TRISTAN

a handbook

MASTER

bnl
at

BNL 35102

July 1984

WHL-35102

DE-AC02-76CH00016

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B R O O K H A V E N N A T I O N A L L A B O R A T O R Y

A S S O C I A T E D U N I V E R S I T I E S , I N C .

Under Contract No. DE-AC02-76CH00016 with the

UNITED STATES DEPARTMENT OF ENERGY

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I. Introduction and Overview

1. Purpose of Booklet

The purpose of this Handbook is to acquaint the community with the capabilities of TRISTAN. We hope it will be of use to frequent users as an update on new developments and to potential new users in giving a feeling for the types of experiments that can be carried out and the ranges of nuclei that can be studied. It is written in an "operational" sense: that is, technical details are kept to a minimum. The purpose of each section is to provide background information and sufficient description such that potential users can judge, or begin to assess, whether their own research interests can be satisfied by working at TRISTAN. Thus, for example, technical details of the various ion sources are minimized in the main body of the report where the emphasis is placed rather on summarizing the isotopes (and their intensities) available from each. Inquiries from new and potential users are encouraged. Please contact one of the undersigned by letter or telephone [(516)282-3908]. A sample beam request form is included in this report.

2. The TRISTAN Separator

TRISTAN is an on-line isotope separator located at the Brookhaven National Laboratory High Flux Beam Reactor (HFBR). Its primary purpose is the study of neutron-rich nuclei far from stability. It is intended principally as a USER facility. Construction, maintenance and improvement of the facility constitute one of the activities of the Neutron Nuclear Group at BNL and are carried out with the advice and help of the TRISTAN user community. The other activities of the BNL group include an extensive program of studies with the (n, γ) reaction, utilizing thermal and resonance energy neutrons, and a related supporting effort in theoretical interpretation of the data from both (n, γ) and TRISTAN studies.

A line drawing of TRISTAN shown in Fig. 1 serves to illustrate its main components. A highly schematic view is also shown in Fig. 2. A neutron beam from the HFBR impinges on a uranium target, inducing fission. The fission fragments, which are neutron-rich nuclei in the approximate mass region $70 < A < 160$, are ionized and extracted as a radioactive ion beam. A particular mass is chosen at the 90° sector magnet and is focussed down one of the beam lines to an experimental

TRISTAN

Fig. 2

end-station by a multi-port switch magnet. At the termini of these beam lines are experimental facilities for γ and β -ray spectroscopy, delayed neutron studies, conversion electron spectroscopy, a dye laser system to measure nuclear isotope shifts and a superconducting magnet for nuclear g factor and $Q\beta$ measurements. The facility operates according to the HFBR schedule, that is, for roughly 40 weeks a year divided into reactor cycles of approximately 25 days of continuous running separated by reactor shutdowns of typically 5-8 days.

The facility is primarily operated in USER mode although, in many cases, experiments are run in collaboration with the local staff. The local staff consists of R. L. Gill (who is in principal charge of day-to-day running and improvement of the separator, ion sources, and experimental facilities), A. Piotrowski (who has principal responsibility for ion source development), and H. Mach (a BNL research associate). The facility is administered by R. F. Casten, Group Leader of the Neutron Group, as one of the principal nuclear physics activities of the BNL Physics Department. D. D. Warner of the BNL Group has also been involved in the interpretation of TRISTAN results and Casten and Warner are also currently involved in several specific experiments as well. For the period June 1984-June 1985, Casten will be on sabbatical leave and Warner will serve as Acting Group Leader.

The number of active users varies with time. Currently, the principal users are the University of Maryland, Iowa State University, Clark University, Cornell University, Oklahoma University, Lafayette College, Pacific Northwest Laboratories, INEL-EGG Idaho, Georgia Institute of Technology, Texas A&M, and McGill University (Canada). In addition, there are active collaborations with several visiting foreign scientists principally from Germany, Israel and Sweden. Additional users are welcome and encouraged. TRISTAN further serves the University community as a resource for the training of graduate students. Currently, approximately ten graduate students are receiving primary Ph.D. training at TRISTAN.

3. Physics at TRISTAN

The physics at TRISTAN is especially broad and deep. The facility provides access to nuclei far from stability on the neutron-rich side and, as such, opens large new areas for nuclear structure exploration. With its combination of ion sources, experimental instruments and capabilities TRISTAN is a unique facility in the world. By giving access to extended and continuous sequences of nuclei, ranging from

near stable to species near the neutron drip line, TRISTAN provides the opportunity to study the evolution of nuclear structure and, in particular, of the collective modes that are central to an understanding of the nuclear many body system, in ways unavailable in experiments limited to near stable nuclei. By giving access to combinations of proton and neutron number not available elsewhere, studies of nuclei far off stability can lead to the discovery of entirely new phenomena, since much of the structure of non-magic nuclei results from valence neutron-proton interactions, whose strength is highly sensitive to the specific orbits involved.

Particularly important areas of study center on the investigation of a wide variety of collective phenomena, of phase transitions, of deformation regions, of symmetries and, possibly, supersymmetries. Regarding the latter, the discovery and study of symmetries is one of the most important areas in modern physics and TRISTAN provides a new resource for their investigation in the nuclear realm. It opens new regions where relatively unstudied symmetries can be explored. This is especially relevant for odd nuclei where the predicted symmetries require specific combinations of single particle and core structure, some of which may not be available near stability. Much of this work fits naturally into the other research interests of the Neutron Nuclear Group at BNL and nicely complements its (n, γ) studies. With (n, γ) one is able to study individual nuclei, near stability, in great detail. At TRISTAN much more extensive sequences of nuclei are accessible, albeit without the same guarantees of spectroscopic completeness.

Besides this work on collective phenomena, TRISTAN provides access to nuclear regions that are expected to be magic in nature. One goal of current TRISTAN studies is the study of nuclei near new doubly closed shell nuclei such as ^{132}Sn , and in the region of ^{78}Ni .

