. Magnetic Spectrometers

i) General Background and Comments

A few developments have carried the state of the art of magnetic spectrometers somewhat beyond that discussed in the July 1979 report.

Several new particle spectrometers have been designed and some of them are already operating. The following list gives some examples, the emphasis is on novel features.

a) A particle spectrometer has been constructed at Oxford University[2] for studies of heavy-ion reactions with beams from a folded tandem accelerator. The design is of the type MDM (multiple-dipole-multipole) with the dipole having a gradient parameter $n = 0.2$. Maximum solid angle is 8 millisteradians, resolution $p/\Delta p \approx 2000$ at full solid angle, and the momentum range is ±12 percent maximum (at reduced solid angle).

b) Two low-energy pion spectrometers have been put in operation recently, one at SIN, Switzerland,[3] and the other at the MIT Bates Linac.[4] A third, being constructed at LAMPF,[5] should be in operation within a year. The Bates instrument is a QQ-split pole with high orders of correction, broad range, and a 40-msr solid angle.

   The SIN instrument is a QQQ-split pole with an intermediate image after the triplet (mainly to reduce background). The LAMPF spectrometer[5] is a single dipole with inhomogenous field. The inhomogeneity is not of the common type, describable with an n-value, but rather similar to the field distribution in an "orange sector" beta spectrometer. In other words, the pole pieces are wedge-shaped, producing a wedge-shaped gap.

c) Sometimes the requirements on resolving power and solid angle are not so stringent that a large instrument is required. An example is the intrumentation needed for analysis of the beam in an accelerator mass spectrometery (e.g., separating ^{14}C from ^{13}C and ^{12}C). A very simple magnet has been manufactored by General Ionex of Newburyport, Mass. It deflects the beam only 45 degrees and yet produces a point-to-point focus with both object and image distances being only one radial distance. This is accomplished by strong alternating gradients built into the dipole.

d) A large particle spectrometer is being constructed for the Superconducting Cyclotron Facility at Michigan State University.[6] The optical layout is QQDD with no hardware corrections even for second-order aberrations. All corrections will be made in the data analysis, requiring angle measurements in both directions accurate to about one milliradian. The maximum dipole field is 15 kG, yet the coils are superconducting - for energy coservation.

ii) Energy-Mass Spectrometers

In heavy-ion reactions it is often desirable to measure energy with good resolution and in addition be able to determine the mass and element number of the ion. One instrument that may be considered is the energy mass spectrograph mentioned in the July 1979 report. For most laboratories, a more attractive solution is a conventional particle spectrometer combined with time-of-flight. This technique has been demonstrated very convincingly by a research group at GSI in Germany.[7] The key to the success is a detector system that can be used to determine stop time, ΔE, E, position, and angle.

iii) Recoil Spectrometers

Heavy-ion fusion reactions produce evaporation residues recoiling in the forward direction in a very tight cone. The first and principal task is to separate these products from the main beam. The July 1979 report mentions two instruments designed for this purpose: the SHIP at GSI and the EMS at Brookhaven. Three new instruments have been put into operation: the Recoil-Mass-Selector (RMS) at Oak Ridge,[8] a recoil mass spectrometer at Rochester,[9] and a recoil mass spectrometer at Michigan State University.[6] The Oak Ridge RMS is a beam filter (like the SHIP) with possible extensions to make it into a mass spectrometer (actually an isotope separator). Both the Rochester and MSU instruments serve both functions directly. A recoil mass spectrometer is being installed at the Daresbury Tandem[10] in England, and an optical design exists for an instrument to be installed at the Padua Tandem in Italy.[11]

iv) A Time-of-Flight Mass Spectrometer at LAMPF

A new type of time-of-flight mass spectrometer for energetic ions has been suggested by Wollnik and Matsuo.[12] An instrument using their fundamental idea is being constructed at LAMPF to be used for measuring the masses of rare light spallation products from a uranium target bombarded with 800-MeV protons. The instrument employs an ion-optical system which is isochronous for variations in velocity. (The higher-velocity ions travel a longer distance than the low velocity ions.) As a result, it is possible to measure the mass by time-of-flight to high precision. The final four-magnet design employs the "unit cell" idea invented by Karl Brown[13] and has spectacularly low aberrations.

v) Needs for the Near Future

Presumably a 4-GeV electron accelerator will be built in the United States during this decade. This facility will need large spectrometer systems for single-channel, as well as coincidence spectroscopy. Two working groups have been formed under the auspices of the Southern Universities Research Association to study these problems.

vi) Conclusion

The field of magnetic spectroscopy in nuclear physics is alive and well. Focal-plane detectors are, however, lagging behind. Part of the trouble is that a universal solution apparently does not exist. Each detector has its strengths and weaknesses, and to cover all applications one needs a multiple of good solutions.

