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THE STUDY OF NUCLEI FAR FROM STABILITY WITH TRISTAN II AT THE HIGH FLUX BEAM REACTOR AT BROOKHAVEN

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ABSTRACT

The ISOL facility TRISTAN II is described and its expected capabilities on-line to the High Flux Beam Reactor (HFBR) at Brookhaven National Laboratory are discussed. In particular, the range of isotopes expected to be available and possible experimental studies of the short-lived fission-product isotopes are described. Background information consisting of an overview of the study of nuclei far from stability and a survey of existing ISOL facilities is presented in order to aid in evaluating the present status of the study of nuclei far from stability in general and the TRISTAN II facility in particular.

I. INTRODUCTION

The study of nuclei far from β stability is a field of research that has experienced considerable growth in recent years. To a large extent the growth has been a consequence of developments and improvements of techniques associated with electromagnetic isotope separation (EMIS). In particular, the growth in the number of nuclei far from stability that are now available for study is due primarily to the facilities known as ISOL facilities (iostope separator on-line). The principle objective of the present report is to describe the ISOL facility TRISTAN II and its expected capabilities on-line to the High Flux Beam Reactor (HFBR) at Brookhaven National Laboratory. In order to provide some of the general background information needed to evaluate the research program possible with TRISTAN II at the HFBR, a discussion of nuclei far from stability and a survey of existing ISOL facilities are first presented.

Section II consists of an overview of the study of nuclei far from stability, containing a brief discussion of interesting features and recent progress in the field. The discussion includes comments on the status of our knowledge, theoretical motivations for the study of nuclei far from stability and a summary of the various experimental techniques used in such studies. Although the presentation is an overview rather than a comprehensive review, the important areas of the field and most significant recent references to the field are included. Thus Section II can be regarded as a brief introduction to the field and a mini-report on its present status.

Section III presents a survey of existing ISOL facilities, including a tabulation of their characteristics and a discussion of the various target-ion source combinations. The emphasis in the discussion is on the range of elements and isotopes currently available for study. Mass and element purities, overall separation efficiencies, and half-life limitations are discussed in terms of target-ion source combinations. A general summary of the types of studies done at ISOL faiclities is also included. Rather than presenting a detailed review of individual ISOL facilities, Section III indicates the present capabilities of operational ISOL facilities in both producing and studying short-lived nuclei far from stability.

Section IV describes the TRISTAN II facility, both in its present ALRR (Ames Laboratory Research Reactor) location and as envisioned at the HFBR location. Fission yields for ^{235}U, half-lives for isotopes in the fission-product range and overall efficiencies for the in-beam integrated target and ion source used with TRISTAN II are discussed. The preceeding information is used to make an cotimation of the activities of various isotopes expected with TRISTAN II at the HFBR. On-line experimental apparatus, both presently available with TRISTAN II and planned for the near future, is also briefly described. Section IV thus provides the specific information (range of isotopes available and possible experimental studies) needed to evaluate the research program possible with TRISTAN II at the HFBR.

II. NUCLEI FAR FROM BETA STABILITY

A. General Comments

Before the middle of the last decade, detailed studies of the decay properties of unstable nuclei were limited to nuclei rather near to the region of β stability with half-lives greater than about 10^3 seconds. The ability to produce many nuclei farther from stability has existed for more than two decades. Nuclei on the neutron-rich side of stability can be produced by asymmetric fission of ^{235}U by thermal neutrons, by symmetric fission of ^{238}U by high-energy protons or alpha particles, by spallation, or by heavy ion reactions. Nuclei on the neutron-deficient side of stability can be produced by high-energy proton spallation reactions or by heavy-ion induced reactions. In the last ten years much progress has been made in developing and improving techniques to utilize such reactions to make available for detailed and systematic studies an ever increasing variety of nuclei far from β stability.

The general importance of studies of nuclei far from β stability has long been recognized and expounded. References 1-3, the three international conferences on nuclei far from stability, contain a wealth of articles, reviews and references about this broad field. The article in 1966 by Ingmar Bergström,[4] entitled "Why Should We Investigate Nuclides Far Off the Stability Line," is a cogent presentation of arguments for extending research efforts further from the stability line. These four basic references (and the references contained therein) include much more detailed information about the field than can possibly be summarized here. However, brief mention will be made in the following of certain features and recent progress in the study of nuclei far from stability.