Finally, the access to unstable nuclei with sufficiently large decay energies leads to the possibility of observing radioactivity in the form of β -delayed neutron emission and, in a few cases, of double delayed neutron radioactivity. Such studies are of both applied and structure importance, since they give information on the emission of decay heat from fission products and because they represent the inverse of neutron capture experiments on unstable targets, so that they can provide information on cross sections of neutron-rich nuclides, which is of particular interest for astrophysics and nuclear theory.

4. Growth of TRISTAN

The TRISTAN facility has experienced a substantial growth in capabilities and productivity during the last 18 months, emerging during this period as a major facility for forefront nuclear physics research. Most importantly, impressive strides in ion source developments have changed the scope and promise of TRISTAN in a qualitative way. The histogram of Fig. 3 shows the growth in the number of available parent ion beams with each successive ion source breakthrough. This increase of a factor of six has led to the current availability of ≈ 300 different parent nuclei. Many additional nuclei are, of course, available for study as daughter activities. Equally important, but not evident in the figure, is that the newer sources provide not only new species of ion beams but, in many cases, much greater intensities for existing beams than previously attainable.

In addition to this, the number of experimental instruments has more than doubled recently. The γ - γ angular correlation facility has been expanded by the addition of a parent port for study of short-lived activities. The colinear dye laser for isotope shift studies has been acquired and successfully tested in the Spring of 1984 (by the Texas A&M Group). A superconducting magnet has been installed and field mapped. Test measurements were performed in the June reactor cycle. It will be used for g factor and high-efficiency, low background Q_β measurements. Finally, an electron detector is now operational for the study of conversion electrons and E0 transitions as a complement to γ -ray studies.

This development in the facility has also transformed earlier promise into current practice and productivity, while further increasing the future potential for exciting, varied research. This is evident most clearly in the publication history of TRISTAN. In the last 15 months the number of publications in refereed journals has jumped by a factor of 4.5 from 4 (for 1982) to 18, including five recent Letters. A list of publications, from 1983 to early 1984, is appended. As a final indication of the development of TRISTAN as an attractive vehicle for University use, the number of graduate students has recently more than doubled.

The next section provides an overview of the current ion source situation with a survey of the ion beam capabilities of each source. The

Fig. 3

following section describes the experimental end-station instruments. An appendix contains technical drawings of the individual ion sources.

This report has been prepared by the Neutron Nuclear Group at BNL with much help and contributions from many of the users.

R. F. Casten

D. D. Warner

R. L. Cill

July 1984

DATE SUBMITTED: _____

TRISTAN SCHEDULING REQUEST FORM

1. Name, Address, Phone:

2. Experiment Title and Brief Description of Aim and Purpose:

3. Ion Source/Beam Requirements:

4. Equipment Needs:

5. Dates and Duration of Requested Runs (List Several Options):

6. Investigators to be Present:

Recent TRISTAN Publications (Refereed)

(1983 -)

Letters

Reeder, P. L., Warner, R. A., and Gill, R. L. Half-lives and emission probabilities of delayed neutron precursors $^{121-124}\text{Ag}$. Phys. Rev. C27 (Rapid Communications), 3002 (1983).

Walters, W. B., Chung, C., Brenner, D. S., Aprahamian, A., Gill, R. L., Chrien, R. E., Shmid, M., Wolf, A. and Yuan, L.-J. Parabolic energy dependence of odd-odd multiplets in $N=83$ nuclides. Phys. Lett. 125B, 351 (1983).

Wolf, A., Berant, Z., Warner, D. D., Gill, R. L., Shmid, M., Chrien, R. E., Peaslee, G., Yamamoto, H., Hill, John C., Wohn, F. K., Chung, C., and Walters, W. B. Magnetic moments of 2^+_{11} states as a probe of the effective proton boson number near the $Z=64$ subshell. Phys. Lett. 123B, 165 (1983).

Wohn, F. K., Hill, John C., Petry, R. F., Dejbakhsh, H., Berant, Z., and Gill, R. L. Rotational structure and Nilsson orbitals for highly deformed odd-A nuclei in the $A \approx 100$ region. Phys. Rev. Lett. 51, 873 (1983).

Aprahamian, A., Brenner, D. S., Casten, R. F., Gill, R. L., Piotrowski, A., and Heyde, K. Observation of 0^+ states in ^{118}Cd and the systematics of intruder states. Phys. Lett. 140B, 22 (1984).

Papers

Aras, N. K., Chung, C., Faller, S., Stone, C. A., Walters, W. B., Gill, R. L., Shmid, M., and Chrien, R. E. The decay of 56-sec ^{148}Ce to levels of odd-odd ^{148}Pr . Can. J. Chem. 61, 780 (1983).

Hill, John C., Yamamoto, H., and Wolf, A. Evidence for the decay of neutron-rich ^{152}Pr and ^{152}Ce . Phys. Rev. C27, 2857 (1983).

Chung, C., Walters, W. B., Brenner, D. S., Aprahamian, A., Wolf, A., Gill, R. L., Shmid, M., Chrien, R. E., Berant, Z., and Yuan, L.-J. Decay of ^{142}Ba to levels of odd-odd ^{142}La . Phys. Rev. C28, 2099 (1983).

Gill, R. L., Shmid, M., Wolf, A., Chrien, R. E., Chu, Y. Y., Brenner, D. S., Sistemich, K., Wohn, F. K., Yamamoto, H., Chung, C., and Walters, W. B. Levels in ^{148}Ce from the decay of mass separated ^{148}La . Phys. Rev. C27, 1732 (1983).

Shmid, M., Gill, R. L., and Chung, C. Comparison between solid graphite and graphite cloth as a target backing material for an ISOL system. Nucl. Instr. & Meth. 211, 287 (1983).

Wolf, A., Chung, C., Walters, W. B., Gill, R. L., Shmid, M., Chrien, R. E., and Peaslee, G. Gamma-gamma angular correlation studies for ^{142}Ce . Phys. Rev. C28, 352 (1983).