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C-4. TARGETS AND ION SOURCES

a. Polarized Beams and Polarized Targets

i) Introduction

Beams of spin-polarized projectiles, as well as targets of spin-polarized nuclei, play an increasingly important role in the study of nuclear phenomena. In some cases polarization phenomena are studied as a means to unravel complicated nuclear reaction mechanisms (e.g., study of coupled-channels effects); in other cases the spin-dependence of the interaction _per se_ is of interest (e.g., spin dependence of the nucleon-nucleon potential, spin-orbit and spin-spin interaction in the optical potential). Other applications include the study of fundamental symmetry laws (e.g., detection of parity violation from the helicity dependence of the cross section, charge symmetry experiments in n-p interactions) and the production of polarized reaction products by bombarding a target with a polarized beam (e.g., polarized β-emitters for weak-interaction studies, polarized fast neutrons).

Polarized ion sources were first developed by nuclear physicists for injection into low-energy accelerators. Use of these devices in high-energy accelerators is relatively recent. The develoment of polarized targets, on the other hand, was carried out primarily for use in high-energy experiments, but their use in medium-energy facilities is now widespread. Besides applications in nuclear and high-energy physics, the developments to be discussed below have recently also become of interest to the effort to achieve controlled thermonuclear reactions, because with suitably chosen spin states of the colliding particles, desired cross sections can be enhanced, undesired ones can be suppressed, or reaction products can be directed preferentially in particular directions. Another, quite recent application of polarized beams is in surface studies, of the depolarization when low-energy ions incident on a surface are re-emitted.

Below, we briefly review the various methods which have been developed to produce polarized beams and targets. Some avenues for further research and development, which have been proposed at various recent conferences and workshops in this field, are presented to illustrate the wide range of opportunities for important advances.

ii) Polarized Positive Hydrogen Ions

Polarized positive ions are used for injection into cyclotrons. The ion sources are based on the atomic-beam method, i.e., spin separation of thermal H_o or D^o atoms by passing a collimated atomic beam through an inhomogenous magnetic field (six-pole magnet), and subsequent ionization of the atoms by electron bombardment. The nuclear spin states are changed by rf transitions between hyperfine states. Sources of this type have been installed on three cyclotrons in the U. S. Typically, the atomic-beam section produces $10^{16}\vec{H}^o$/s with an average velocity of $v \sim 3 \times 10^5$ cm/s. About 1% of the atoms are ionized, yielding some 20 μA polarized beam of about 80% polarization.

Improved beam currents resulted from the development of new ionizers (CERN in collaboration with ANAC Inc., and ETH, Zürich). Electrons of several

A/cm^2 current density are produced by a plasma discharge (supported by electrons from a filament), and confined in magnetic and electric fields, resulting in an ionization efficiency of a few percent, and yielding beam currents of 100 μA (ETH, Zürich). A commercial ionizer of this type is installed at the Berkeley 88[11] cyclotron. Other development work attempts to confine higher current densities of electrons in superconducting solenoids (Bonn, Germany; Saclay, France).

The flux of polarized atoms from the atomic-beam stage is limited by gas dynamics in the dissociator-nozzle from which the atoms escape to form the atomic beam. However, it has been shown that improved ion currents can be obtained by cooling the nozzle, e.g., to 20 K (pulsed dissociator at Argonne ZGS). While cooling reduces the effusion rate from the dissociator, it improves both the acceptance angle of the six-pole magnet and the ionization efficiency (the latter on account of the longer dwell time in the ionizer). Application to DC beams requires a solution to the heat transfer and recombination problems in the cooled nozzle. Successful cooling to liquid nitrogen temperature is in progress (SIN and ETH, Zürich; CERN, Geneva).

The large velocity spread of the atomic beam causes a problem in transporting the beam without loss from the exit of the six-pole magnet to the ionization region, because atoms of different velocities emerge from the magnet in different directions (chromatic aberrations). Recent work has shown that atomic beam transport to the ionization region can be improved by proper field contours of the six-pole field along the axis (use of several separate tapered six-poles; in Bonn, Germany). Further reduction of chromatic aberrations may be achieved by combining six-pole and quadrupole magnets.