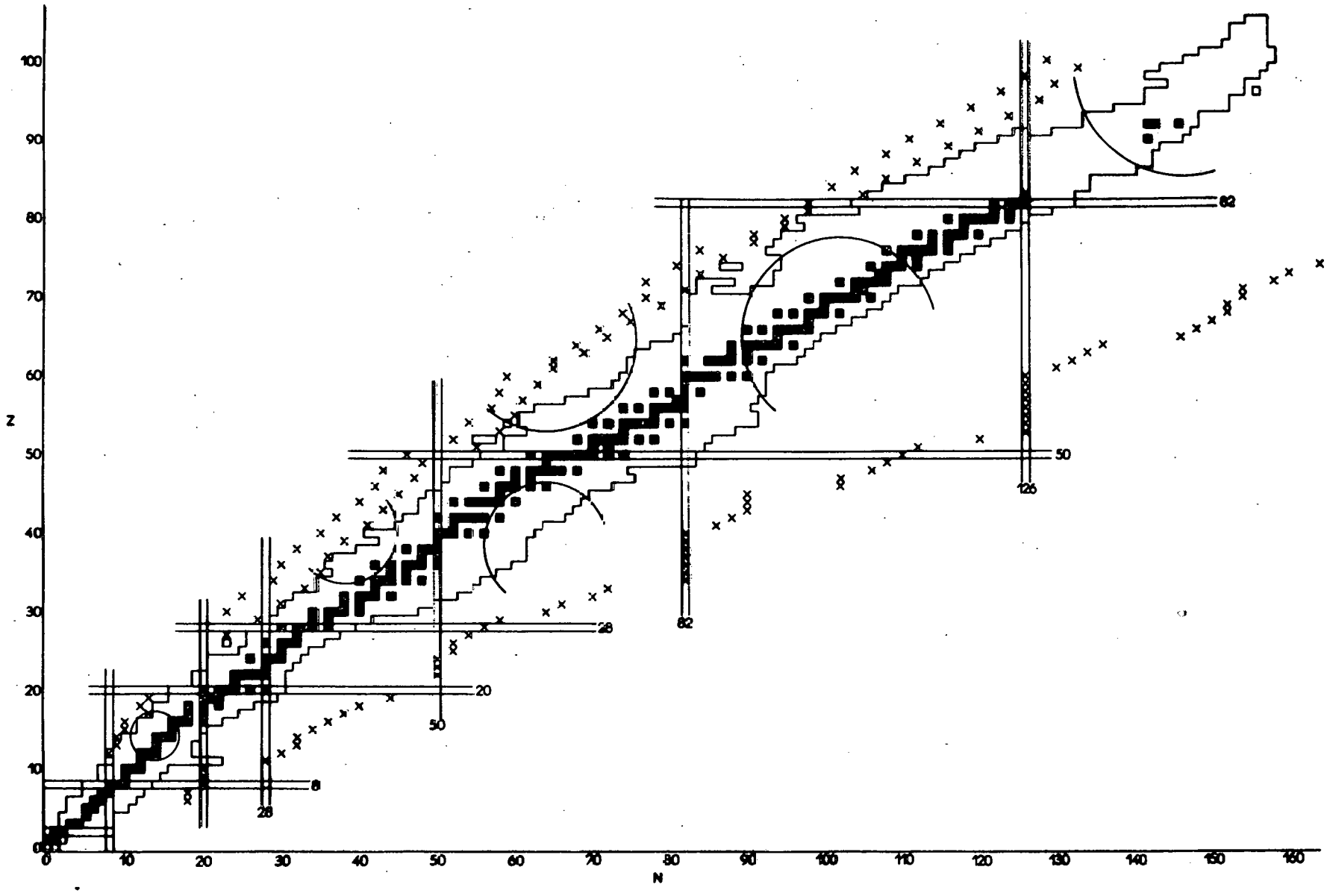

Fig. 1: Chart of the nuclides, showing the limits of our present knowledge, particle drip-line predictions, magic nucleon numbers, and regions of deformation.