Wolf, A., Chung, C., Walters, W. B., Peaslee, G., Gill, R. L., Shmid, M., Manzella, V., Meier, E., Stelts, M. L., Liou, H. I., Chrien, R. E., and Brenner, D. S. A four detector system for γ - γ angular correlation studies. Nucl. Instr. & Meth. 206, 397 (1983).

Reeder, P. L. and Warner, R. A. Delayed neutron precursors at masses 97-99 and 146-148. Phys. Rev. C28, 1740 (1983).

Chung, C., Walters, W. B., Aras, N. K., Wohn, F. K., Brenner, D. S., Chu, Y. Y., Shmid, M., Gill, R. L., Chrien, R. E., and Yuan, L.-J. The decay of 0.61-sec $^{148}_{56}\text{Ba}_{92}$ to levels of odd-odd $^{148}_{57}\text{La}_{91}$. Phys. Rev. C29, 592 (1984).

Hill, John C., Wohn, F. K., Berant, Z., Gill, R. L., Chrien, R. E., Chung, C., and Aprahamian, A. Identification and decay of ^{124}Ag . Phys. Rev. C29, 1078 (1984).

Reeder, P. L. and Warner, R. A. Distribution of delayed neutron yields versus Z, N, and A: application to proton pairing in fission yields. Nucl. Sci. Eng. (in press).

Piotrowski, A., Gill, R. L., and McDonald, D. C. A new TRISTAN thermal ion source. Nucl. Instr. and Meth. (in press).

Berant, Z., Gill, R. L., Rafailovich, M. H., Chrien, R. E., Hill, J. C., Wohn, F. K., Petry, R. F., Chung, C., Peaslee, G., and Mohsen, M. g-factor of the $7/2^+$, 1264.4 keV level in ^{97}Zr . Phys. Rev. C, Brief Reports (submitted).

Gill, R. L. and Piotrowski, A. A new FEBIAD-type ion source for use at the reactor-based ISOL facility TRISTAN. Nucl. Instr. and Meth. (submitted).

Related Publications

Brenner, D. S., Barkey, D., Blair, S., Warner, D. D., and Meyer, R. A. The level scheme of ^{183}Re and systematics of odd-A Re isotopes: interplay of ϵ_2 and ϵ_4 deformations in the W-Re region. Nucl. Phys. A408, 285-309 (1983).

Casten, R. F., Warner, D. D., and Aprahamian, A. Role of finite boson number in the interacting boson approximation description of γ -g transitions in deformed nuclei. Phys. Rev. C28, 894 (1983).

Casten, R. F., Aprahamian, A., and Warner, D. D. Axial asymmetry and the determination of effective γ values in the interacting boson approximation. Phys. Rev. C29 (Rapid Comm.), 356 (1984).

Casten, R. F. and Aprahamian, A. Empirically determined limits on absolute boson numbers for well deformed nuclei. Phys. Rev. C29, 1919 (1984).

II. Ion Beams

1. Generic Ion Source Description

This section summarizes the beams available from each ion source and at least a rough guide to their relative intensities. It should provide the user with a means of identifying the optimum source for a particular experiment. A brief description of a simplified "generic" source and of the special design/performance features of each source are included. Technical drawings are reserved for the appendix.

The most critical subsystem of any ISOL facility is its ion source. Element availability, beam intensities and, to a large extent, focal properties and mass resolution are all determined by the ion source type and operating conditions. Although it plays a central role, the ion source is usually the least understood component of an ISOL facility, since it is very complex in mechanical design, in the physical and chemical processes involved with its functioning, and often in the manner of its operation. In spite of the complexities involved, the general principles of a typical ion source can be easily discussed, provided that no attention is given to the details of how, quantitatively, each process is accomplished. Even with these restrictions, it is possible to understand some of the design and operational conditions necessary for a good ion source.

As a pedagogical exercise, then, consider the ion source schematically shown in Fig. 4, which shall be referred to as the "generic" ion source. In the figure, the circled U's represent groups (crystals) of uranium containing compounds (normally UO_2 and/or UC_2). The circled F's represent fission fragments. The functioning of the generic ion source has been broken down into six steps, as indicated in Fig. 4. The assumed conditions of the source are that the target is at a high, but unspecified, temperature, heated by an also unspecified method and operating at an unspecified, but appropriate, pressure (this is, after all, a generic ion source). Each step will now be discussed in turn.

1. The first step is obvious and needs little comment for the discussions here, other than to point out that it is desirable to have a target large enough to absorb all of the incident neutrons.

2. The second step also appears at first glance to be trivial but has very important consequences with respect to the ultimate mass resolution and efficiency of the separator. Some ISOL facilities (often referred to as recoil mass analyzers) do not thermalize or stop the fission fragments but use them directly to form the ion beam without an ion source. Since fission fragments have a large distribution of both charge and kinetic energy, the resulting mass separated beam yields also have a large distribution. At TRISTAN and other ion source ISOL facilities, stopping the fission fragments and reionizing them gives a low velocity spread resulting in high resolving power and efficiency.
3. In order to get out of the target, the fission fragment must first diffuse to the surface. If the fragment is already at the surface when it stops, the diffusion time will be small. Unfortunately, this is not usually the case. Most atoms will have to diffuse from deep within the target to the surface. If the fragment stops within a "uranium crystal" or leaves the target and strikes a wall of the ion source, it will probably not become part of the ion beam. Diffusion through the target matrix will depend on the mobility of the particular element and the type of matrix material (usually graphite) in the target, as well as the temperature. The relationship between the diffusing atom and the matrix atoms is complex, but the rate of diffusion (in one dimension) is empirically known to be directly proportional to the target temperature. Therefore, step three implies that a high target temperature and a large effective target surface area are desirable when studying short-lived nuclides.
4. Once the atom has reached the target surface, it must evaporate and enter the gas phase to become a candidate for ionization. In principle, it is possible to design an ion source where the target is also the ionizer, obviating the need to evaporate the atom. However, most materials which are good surface ionizers (high work function) are not suitable materials for efficient diffusion. To evaporate the atom from the surface requires energy in the form of heat from the target. The energy required is not numerically equivalent to the heat of vaporization of the particular element. In the ion source, the atom is isolated, that is, it is a single atom in a large ensemble of unlike neighbors whereas such concepts as heat of vaporization are applied to atoms with many like neighbors. In this case, surface effects usually dominate, and the vaporization probability depends

exponentially on temperature. Therefore, step four also implies that a high target temperature is desirable. The time to complete steps three and four is the determining factor in what is referred to as the holdup time. Even though average holdup times may be on the order of minutes for certain elements, enough atoms deviate sufficiently from the average to make studies of even very short-lived nuclides possible.