These development projects, if successful, will yield polarized proton and deuteron currents of approximately 500 μA. A gain by another order of magnitude might result from a recent proposal (D. Kleppner, MIT) to use a very cold neutral atomic beam (0.3 K), which would be accelerated in the fringe-field of a superconducting solenoid to form a nearly monoenergetic forward-directed, cold (~8 K) atomic beam. This would drastically reduce chromatic aberrations and increase the efficiency of the ionizer. Recommended research in the short term includes development of dissociators producing intense cold atomic beams and magnet systems that match the velocity distribution of the cold source. In the long term, the development of intense ultracold monochromatic atomic beams should be pursued. These developments would also have direct application to the production of more intense beams of negative ions (Section iii) and to polarized gas targets (Section viii).

iii) Polarized Negative Hydrogen Ions

Polarized negative ions are required for injection into tandem accelerators and medium energy accelerators (LAMPF, TRIUMF). In addition, negative ions are preferred for large synchrotrons (Brookhaven AGS) because they allow multiturn injection by stripping at insertion into the ring.

Most sources for polarized negative ions operating on accelerators in the U. S. use the Lamb-shift method, in which the special properties of the metastable $2S_{1/2}$ excited state of the hydrogen atoms are exploited. Polarization is achieved by quenching the undesired excited hyperfine states (i.e. removing them by inducing transitions to the ground state). This is the only type of source with sufficiently good gas economy to produce polarized tritons (LANL). Also, the source is capable of large deuteron alignment (spin-filter, LANL) and permits easy velocity modulation for beam bunching. On the other hand, in spite of skillful development efforts, the beam intensity has been stalled at the 1 μA level for a number of years. The problem is thought to be related to the fact that with increasing beam, the electric field from space charge of the H^+ beam quenches the H(2S) atoms. Recent attempts (TRIUMF, in collaboration with TUNL) to produce the H(2S) atoms in a space-charge neutralized environment, using an electron-cyclotron resonance (ECR) source, have been unsuccessful.

The best polarized negative ion currents available are produced by atomic-beam sources. Negative ions are produced either by charge exchange of a polarized H^+ beam in Na vapor, yielding as much as 6 μA H^- (ETH Zürich, Switzerland), or by direct electron transfer from fast (50 keV) Cs^0 atoms to the thermal polarized H^0 atoms, which has produced 3 μA H^- (colliding-beam principle, University of Wisconsin). A colliding-beam source of the Wisconsin design has been constructed for the Brookhaven AGS and has produced up to 25 μA in a pulsed mode. Both of these methods would benefit from the development of improved atomic beams mentioned above. In addition, the colliding-beam source would benefit from further developments of the fast Cs^0 beam. Recent tests (University of Wisconsin) have shown a three-fold increase of the Cs^0 beam. With improved atomic-beam devices, atomic-beam sources have the potential to produce some 50 μA of polarized H^- and D^- in DC operation, and 100 μA for pulsed operation (synchrotrons). With the development of a very cold atomic beam, intensities of a few hundred μA may be possible. Such large intensities would permit qualitatively new experiments e.g. for the production of polarized fast neutrons at LAMPF. That facility has at present a Lamb-shift source that delivers typically 0.5 μA DC with 80% polarization. Because of the LAMPF duty factor, about 15-25 nA average is available for sharing between three areas: the High Resolution Spectrometer (HRS), the External Proton Beam (EPB), and the polarized neutron area. The available intensities are adequate for the first two areas but fall far short of optimum for production of polarized neutrons. A development project now underway is expected to double the available beam. In November 1983, a workshop was convened to determine the physics justification for a source 10-100 times as intense as the present one.

Currently there is interest in a promising new scheme to produce polarized beams, based on the use of optically-pumped alkali vapor (e.g., Na) as a donor of polarized electrons. When unpolarized protons of a few keV energy pass through polarized Na vapor, they pick up polarized electrons to form fast polarized H^0 atoms. After transferring the electron polarization to the nucleus (sudden field-reversal method), the atoms pass through a second (unpolarized) vapor cell, where they are ionized. The method was first proposed in the U. S. (University of Wisconsin), and some initial experiments were carried out at LAMPF, but the only sustained development effort is in Japan for eventual injection into the KEK synchrotron. A beam current of 20 μA H^- has been obtained at KEK. This type of source is primarily of interest for protons (and tritons). The source is not expected to provide the necessary flexibility to produce, at will, vector or tensor polarized deuterons.