B. Status of Our Knowledge

Before proceeding to outline the concepts of nuclear theory involved in the properties of nuclei far from stability, it is worthwhile to review the status of our knowledge of such nuclei. In the chart of the nuclides given in Fig. 1, the solid squares indicate the stable or naturally-occuring radionuclides. The squares representing presently known nuclides (as of mid 1976) are contained within the solid outline. The predicted particle stability limits, or proton and neutron drip lines, are indicated by X's. The locations of these drip-line nuclei were obtained by rather severe extrapolations of the mass formula of Seeger and Howard[5] or, for the low-mass region, the systematics of Garvey et al.[6] Although experimentally unconfirmed, these drip lines serve to outline the region of interest of the chart of nuclides for nuclear structure studies.

Between the particle-stability limits lie approximately 5100 nuclei, for which it is interesting to consider to following numerology.

Class of Nuclides	Number	% of Total
Stable or naturally occuring radionuclides	283	< 6%
Known neutron-deficient radionuclides	∿ 970	∿ 19%
Unknown neutron-deficient radionuclides	∿ 570	∿ 13%
Known neutron-excess radionuclides	∿ 650	∿ 11%
Unknown neutron-excess radionuclides	∿ 2600	∿ 51%

The stable and known radionuclides number about 1900, or less than 40% of the total. For a large fraction of these 1900, our knowledge is either very incomplete or quite skimpy, particularly as concerns detailed

decay scheme or level structure information on the nuclei farthest from stability. When we consider this numerology, we can only conclude that we have merely scratched the surface with our present knowledge and have much yet to explore.

As an indication of the progress made in this exploration since the beginning of this decade, we can compare the above numerology with that made by Dropesky and Talbert[7] in 1970. The known neutron-deficient and neutron-excess nuclei have increased in number by $\sim$ 185 and $\sim$ 140 respectively, thereby increasing the number of "known" nuclei from $\sim$ 1600 to $\sim$ 1900. Naturally the study of many of these "new" nuclei has just begun and only a small fraction of these has been studied in detail. However, this substantial increase in number shows that facilities and techniques now exist that allow the properties of nuclei far from stability to be pursued with increasing success.

C. Theoretical Motivations

The two basic frameworks of our present understanding of nuclear structure were built upon the shell closure and collective effects deduced from the properties of nuclei lying reasonably close to the stability line. The magic nucleon numbers for spherical nuclei are indicated in Fig. 1 by heavy lines. The regions between closed shells where nuclear deformation and the resulting collective effects are known or predicted to occur are also indicated in Fig. 1. To quote from the recent review talk by Ray Sheline,[8] such a chart as Fig. 1 can be considered as "a kind of road map of the interesting places we hope to visit in the years ahead." The following paragraphs provide a brief discussion of the highlights of some of the more interesting places.

As concerns shell closure effects, it is of special interest to determine whether the magic numbers valid near stability remain valid far from stability. The doubly magic nuclei ^{4}He, ^{16}O, ^{40}Ca, ^{48}Ca and ^{208}Pb were instrumental in establishing our present understanding of nuclear shell structure. However, other doubly magic nuclei lie farther from stability than do the above nuclei. The predicted doubly magic nuclei ^{56}Ni, ^{78}Ni, ^{100}Sn and ^{132}Sn are of extreme interest (as would be ^{28}O, if it is particle stable). Since 1970, the properties of ^{56}Ni have been extensively studied and the study of the region around ^{132}Sn has recently begun in earnest. The studies indicate that the ^{56}Ni and ^{132}Sn regions can be interpreted in terms of double shell closure. The systematic studies of these regions have been both interesting and rewarding. Decay studies in these regions are providing essential information about the single-particle excitations and nucleon couplings which are necessary to determine the details of the shell closure effects. The success in reaching the ^{132}Sn region in the last few years also increases our expectations that the other exotic regions around ^{78}Ni and ^{100}Sn may be obtainable in the not too distant future.