5. The atom enters the ionization region and is ionized by whatever mechanism the source was designed to use. For surface ionization, the atom must collide with the ionizing surface; thus a geometry which increases wall collisions is desirable. However, increased wall collisions will also result in longer holdup times, so some compromise must be reached. Ionization in a plasma-type ion source is considerably more complicated since ionization can result from collisions with electrons, neutral atoms, metastable atoms, and ions. The collision rate will be determined primarily by the concentrations of the other species present in the source and can usually be controlled by varying the operating parameters. The efficiency of ionization will be determined by the effectiveness of each of the mechanisms as well as the concentration of the species. Even a highly effective species, such as metastable atoms, can become a detriment to ionization if the concentration is too high, since additional collisions can cause the loss of a desired ion. In general, the best conditions must be found by trial and error, at least initially. As experience with a particular source increases, it becomes easier to optimize the source for the highest yield of a particular element.
6. After the ion has been formed, it is removed from the plasma (even a surface ionization source has a plasma boundary sheath at the ion source orifice) by an extraction electrode. The size and shape of the exit orifice, as well as the extraction field, has a large effect on the final shape of the beam and the mass resolution. A smaller hole will give a higher mass resolution, but a lower efficiency, whereas a larger hole gives the opposite effect. Since TRISTAN employs a two-magnet system, it is usually possible to have a large exit hole (to get maximum yield) and still maintain a very high beam purity (low contamination from adjacent masses) at the experimental apparatus. Normally, the plasma region is at a higher potential than its surroundings (heat shields, vacuum chamber walls, etc.) making it possible to

extract ions from any opening in the ionization region. Therefore, it is extremely important for the ion source to be hermetically sealed with only one pathway for the ions to escape.

While this examination of the generic ion source has told us nothing about how to mechanically construct an ion source, it has illustrated the basic processes inherent in any ion source and has indicated the role of high temperature operation in reducing the holdup time. However, the need for high temperatures and the equally important low pressures often conflict. As the temperature increases, so does the vapor pressure of the target itself. Thus, the ion source pressure cannot, in general, be controlled independent of the temperature. Furthermore, the target and matrix itself have temperature limitations; it is possible (and in some instances, easy) to melt the target, resulting in a loss of efficiency or destruction of the ion source itself.

2. Ion Sources

The primary emphasis on ion source development at TRISTAN has been to produce very long-lived, stable ion sources. The importance of long ion source lifetimes and stable operation is evident by considering that TRISTAN receives 25 days of neutron beam per month. Demands for beam time require that the separator operate continuously during that time period. Such a schedule (25 days on, 6 days off) is exhausting to both equipment and personnel, but makes it possible to perform long-term experiments that could not be attempted under other circumstances. Last year (1983), TRISTAN operated for greater than 90% of the available reactor time. To maintain this level of performance, an ion source must reliably operate for one full cycle, and preferably two. Thus, our goal for an ion source lifetime is 1200 hours, although 600 is acceptable.

All of the sources use highly enriched uranium targets, prepared by impregnating graphite or graphite cloth with uranyl nitrate, which is converted to uranium dioxide or uranium carbide at high temperatures. The targets can contain up to 10g ^{235}U , resulting in very high levels of radioactivity, making frequent ion source changes undesirable. A brief summary of the characteristics of each source is given in Table I.

Table I

Ion Source	g of ^{235}U	Temp. °C	Ionization Mechanism
Positive Surface Ionization	10	2200	Surface (Re/Ta)
FEBIAD	2.5	1700	Plasma (electron impact)
Thermal	10	2500	Thermal Equilibrium Plasma
Negative Surface Ionization	10	2000	Surface (LaB_6)
High Temperature Plasma	10	2500	Plasma (multiple processes)

a) Surface Ionization Source

The first successful ion source at TRISTAN was the surface ionization source developed by Schmid et al. [NIM 211 (1983) 287]. The source can be heated to $>2000^\circ\text{C}$ using 2500 W of electron bombardment power. Ionizing surfaces of Re and Ta have been used. Ta gives lower yields of Sr and Ba, making it more desirable than a Re ionizer for experiments on Rb and Cs decay. This source is fully developed and has lifetimes of >2500 hours. The surface ionization source allows experiments on beams of Rb, Sr, Y, Cs, Ba, Ce, and Pr and their decay products.

b) The FEBIAD Source

A FEBIAD source, modeled after that of Kirchner [NIM 186 (1981) 275] is also in use. The source is modified to provide longer lifetimes and a larger target area to make use of the full size of the neutron beam. Details of the TRISTAN FEBIAD source will be given in a forthcoming publication. Lifetimes of up to 1500 hours have been achieved. The lifetime and wide array of elements available from this source have made it the source most used at TRISTAN. The FEBIAD ion source allows experiments on beams of Cu, Zn, Ga, Ge, Se, Br, Kr, Rb, Ag, Cd, In, Sn, Sb, Te, I, Xe, and Cs and their decay products.