Recommended research in the short term includes improved designs of the charge exchange cell and ion optics for conversion of polarized H^+ to H^- (e.g., charge exchange in Rb at 1 keV instead of Na at 5 keV) and the development of more intense Cs^0 beams for ionization of polarized H^0. In the long term, large gains may be possible by ionization of polarized H^0 with a beam of D^- ions of $\leq$ 1 keV energy (larger cross section than ionization by Cs^0, but severe space charge problems). In addition, for the scheme used at KEK, significant advantages would result by replacing the optically pumped Na cell with a dense gas target of polarized H^0.

iv) Polarized Heavy Ions

Negative ions of polarized ^6Li, ^7Li and ^{23}Na have been in use at Heidelberg, Germany, for several years to study the spin dependence in heavy ion scattering (shape effects) and reactions. The source uses the atomic beam principle but exploits the fact that very high (~100%) ionization efficiency can be obtained for alkali atoms by surface ionization on a suitably prepared hot tungsten surface. Positive polarized ion currents of tens of μA can be obtained, yielding (after charge exchange) negative beams of the order of 1 μA. No equipment of this type exists in the U. S., but a source for polarized Li negative ions is under construction at Florida State University. Calculations indicate that ionization with useful efficiency can also be obtained by the colliding beam method.

It is known that the nuclei of alkali atoms can, in principle, be completely polarized (state of maximum m_F) by repeated absorption of circularly polarized photons of appropriate wave length (optical pumping). A number of laboratories have now demonstrated in practice that a very large percentage of the nuclear spins can be pumped into the state of highest angular momentum. Polarized sources of Na and Li ions based on optical pumping are currently being developed (Marburg and Heidelberg, Germany; University of Wisconsin).

For the production of polarized alkali ions, it is recommended that the present development work using optical pumping be continued. If heavy ion nuclear research establishes a need for other types of polarized heavy ions, further development of the atomic beam method will be required.

v) Polarized ^3He Beams

The Lamb-shift method has been applied to polarize $^3He^+$ ions, with subsequent ionization to $^3He^{++}$ at the University of Birmingham, England. This is the only source of polarized ^3He in operation. Currents from the ion source prior to injection into the Birmingham fixed-frequency cyclotron (33 MeV ^3He) are of the order of 0.1 μA, with 60% polarization.

There is continued interest by nuclear physicists in beams of polarized $^3He^+$ for cyclotrons, or $^3He^-$ for tandem accelerators. Work has been reported on extraction of polarized ions from an optically-pumped ^3He gas cell (Texas A&M) and with a scheme to polarize ^3He via the hyperfine interaction in the metastable excited state (Laval).

Exploratory research and development are needed in order to establish the principles on which improved sources can be based.

vi) Polarized Electrons

Polarized electron sources in use at SLAC and other high-energy accelerators have been of two general types. The first is based on photoionization of a polarized ^{6}Li atomic beam and produces pulsed beams with more than 80% polarization and about 10 nA average current. The second type is based on photoemission of polarized electrons from GaAs or GaP with circularly polarized laser light. The pulsed version developed at SLAC operated at about 10 μA average current and about 37% polarization.

Recent development work has been centered on photoemission sources, in particular on the development of new photoemissive materials to improve intensity and polarization and on shifting the photoemissive materials to more convenient wavelengths. The development of $Al_{1-x}Ga_xAs$ compounds has produced polarized beams with ≈ 40% polarization at HeNe laser wavelengths. Beams of 1.5 mA DC at 35% polarization have recently been obtained from GaAs with a Kr ion laser.

Future progress will depend upon the development of photoemissive materials with band structure suited to > 90% electron polarization at wavelengths obtainable with high-power lasers. Photoluminescence measurements have demonstrated that the application of large uniaxial stress to GaAs can result in > 90% electron polarization in the bulk material, but the application to the enhancement of the electron polarization in photoemission is still uncertain. Further development work on multilayered GaAs and $Al_xGa_{1-x}As$ structures and on other compounds is in progress (SLAC-Bell Labs collaboration).