Nuclear deformation occurs for nuclei with nucleon numbers intermediate between closed shell numbers. Studies of collective effects in the deformed regions of the rare earths and actinides near stability have resulted in the formulation of a variety of interpretations based on collective behavior of nucleons. Other deformed regions which lie further from stability have been predicted to exist. On the neutron-deficient side of stability the deformed regions that are indicated in Fig. 1 as roughly centered near ^{80}Zr and ^{128}Gd have begun to be explored.

In the latter case only the edges of the region have been preliminarily studied and the center of the region remains conjectural. The neutron-deficient Ra and Th nuclei near A = 205 are predicted to exhibit rotational features similar to those seen in the neutron-deficient Ba isotopes.[8] On the neutron-excess side of stability the deformed regions centered roughly near ^{104}Zr and ^{168}Dy are beginning to be explored. A very large number of potentially deformed neutron-rich lanthanides around ^{180}Gd have not yet begun to be studied. In the region approaching ^{104}Zr, systematic studies have been made in the last few years and the results to date have indicated very interesting features in this region. The study of these deformed regions off the stability line will undoubtedly extend our understanding of the modes of collective behavior in nuclei and perhaps provide a more fundamental basis for such behavior.

Transitional nuclei, with nucleon numbers too far from closed shells to be adequately handled with a spherical shell-model approach and too close to closed shells to be deformed, comprise the most numerous class of nuclei. Because of their structural complexity, they are the most poorly understood. Their interpretation requires a unification of the shell-model and collective approaches. The systematic study of such nuclei, by following the evolution of level structures as the proton and neutron numbers progress through the transition regions, is required to obtain the understanding needed to formulate an adequate unified interpretation. Such systematic studies are beginning to be made in transitional regions away from stability. For neutron-deficient nuclei of the rare-earth transitional region, both high-spin state phenomena and detailed decay schemes are being systematically mapped. Neutron-rich

transitional nuclei in the second transition-metal region are also beginning to be systematically explored via decay studies. The structures emerging from this very rewarding research include many features, such as decoupled bands, highly distorted rotational and vibrational bands, and vibrational-rotational coexistence. Some of these features seem to be quite different from the behavior of nuclei nearer stability. The theoretical concepts of shape coexistence and triaxial nuclei are only two of the ideas currently being applied to these nuclei. Continued systematic studies of transitional nuclei away from stability may provide the experimental information needed to test the various theoretical approaches to such nuclei and contribute to the formulation of an adequate unified model.

One of the unique features of nuclei far from stability is the process of delayed particle emission, which becomes increasingly important for nuclei farther and farther from stability. Due to the high β-decay energies of such nuclei, β-delayed particle emission (neutron emission for neutron-rich nuclei and proton or alpha emission for neutron-deficient nuclei) occurs following β-decay to excited states whose excitation energy exceeds the particle binding energy in the product nucleus of the β-decay. Although the existence of delayed particle emission had been known for many years, until the last few years the only information consisted of half-lives and emission probabilities. Recent measurements of delayed-particle energy spectra, β strength functions, and competition between particle emission and γ decay have stimulated increased theoretical attempts to explain the observed features. At the Cargèse Conference[3] several papers were presented on recent data and statistical models, including extensions and refinements to such

models. The statistical approach can account reasonably well for delayed-proton spectra, but structure effects need to be included to account for the prominent line structure observed in delayed-neutron spectra. In both cases our understanding is not adequate, although explanations are beginning to be formulated. Although progress has been made in the last few years, it is clear that much more information is needed to obtain an adequate understanding of delayed particle emission.

For certain astrophysical theories, it is necessary to obtain increased knowledge of properties of nuclei very far from stability, particularly on the neutron-rich side. Models of the nucleosynthesis of the heavy elements, including superheavy elements, require as input data such properties as β-decay energies, neutron separation energies, β-decay rates and neutron capture rates. Improved knowledge of the mass surface is crucial since severe extrapolations (well beyond the nuclei used in establishing present mass formulas) are made in the calculations. In addition to the static r-process models of nucleosynthesis, recent efforts have involved dynamical r-process models and dynamic models of a more general n-process in which neutron-capture and β-decay rates may be comparable.[3] These dynamic models require absolute rates for β-decay and neutron capture. In addition, delayed-neutron and delayed-fission branching rates affect the calculations. The latter in particular may be crucial in determining whether the r-process could produce superheavy nuclei or would terminate at lower atomic numbers. The development of these more refined nucleosynthesis models has resulted in increased demand for new information on neutron-rich nuclei.