c) Thermal Ion Source

The TRISTAN thermal ion source is described in detail by Piotrowski et al. [NIM (in press)]. This source was based on the TRISTAN surface ionization source and was the first of a "family" of ion sources which share a common design for the target, heater, base plate, and heat shields. This family of TRISTAN ion sources includes the thermal, negative, and high-temperature plasma sources (to be described below). The targets use graphite or graphite cloth to contain the uranium in a tube which is heated by electron bombardment from a Ta filament. The thermal ion source produces beams of Ga, Ge, As, Rb, Sr, Y, In, Sn, Cs, Ba, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, and Ho and their decay products.

d) Negative Ion Source

The TRISTAN negative ion source produces beams of halogens (Br and I from neutron fission of ^{235}U). An important feature of this type of source is that it produces only Br^- and I^- , so that experiments on low yield masses of Br and I can be studied without the otherwise intense interferences from Kr, Rb, Xe, and Cs. The source is constructed in the same fashion as the thermal ion source, except that the Ta/Re ionizer is replaced by a Ta tube with a LaB_6 ionizer. Electrons from the source are deflected by a permanent magnet and a plate with a 1000 V potential.

e) High Temperature Plasma Ion Source

This source represents a novel concept in ISOL ion sources in that the target is located (and is actually part of) the cathode. The high temperature ($\approx 2500^\circ\text{C}$) at which this source operates gives much faster diffusion than the lower temperature FEBIAD source, and overall gives higher yields by a factor of 10. The high temperature plasma ion source allows experiments on beams of Cu, Zn, Ga, Ge, As, Se, Br, Kr, Rb, Sr, Y, Ag, Cd, In, Sn, Sb, Te, I, Xe, Cs, Ba, Ce, and Pr and their decay products.

Of the above, the thermal, negative and high temperature plasma ion sources are still partially in the development stages, especially as concerns increased longevity and reliability.

3. Ion Beams and Intensities

Table II summarizes ion source yields, along with a rating of the usefulness of each ion source for each element. The yields are approximate and rounded to the nearest power of 10. The rating, from A to F, is subjective, based on experience at TRISTAN. In all cases, the elements refer to the β -decaying parent. Thus, to study levels in Ge, for example, refer to the yields and ratings given for the parent isotope of Ga. If an element is not produced by the ion source, a null entry is made. An "F" does not mean that the source does not produce the element, but that the source is not a good choice for that element. For some elements two ion sources may have the same rating where there is no clear choice. Anticipated, but as yet unobserved, beams are given a rating, but no yield. An "A" rating is not given for instances where no ion source gives high yields, to indicate that studying the decay of isotopes of these elements may not be easy. For the heavy rare earths, the thermal ion source is given an "F" rating, even though the yields are quite high. This is due to the very low fission yields in this region causing observable isotopes to be only one or two neutrons removed from stability. These isotopes have usually been studied by neutron capture or other reactions which give higher yields.

The ratings consider factors other than sheer yield, such as contamination from other elements and diffusion times. The latter are an important consideration in choosing a source for the short-lived isotopes furthest from stability.

The number in parenthesis after each element is the mass number at which the stated yield can be obtained. By using Fig. 5, which shows fission yield cross sections (F. K. Wohn, Proc. of the ISOL Workshop, BNL, Oct. 31-Nov. 1, 1977, p. 52), one can estimate the yield of any isotope of that element. Simply find the cross section corresponding to the mass number of the quoted yield and the cross section for the desired mass number and multiply the yield in the table by the appropriate ratio. Be advised, however, that yields for isotopes with shorter half lives will probably be lower than estimated due to additional hold up time losses.

The last column of Table II gives the heaviest isotopes available for each element in yields that can be reasonably expected to be adequate for typical γ -ray spectroscopy experiments. Further ion source developments will undoubtedly extend these limits. Inasmuch as ion

source use involves art as well as science, this Table should be considered only as a first order guide. For more precise and/or technical assistance, the user should contact R. Gill or A. Piotrowski.

Table II

Ion source ratings for each element. The approximate available yield for each element, in atoms/sec is also indicated. The number in parenthesis after the element is the mass at which the approximate yield is given.

Element	Surface Ionization	FEBIAD	Thermal	Negative Surface	High Temp. Plasma	Heaviest Usable Isotope
Ni		D			F	
Cu(75)		C 10^2			L	75
Zn(77)		B 10^3			A 10^4	80
Ga(80)	D 10^2	C 10^4	A 10^4		B 10^4	82
Ge(82)		B 10^4	A 10^4		B 10^4	84
As(82)		C 10^2	A 10^4		B 10^3	87
Se(82)		C 10^2	B 10^3		A 10^3	89
Br(86)		C 10^5		A 10^8	C 10^6	92
Kr(90)		A 10^7		D 10^6	B 10^6	94
Rb(93)	A 10^9	C 10^6	B 10^9	F 10^4	C 10^6	100
Sr(94)	B 10^6	C 10^4	A 10^7	F 10^2	C 10^4	103
Y(96)	B 10^5	D 10^4	A 10^6		D 10^4	104
Zr(97)	B 10^3	F 10^2	A 10^4		F 10^2	102
Nb(98)	C 10^2		B 10^3			102
Mo(99)	F 10^1		F 10^2			102
Tc(99)			F 10^1			102
Ru			F 10^0			
Rh						
Pd					F	
Ag(116)		B 10^4			A 10^5	124
Cd(118)		B 10^4			A 10^5	128
In(129)	D 10^3	B 10^5	A 10^5		B 10^5	133
Sn(130)	F 10^2	A 10^6	C 10^4		B 10^5	134
Sb(132)		B 10^4	C 10^4		A 10^5	136
Te(133)		A 10^5	C 10^3		B 10^5	138
I(133)		C 10^5		A 10^8	C 10^6	142
Xe(137)		A 10^7		D 10^6	B 10^7	144
Cs(138)	A 10^9	C 10^6	B 10^9	F 10^4	C 10^6	148
Ba(140)	B 10^7	D 10^4	A 10^8	F 10^2	C 10^5	148
La(141)	B 10^5	D 10^3	A 10^6		C 10^4	148
Ce(143)	B 10^5	F 10^2	A 10^6		F 10^2	149
Pr(144)	B 10^3		A 10^5			152
Nd(147)	B 10^4		A 10^5			154
Pm(149)			C 10^2			154
Sm(153)			D 10^3			156
Eu(156)			D 10^3			158
Gd(159)			F 10^2			162
Tb(160)			F 10^3			164
Dy(165)			F 10^4			168
Ho(166)			F 10^4			168

Fig. 5

III. Instruments

Each of the major TRISTAN instruments is described with a view toward helping the user to decide on the feasibility and requirements for a given experiment. Some of these instruments have been built and are used primarily by specific users; others are general facilities commonly used by many members of the user community. The latter, being generally available, are described in more detail.