Development work on polarized electron sources for accelerators has largely been carried out by individual groups interested in a specific parity violation experiment. With the current interest in high energy CW electron accelerators, the expansion of development work on polarized electron sources is particularly important. Polarized beams will be necessary for a variety of proposed nuclear structure and weak interaction measurements.

Substantial research is required to combine the large intensity (> 1 mA) obtained from photoemission sources with the large polarization (> 80%) obtained from atomic beam sources. Often, low polarization cannot be offset by larger beam intensity because of radiation damage to the target (e.g. polarized target). Work to enhance the electron polarization from photoemission sources is needed, as well as studies on efficient ionization (with photons or protons) of intense, optically pumped alkali atomic beams or vapors.

vii) Polarized Solid Targets

For many years, experiments on high-energy and medium-energy accelerators have employed targets containing polarized protons or deuterons. Most of these targets are based on dynamic nuclear polarization (DNP). Paramagnetic electronic impurities are introduced in the sample, and the electronic spins are cooled by performing adiabatic demagnetization on the electronic spins in the presence of a microwave field. The target materials are primarily organic substances, doped with free radicals. Recently, DNP has been applied successfully to solid NH_3 (CERN) achieving almost complete polarization of the three protons. The paramagnetic centers are produced by irradiation of the frozen NH_3. Contrary to other types of target materials, for which radiation damage reduces the polarization, these new targets are sometimes found to improve with use (BNL).

The goal of additional research is to polarize solids that contain a larger fraction of polarizable protons than NH_3. Also, there is a need for deuterium targets of large nuclear polarization, since the small g-factor of the deuteron causes additional problems. Work is in progress on ^{6}LiD for which both the free deuteron and the deuteron bound in ^{6}Li are polarized. Polarization of some substances by the "brute-force" method ($\mu_{nuclear}$ B >> kT) has become feasible through the increased availability of refrigerators operating at very low temperatures. Current interest centers on polarizing protons in HD and in metal hydrides.

Certain nuclear-physics problems (e.g. study of the spin-spin interaction in the nuclear optical potential) require samples of polarized heavy nuclei. A project is in progress (TUNL) to polarize a number of different samples by brute force for use in a variety of nuclear reaction experiments.

There is an immediate need for development work to reduce the cost of construction and operation of polarized targets and to increase the mass of polarizable material. In addition, it is important to develop targets which operate without the need of a very strong magnetic field. In the long term, research on frozen spin targets (e.g. HD) which contain a large fraction of polarizable nuclei is a high priority, since they hold promise of permitting large sample size and high polarization.

viii) Polarized Gas Targets

Some applications (low-energy charged particle experiments, targets in storage rings) require polarized targets of low density, which will operate preferably in a magnetic field of only a few Gauss and which will not radiation damage.

Samples of polarized atomic hydrogen have been produced in a strong magnetic field at very low temperatures, and it has been shown that large nuclear polarization can be obtained by preferential recombination of one of the hyperfine states, and subsequent freezing of the undesired molecules on the wall. To use such samples as targets, techniques are under development (MIT) to access the polarized atoms by an ion beam without disturbing the operation. For lower target densities ($\lesssim 10^{13}$ cm^{-3}), a simpler approach is to use polarized atoms from an atomic-beam source. Scattering of α-particles from a free beam of polarized hydrogen atoms has been demonstrated (Stanford), and increased density in a practical target by storage of polarized atoms in a coated pyrex target cell has been obtained (Wisconsin). Further studies are required to increase the density in storage cells, by cooling the cell walls and by reducing the gas conductance of the access ports to the target. The developments mentioned earlier in connection with atomic-beam polarized ion sources would be of direct benefit when an atomic beam is to be used as a polarized target. One of the key advantages, e.g., for storage rings, is that these targets require essentially no magnetic field (provided the atoms are prepared in a pure spin state) and that the polarization can be rapidly reversed. A polarized jet target is in the development stage at CERN. The atomic-beam method to produce a polarized jet target is in principle applicable to any atom that has an electronic magnetic moment and that can be formed into an atomic beam.

Other target gases and vapors can be polarized by optical pumping. In particular, alkali atoms can be optically pumped to produce polarized targets either by confining the vapor to a cell or by producing a free atomic beam. The possibility of using optically pumped vapors to polarize other atoms (e.g. hydrogen) by spin-exchange collisions has recently been proposed (Princeton). Optically pumped ^{3}He gas has been used for many years in nuclear scattering experiments, and it has been shown that the gas can be compressed without losing the polarization.

Recommended research in the short term includes the development of free atomic beams of higher density by the techniques listed in Section ii), and the development of wall coatings for cooled storage cells. In the long term, large increases in density can possibly be achieved by employing spin exchange collisions with optically pumped vapors, or by exploiting the high density hydrogen atoms in ultracold spin stabilized cells. To permit access to the atoms in the cell by the beam from an accelerator, methods of efficient ejection of atoms from the cold cell should be developed.

ix) Conclusions

The development of polarized beams and targets has made it possible over the last decade to address fundamental questions about spin dependences and symmetry laws in nuclear interactions. Experiments of this type are still limited by the intensity and variety of the available beams and targets. Development in this area offers a cost-effective way to address new physics problems. The cost of these development projects is small compared to the construction cost of accelerators, but the result significantly enhances the usefulness of existing and planned machines.

b. High Charge State Ion Sources

i) Introduction

For positive heavy ion accelerators, an increase in charge state in the accelerated ion can provide higher energy in a given accelerator size. In the case of cyclotrons or synchrotrons, a magnet with a given $B\rho$ will contain a momentum proportional to charge state, or (non-relativistic) energy proportional to $(\text{charge})^2$. An advanced high charge state ion source provides a cost-effective upgrade option for many cyclotrons now using a PIG source. For single-stage cyclotrons, an advanced ion source can give a factor of 2-3 increase in energy. Even for a two-stage cyclotron system (MSU, Texas A&M) an advanced source injecting the first cyclotron will expand the energy range of beams of the heaviest ions. A deuteron synchrotron (CERN, Saturne, Dubna) can expand its program to fully stripped lighter heavy ions with an advanced ion source. A heavy-ion linac can be designed with an advanced source to give higher energy or mass range with a given length and voltage gradient. An existing linac that does not accelerate all masses may be upgraded in mass range by the addition of a high charge state source and a suitable pre-injector.

In addition to providing higher performance for nuclear science accelerators, high charge state beams are in demand for atomic physics research, such as charge exchange reaction studies, ionization by electrons, and spectroscopy.

The production of high charge state ions is accomplished by bombardment with a high density electron beam, for a sufficient time. The electrons must have energies of several times the high charge state ionization potentials. The background pressure must be low to avoid charge exchange.

ii) The PIG Source

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 arc in a uniform magnetic field. The plasma is about 10 cm long by 1 cm in diameter. The PIG source produces beams of all ions, DC or pulsed with tens 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 of this source for high charge state production are the short ion containment time and high background pressure. The source lifetime is determined by sputtering of the metal cathodes and ranges from a few hours to a few days for high duty factor operation.

iii) The ECR Source

The most widely used of the advanced high charge state sources is the electron cyclotron resonance (ECR) source. This source uses microwave power to heat electrons trapped in a magnetic mirror configuration. Electron energies can be 10-100 keV. The plasma chamber is 50-100 cm long and 10 to 30 cm diameter. The resulting plasma is stabilized by a multipole magnetic field. A small injector stage is normally used to form the plasma at 10^{-3} torr, so that the main stage can operate at 10^{-6} torr. The superior performance of the ECR compared to the PIG is due to its longer ion confinement time and its better vacuum. The ECR source produces continuous beams of 0.1 to 1 electrical milliamps (sum of all charge states), and an electrical microamp of Ne^{8+} and Ar^{11+}. Hence, replacing a PIG source by an ECR source can double a cyclotron energy for mass 40 ions, with an external beam intensity of 0.1 electrical microamp, assuming 10% overall cyclotron transmission. The source lifetime is limited only by the electronic components and is typically many months.

The development of the present ECR sources started with Geller's work at CEN, Grenoble, France, using a large existing plasma machine (SuperMAFIOS). Geller subsequently built compact ECR sources called MicroMAFIOS and MiniMAFIOS, which fortunately gave about the same charge state distribution as the large source. Other laboratories in Europe are operating or planning such sources. In the U. S. compact room-temperature ECR sources are being constructed at the LBL 88-Inch Cyclotron and at Oak Ridge for atomic physics research. Laboratories at Karlsruhe and Julich, Germany, and at Louvain, Belgium have built large ECR sources using superconducting coils.