1. Data Acquisition and Analysis Facilities

Users at TRISTAN have access to several dedicated PDP-11 based computing systems for data acquisition and analysis. The hardware is maintained by an on-site service group. The software is developed and maintained by the local staff with contributions from users. Since the purpose of this section is to acquaint users with the computing capabilities, the hardware and software will not be described in any detail. The data acquisition system interfaces to experiments via CAMAC and NIM modules. Thus, in many cases, setting up an experiment at TRISTAN will be much like using any multichannel analyzer. The system has the following simultaneous capabilities as the standard configuration: four-8K singles channels, a multiparameter channel capable of recording $\gamma\gamma t(\theta)$ events in up to four detectors, a gamma-multispectrum scaling channel capable of recording 16-8K time sequenced energy spectra, and four-128 channel multiscalers. Additional memory areas are available for temporary storage of spectra. Data may be written out on disk or magnetic tapes. Magnetic tapes can be written in four different formats: event mode (for coincidence data), binary, BCD, and RT11 file structure. All of these formats can be read by the data analysis computers and by other computers, for example, at users' institutions or at the BNL computing center. The data acquisition system is controlled by a single program which was designed primarily for nuclear spectroscopy applications. The data analysis software was also designed primarily for nuclear spectroscopy and provides for data manipulations, peak finding and fitting, coincidence gate setting and scanning, decay curve analysis, plotting and other useful functions. Although all of the data analysis can be done at TRISTAN, many users prefer to take data to their home institutions for final analysis, using the in-house facilities as a pre-analysis check of the data quality. Tapes written in all of the formats have been successfully transported to many different facilities.

2. γ - γ Spectroscopy and Angular Correlation System

Situated close to the switching magnet on the 45° line is a γ -ray spectroscopy facility that incorporates capabilities for γ -ray singles, β -gated γ -ray spectroscopy, γ -ray multiscaling studies for assignment of γ lines to specific half-lives, close geometry 2-detector γ - γ coincidence measurements and γ - $\gamma(\theta)$ angular correlation studies.

Gamma-gamma angular correlation measurement techniques which allow spin assignments are extremely useful complements to all types of nuclear structure studies. However, such studies necessitate ion beams of high intensity. This requirement has been amply fulfilled in many even-even neutron-rich nuclei by the tremendous advances made in the development of more efficient ion sources coupled with the development of a fixed-angle 4-detector angular correlation system [A. Wolf et al., NIM 206 (1983) 397-402]. The system allows simultaneous measurements at six different angles, thereby reducing the running time compared to a two detector variable angle system.

The system can be operated at either one of two "ports": the "parent" port (point of ion-beam deposit) or the "daughter" port (60 cm away from point of deposit). The choice of station is dependent on the specifics of the desired experiment, such as the lifetime of the parent isotope whose decay is to be studied and its position in the decay of a given mass chain. The beam of fission products is deposited on aluminized mylar tape which can be moved into either position. The parent port position allows the study of very short-lived, as well as long-lived, isotopes whereas the "daughter" port proves to be most beneficial in the study of isotopes further down the decay chain. The aluminized-mylar tape is moved by an automatic tape controller which is preset to a certain timing sequence of collection-delay-measurement in order to enhance the desired activity. Measurements at the parent port obviate the need for a time consuming tape move, permitting angular correlation studies further from the stability line. Moreover, they lessen the dependence of the experiment on the mechanical tape moving system. The limits on the lifetimes that can be studied depend in this case on the fission yields and on the overall efficiency of the ion source.

As a recent example, in an angular correlation study of the very short-lived parent isotope ($T_{1/2}=0.3$ and 1.3 sec) of ^{120}Cd , the parent port configuration was used with success whereas the experiment

would not have been feasible at the daughter port. In this experiment 9×10^7 coincidence events were recorded in approximately five days. A spectrum from the 505 keV gate is shown in Fig. 6.

The daughter port configuration may be more desirable for studies of longer-lived nuclei, or for the decay of isotopes further down the decay chain. The tape controller requires a few tenths of a second to move the beam spot from parent to daughter port. Moreover, it is possible to introduce delays in the cycle in order to enhance certain activities. In the A=120 decay chain, if the desired activity was the decay of Cd into In ($T_{1/2}(^{120}\text{Cd})=50.8$ sec), the daughter port configuration would be used along with an additional delay to insure that no Ag contamination is present, since the ion source production at A=120 is predominantly Ag.

3. Superconducting Magnet for PAC and Q β Studies

The superconducting magnet facility is intended principally for the measurement of g-factors via the perturbed angular correlation technique. The facility consists of a split pole Nb-Ti superconducting magnet housed in a ^4He cryostat, which also contains a λ -point refrigeration unit. The maximum field available is 6.25 Tesla when the system is operated at 4.2°K, and 6.75T if the λ point refrigerator is used to cool the magnet to 2.2°K. These fields are approximately three times those obtained with the normal magnet used in earlier g factor measurements at TRISTAN. Since the figure of merit for such a system varies rapidly with field, this represents a large improvement in experimental capabilities, in particular, by allowing states with much shorter half-lives to be studied. Field homogeneity is such that the magnetic field changes by <1% over an area of 1 cm^2 at the target position. The activity is transported from one of two possible collection points to the measuring position via a moving tape system running in a room temperature horizontal bore tube through the center of the magnet. A maximum of four Ge detectors can be positioned in the plane perpendicular to the field direction, at a minimum distance of 8.5 cm from the source. The design of the cryostat and magnet coils is such that the absorbing material between source and detector is minimal. Operation of the cryostat is straightforward, and the useful holding time for the liquid ^4He is 3-4 days once the magnet is in persistent mode. Field reversal requires a total elapsed time of 3-4 hours. An additional feature of the design allows the system to be used in an alternative configuration as a solenoid magnet for

Fig. 6

electron measurements, such as Q_β studies. By removing the lower iron pole piece from the magnet, a detector may be inserted on the vertical axis and connected to a feed-through connector in the outer vacuum shield. The magnet field can then be used to focus electrons on the face of the detector, thus greatly enhancing the solid angle for electron detection, relative to that for γ rays.

A schematic side view of the magnet and its housing is shown in Fig. 7, along with curves showing the field values as a function of position. The upper curve gives the radial dependence of the field measured inside the bore tube. The curve on the left shows the magnitude and vertical dependence of the fringing field just outside the housing.

4. Conversion Electron Instrument

To complement the study of γ -ray activities at TRISTAN a conversion electron instrument has now been put into operation. Initial tests were carried out in May, 1984 and spectra from a Bi source and from a radioactive beam are shown in Fig. 8. The facility should be of use in obtaining multipolarity information and for disclosing E0 transitions. The detector is a windowless 3 mm Si(Li) diode installed at the 0° beam line. A moving tape collector positions the deposited activity in front of the detector. A β detector is also incorporated into the chamber and a re-entrant cavity allows a Ge detector to be placed close to the deposit as well. Thus, electron singles, electron- γ -ray coincidence and 2π β -gated electron spectra can be simultaneously accumulated. The electron detector operates at liquid nitrogen temperature and at a distance of 15 mm in front of the tape. Electron energies down to 60 keV and up to 1500-2000 keV can be detected. At present the energy resolution ranges from 2.5 keV FWHM at 400 keV to 2.9 keV at 1 MeV. The peak shapes exhibit slight tailing on the low energy side. Nuclei with half lives > 0.5 sec can be investigated. From the electron conversion spectra one should be able to distinguish E1 from M1 or E2 transitions over a large energy range and for all nuclei of interest. In the mass region $A=100$ one can distinguish M1 from E2 transitions for $E_\gamma < 350$ keV. Radioactive sources of ^{137}Cs , ^{208}Bi and ^{133}Ba mounted on a rotating carousel can be used for quick checks of detector performance. A system of specialized computer programs for electron spectrum analysis is being implemented for both PDP-11 and CDC computers at BNL.

Fig. 7

Figure 8 shows a ^{207}Bi spectrum obtained from the standard source and a spectrum of the conversion electrons from the 569 keV transition following the decay of ^{144}La to ^{144}Ce ($T_{1/2}=40$ sec). These latter data were collected over a period of 100 minutes using a cycle of 140 sec of deposit collection time followed by 140 sec of counting time. The K, L, M and a hint of the N lines are visible. At present, the resolution is insufficient to separate subshells but can clearly be used for α_K and K/L measurements.

5. Delayed Neutron Instruments

The high decay energies of nuclei far off stability lead to the possibility of β decay to daughter nuclei at excitation energies above the neutron binding energy. Such daughters can then become delayed neutron emitters. Figure 9 shows a schematic representation of the delayed neutron process. The labels at the bottom, in effect, provide a caption. There are three distinct instruments for delayed neutron studies at TRISTAN. These have been developed by users at Cornell University, Pacific Northwest, and INEL-EGG Idaho and are alternately installed at the end of the 22-1/2° line. The beam line is equipped with an electrostatic quadrupole doublet lens and steering plates located just after the switch magnet. A moving tape collector system is available at a position about 3m from the magnet. The instruments differ in the energy ranges covered, their efficiency and resolution and each emphasizes a different aspect of delayed neutron physics. Short descriptions of each follow.

Data on delayed neutrons from fission products have practical value for reactor applications. The phenomenon also affords unique empirical clues to neutron cross sections of far-unstable nuclides, including cross sections of nuclei in excited states. The key point is to exploit the inverse relationship between neutron emission and absorption by compound-nuclear levels above the neutron binding energy. An instrument has been designed by the Cornell University User Group that utilizes the time-of-flight technique for neutron spectra between 1 and 100 keV. It features better resolution than available in previous studies of these neutron energies. One purpose is to provide spectra to lower energies than previously observed, but the major motivation is to obtain data of sufficient quality and quantity to allow construction of empirically-based neutron capture cross sections for very neutron-rich nuclides. Such cross sections are of interest for astrophysics and for nuclear theory.

Fig. 8

Proton-recoil counters provide another technique for measuring delayed neutron spectra at low energies. These detectors are hydrogen gas (pressure >1 atm) proportional counters. Although the detectors have a fairly large γ -ray response, the use of lead shields and pulse shape discrimination can reduce the undesired γ -ray sensitivity so that neutron spectra can be observed down to 10 keV. The collected spectra must be differentiated and efficiency corrected to obtain the final neutron spectrum. Recent experiments by the INEL-EGG Idaho User Group at TRISTAN have demonstrated, for the first time, that there is a one-to-one correspondence in neutron peaks observed by ^3He ionization counters, time-of-flight spectrometers and proton recoil counters. This observed correspondence gives confidence in the ability to interpret neutron peaks as true spectral features which can be related to nuclear properties such as level energies and widths.

A high efficiency ($>50\%$) neutron counter consisting of 40 ^3He filled proportional counter tubes embedded in polyethylene moderator has been developed by the Pacific Northwest Laboratories User Group. As compared to the detector systems discussed above, this system has low resolution but very high efficiency. The tubes are arranged in 3 concentric rings with separate preamps, amplifiers, and scalars on each ring. The ion beam is deposited on the axis at the center of the counter. A Si surface barrier beta detector and/or a Ge(Li) gamma detector can be placed along the axis close to the beam deposition point. Thus, simultaneous neutron, beta, and gamma counting experiments can be performed. The residence time of neutrons in the moderator is about 35 μs which is short enough to permit neutron- β or neutron- γ coincidence counting. An electronic module is available which measures the distribution of time intervals between successive pulses from the neutron counter. This device has been used to identify β -delayed two-neutron emission from the precursor ^{98}Rb , and delayed neutron emission probabilities (P_n) for a large number of nuclei.