In the last several years, the successful construction and operation of these ECR sources has given us confidence that reliable sources can be built. The scaling laws of charge state output with source size and microwave frequency have been investigated. At Louvain, tests of scaling with source size have shown that larger size gives longer confinement time at lower density and produces somewhat higher charge states. Higher microwave frequencies can penetrate denser plasmas, with the dependence density ~ $(\text{frequency})^2$, so we might expect higher charge states in higher frequency (requiring higher field) sources, because of their higher electron densities. One test has been made varying the frequency, showing that the charge states do not change much. But more detailed tests will be made on new sources during the next year. Solid material feed systems have been developed by Geller, and more experience will be obtained as other labs begin work in this area.

The ECR source appears to be the most suitable of the advanced sources for use on a high duty factor nuclear science accelerator such as a cyclotron or heavy-ion linac because of its high intensity and duty factor. For laboratories wishing to build ECR sources, the designs of existing sources are available, except for that of the MiniMAFIOS, at CEN, Grenoble. This source design has been assigned to the French company CGR-MeV, which has offered to sell complete sources for about $800,000. The source can be built for a comparable amount by a laboratory. The price of a superconducting source would be $1-2 million.

iv) The EBIS Source

The other important type of advanced heavy ion source is the EBIS (electron beam ion source). It was developed first at Dubna, U.S.S.R. In its high charge state form it uses a 0.1-1 mm diameter electron beam of 5-20 kV traveling along the axis of a 1-m long superconducting solenoid magnet, to produce step-by-step ionization. The EBIS uses a batch process, in which a group of ions is injected, ionized to high charge states during a containment time varying from a few milliseconds to a few seconds, and then extracted. High charge states produced at Dubna include fully stripped ions up to Ar^{18+}, and heavier species up to Xe^{52+}. Intensities are typically 10^8-10^{10}

particles/pulse. So average intensities would lie in the range 10^8-10^{12} particles/s, going from very high charge states to low charge states.

An EBIS is injecting the 10 GeV synchrotron at Dubna, and a similar source is being developed for the Saturne synchrotron at Saclay. Other superconducting sources have been built at Frankfurt, Germany, and Nagoya, Japan. Orsay has embarked on an ambitious project to build an EBIS to produce Xe^{54+} and U^{90+} using a high compression 50 keV electron beam in a 5 Tesla solenoid. A two-year EBIS R&D program was recently completed at LBL using a room temperature test EBIS, to evaluate the merit of an EBIS injector for the 88-Inch Cyclotron. High rep-rate, duty-factor stretching and reproducible operation were demonstrated in this program. The conclusion was that, although EBIS charge states were higher, an ECR source is a better match to the beam intensity and duty factor requirements of typical cyclotron experiments. Work was also done on understanding the plasma stability in this source.

The EBIS is technically demanding in the construction of the version producing highest charge states, requiring high vacuum (10^{-10} torr), superconducting solenoid and precision alignment (< 0.1 mm) in the magnetic field and electron beam axes. Its batch type operation makes it more suitable as an injector for a synchrotron than for a cyclotron or high duty factor linac. Development work remaining to be done includes investigating the anomalously high electron density mode observed by Orsay, further developing high rep-rate and high duty-factor beams, and developing the feed of solid source material.

In building a high-performance EBIS, particular care must be taken in the construction symmetry of the superconducting magnet and in the alignment of all the components. In some laboratories years have been spent in solving these problems. The cost of such a source is in the $2-3 million range.

v) Other Sources

High charge state plasmas have also been produced by laser bombardment of a surface, pulsed vacuum arcs, and exploding wires, but duty factors have been too low for use in nuclear science accelerators.

c. Negative Ion Sources

Since the status of negative ion source development was discussed in some depth in the report of 1979, here we merely present an update. The development of new types of high intensity sputter ion sources, referred to in the previous report, has continued at several laboratories, in particular the Universities of Wisconsin and Pennsylvania.

Some typical negative ion currents from the Penn source are as follows: 30 μA of $^{11}B^-$, 300 μA of $^{12}C^-$, 250 μA of $^{16}O^-$, 4 μA of $^{27}Al^-$, 200 μA of $^{28}Si^-$, 200 μA of $^{32}S^-$, 150 μA of $^{58}Ni^-$, 150 μA of $^{63}Cu^-$, 200 μA of $^{197}Au^-$, and 0.4 μA of $^{208}Pb^-$. Emittance is relatively low (2 - 3 π mm mrad $MeV^{1/2}$) and sputter targets can be changed in 5 to 10 minutes.