6. Dye Laser Facility

Laser measurements use atomic spectroscopic techniques to provide valuable information for the study of nuclear structure. For a suitable nucleus, it is possible to determine spins and moments from the hyperfine structure and the charge radius from the isotope shift. The dye laser facility at TRISTAN was built and is operated by the Texas A&M User Group and uses the colinear fast beam method. This technique studies the ions from the separator by allowing the laser and ion

beams to intersect in an interaction region approximately 10 cm long. An argon-ion laser is used to pump a ring dye laser, which is tunable over a wide range of frequencies in the visible region. The laser voltage is then scanned over a region corresponding to optical transitions. Light emitted by the decay of those excited atomic levels is detected by a photomultiplier. The experimental setup at TRISTAN is shown in Fig. 10 which also shows a hyperfine spectrum from $^{131}\text{Xe}^+$. From the hyperfine splittings, the magnetic moment of the $I = 3/2$ ground state of ^{131}Xe was determined and is also shown in the box in the upper left hand corner of the figure. The upper right hand portion of the figure shows the atomic states being populated by the laser excitation. The corresponding peaks in the spectrum are indicated.

Further refinements of the apparatus are being introduced before experiments on radioactive beams are attempted. Radiation detectors to assist in separator beam timing and improved ion optics are being implemented to give higher sensitivities. Present estimates are that experiments can be performed with ion beam intensities as low as 10^4 atoms/sec.

Another type of experiment is also being planned. A quadrupole ion trap has been constructed by the Texas A&M Group. In this apparatus, the ions are decelerated to appropriate injection energies and can then be trapped and stored for long periods of time. In principle, this will make it possible to study even low yield nuclides by storing enough ions to get a good signal or by re-exciting the same ion many times.

7. Future Developments

There are several improvements and additions to TRISTAN that are currently being considered. One of these is a second mass line which would enable experiments to be carried out simultaneously on more than one isotope. To achieve this, the collector box would be replaced by one incorporating deflector plates capable of selecting two (or more) masses and directing them to different beam lines. In effect, this would double the amount of available beam time although, clearly, there are constraints on the range of masses simultaneously available and it would be necessary to correlate the requirements of different experiments. Such a facility would be especially useful for studies involving sequences of isotopes of a given element. It is possible

Fig. 10

that a new beam line and end-station might be installed for further studies of a third mass.

An additional expansion of TRISTAN's ability to measure electric and magnetic moments of nuclei far from stability is being considered. It would involve the construction of a post-accelerator on the 0° line, situated upstream of the electron detector, which would boost the total ion energy up to 150 keV for implantation of radioactive ions into a solid target, thus allowing the measurement of moments of excited nuclear states via the γ - γ PAC technique.

In its presently conceived configuration, which is subject to change, the instrument would consist of three sections. The first, past the switching magnet, would house a set of two quadrupole lenses, a set of horizontal and vertical electrostatic plates for beam handling purposes, as well as a cryogenic pumping station. The next section would be an acceleration tube capable of holding 100-200 kV. The last section would be an experimental end-station specialized for a particular mode of experiment.

We are currently carrying out feasibility studies to determine if these projects are compatible with manpower and funding constraints and with the long-term evolution of the TRISTAN facility. Suggestions and comments are very welcome, especially in this formative stage.

Appendix

This appendix contains assembly drawings of the ion sources used at TRISTAN. Figure A.1 shows the positive surface ionization source, which was the earliest successful source used at TRISTAN. The source is used with either graphite cloth targets (for shortest holdup time) or solid graphite (for longest lifetime). The ionizer is either Re or Ta. Ta is preferable for experiments on the decay of Rb and Cs to reduce interferences from daughter products. Figure A.2 shows the FEBIAD ion source. The target is produced by saturating graphite tubes with a uranyl nitrate solution and is located inside the anode, as shown by the solid black areas. A gas inlet is also provided (along the anode contact) to make it possible to add support gas (typically He, Kr and/or Xe) to control concentrations of metastable atoms, provide known mass markers, and to check ion source performance. Other gases (such as CF_4) may be added to produce desired molecular ions. Figure A.3 shows the thermal ion source. Figure A.4 shows the high-temperature plasma ion source, where the heat shield arrangement has been omitted for simplicity. The heat shield and filament support in the high temperature plasma source is the same as that for the thermal ion source. Finally, the negative surface ion source is not shown, since it is still under development and the design is not yet finalized, but it will be similar to the thermal ion source.

Fig. A.2 FEBIAD Ion Source

Fig. A.3 Thermal Ion Source

Fig. A.4 High Temperature Plasma Ion Source

TABLE OF CONTENTS

I.	<u>Introduction and Overview</u>	<u>Page No.</u>
	1. Purpose of Booklet	1
	2. The TRISTAN Separator	1
	3. Physics at TRISTAN	4
	4. Growth of TRISTAN	6
	Sample Beam Request Form	9
	Recent Publications	10
II.	<u>Ion Beams</u>	
	1. Generic Ion Source Description	12
	2. Ion Sources	16
	3. Ion Beams and Intensities	19
III.	<u>Instruments</u>	
	1. Data Acquisition and Analysis Facilities	23
	2. γ - γ Spectroscopy and Angular Correlation System	24
	3. Superconducting Magnet for PAC and Q_β Studies	25
	4. Conversion Electron Instrument	27
	5. Delayed Neutron Instruments	29
	6. Dye Laser Facility	32
	7. Future Developments	33
	<u>Appendix</u>	36
	Assembly Drawings of Ion Sources	