A particularly exciting application of the Penn source was recently reported by the Brookhaven group. The source was operated in pulsed mode to provide 100 to 200 μA negative ion currents in 230 μsec square pulses, 10 pulses/sec. These pulses, which are 50 to 100 times more intense than normal DC beams, were accelerated through the MP7 tandem while operating at 14 MV. After charge state analysis, the emittance of the pulsed beam was also measured. The very stable accelerator behavior indicated that even higher currents are possible. Values for ^{16}O are as follows: 115 μA $^{16}O^-$ injected, 100 MeV $^{16}O^{6+}$, 260 μA (43.3 pμA), 1.8 mm mrad; and for ^{32}S, they are: 170 μA $^{32}S^-$ injected, 140 MeV $^{32}S^{9+}$, 240 μA (26.7 pμA), 0.51 mm mrad. The high intensity and low emittance of these ion beams make them ideal for injection into a synchrotron such as the AGS 30 GeV proton accelerator at BNL. The very good beam quality would allow many more turns to be injected into the AGS than is customary with linac injection.

C-5. ACCELERATOR MASS SPECTROMETRY

During the six years that have passed since the revitalization of accelerator mass spectrometry great advances have been made which benefit both nuclear science and the physical sciences at large. The essence of the technique is conventional mass spectrometry with the usual combination of electric and magnetic deflecting fields but performed at energies of a few MeV/nucleon. High energy has the advantage that interfering molecules can be completely eliminated by dissociation and, after analysis, the Z of the final particles can be determined by energy loss measurement. In principle, any type of accelerator can be used for mass spectrometry but the heavy-ion capabilities of a tandem make it particularly well suited and occasionally it is possible to capitalize on the lack of stability of a particular negative ion.

Although accelerator mass spectrometry is applicable to all elements, it has found greatest use with the cosmogenic radioisotopes such as ^{10}Be, ^{14}C, ^{26}Aℓ and ^{36}Cℓ. Direct atom counting has the advantage over decay counting that extremely small samples can be studied. To cite but one example, the ^{10}Be and ^{26}Aℓ content of a single cosmic spherule of ~150 μg mass has recently been measured, shedding light on whether these enigmatic objects are ablation products of a meteorite or exist in space as small objects.

There can be little doubt that the impact of accelerator mass spectrometry has been greatest in fields of terrestrial and planetary sciences, but one should not lose sight of contributions made to nuclear science. For example, the technique has been used to make searches of unprecedented sensitivity for the possible existence of anomalously heavy stable hadrons and super-heavy elements in nature. A similar search for free quarks is in the planning state. It has also been used to determine the number of atoms in a radioactive source of known strength permitting a determination of the half-life; the half-lives of ^{26}Aℓ, ^{32}Si and ^{60}Fe have been measured this way. The cross section of the ^{26}Mg(p,n)^{26}Aℓ reaction has been determined by measuring the number of ^{26}Aℓ atoms in a target of ^{26}Mg which had been bombarded by a known integrated flux of protons. Recently, by accelerating and individually counting ^{7}Be atoms, an ultra-accurately known source was produced and later used to determine the branching ratio of ^{7}Be. It is likely that the use of accelerator mass spectrometry to solve unusual nuclear problems will continue. Possibly, someone will take up the challenge to use it to look for proton decay, as was recently suggested.

Most existing tandem accelerators, particularly those built ten or more years ago (the majority), have low-resolution injectors, poorly regulated steerer and lens power supplies, and generally inferior ion optics resulting in low and erratic transmission. Although holding considerable potential for accelerator mass spectrometry, none are well suited without upgrading and modification. To date, only the EN tandem at the Eidg. Technische Hochschule, Zürich, has been extensively modified and, other than the so-called new dedicated tandems, is the only accelerator capable of measuring isotopic ratios with 1% precision. A few other laboratories have made less extensive modifications, largely as a result of financial constraints, and they are currently able to measure isotopic ratios with a precision of about 4% or 5%. It is noteworthy that where modifications have been made the nuclear capabilities of the accelerator have been improved. For example, the addition of a high-resolution injector to the University of Pennsylvania tandem has enabled ^{29}Si to be routinely accelerated from sputter targets of natural silicon. Since the needs of accelerator mass spectrometers and nuclear research are compatible and the former activity appears likely to continue to make valuable contributions to nuclear science, it is urged that more funds be made available to modernize some of the nations ageing tandem accelerators.