D. Techniques for Studying Nuclei Far from Stability

Several different techniques have been used in the study of highly unstable nuclei. The nuclear reactions used to produce the isotopes of interest span a large range of primary production rates. Reaction production rates as high as 10^{11}/sec can be obtained with high-energy spallation reactions or thermal neutron fission. For heavy-ion reactions the highest production rates are of the order of 10^{6}/sec due to beam intensity limits on the thin targets used and low cross sections. Production rates for other types of accelerators generally fall in the intermediate region. Production rates for the more exotic nuclei can be well below these approximate upper limits since the lower limits of useful radioactivity rates depend not only on the primary rate factors (such as target, type of projectile, projectile energy, etc.) but also on the particular technique used to study the reaction products of interest.

Secondary rates can be defined as the radioactivity rates of the isotopes of interest at the detection stations of the system. The minimum secondary rates available depend quite strongly on the production technique used. The minimum secondary rates needed, however, depend on the type of study to be made and, except for considerations of background or other interfering radiation rates, are essentially independent of the technique used.

For detailed decay scheme studies, minimum rates of 10^{3}-10^{4}/sec are needed. For singles studies of major γ-transitions or for yield determination, the minimum is $\sim 10^{2}$/sec. If background levels are low enough, it is possible to measure half-lives with rates of 1-10/sec,

identify new isotopes far from stability with rates of 1-10/min, and search for especially exotic nuclei, such as superheavies, with rates as low as $\sim$ 1/hr.

A technique in which primary and secondary rates are nearly identical is in-beam spectroscopy for reactions that are extremely selective in production of the product nucleus of interest. Heavy-ion reactions with strong energy-dependent cross sections are best suited for in-beam studies. The limiting factors are background and interferences from other reaction products. The latter can often be circumvented by repeating the experiment at different projectile energies in order to correct for the interfering contributions. In-beam studies are particularly suited to studies of very short-lived high-spin states of neutron-deficient nuclei. Since the only product selectivity is the energy dependence of the cross sections, the lack of mass and element selectivity among the reaction products provides a severe limitation of in-beam spectroscopy for general or detailed decay scheme studies.

Chemical techniques to separate reaction products according to their chemical properties are some of the oldest techniques used. Off-line methods involving separate steps of production, chemical separation (and possibly subsequent mass separation) are basically limited to products with half-lives greater than a few minutes due to the inherent slowness of conventional chemical separation techniques. Recent developments in rapid radiochemical techniques, spanning continuous and discontinuous methods for separation in both liquid and gas phases, have been reviewed by Trautmann and Herrmann.[9] The recent advances have made possible studies of activities with half-lives as low as $\sim$ 1 sec.

One of the major advantages of such techniques is the high elemental selectivity and sensitivity, which may be sufficient when interferences from other radioactive isotopes of the separated element are not restrictive. Combinations of rapid chemical techniques with mass separation for a variety of short-lived isotopes remains a basic goal which may hopefully be obtained within a few years.

The gas-jet recoil transport technique has had widespread use to transport reaction recoil products to detector locations. Transport times, which are determined by the gas flow rate, are typically $\sim$ 1 sec. As the process is essentially chemically unselective with no mass selection, the main advantage for nuclear spectroscopic studies is the reduction of background by transport to a well-shielded detector location. Decay studies in coincidence with x-rays can restore a degree of element selection but would still have no mass selection. Plans to couple the gas-jet technique to a time-of-flight system to detect the nuclear recoils following decay events would add mass selectivity to a gas-jet transport system. The coupling of gas-jet systems to standard mass separator systems will be discussed in the following section.

Reaction recoil products can be directly identified and labelled according to mass A and charge Z for light and medium mass nuclei. Measurements of differential energy loss ($\Delta E/\Delta x$) and kinetic energy E can identify A and Z for light nuclei. With rapid time-of-flight detectors in conjunction with ΔE detectors, A and Z identification can be extended to slightly higher A and Z values. With the addition of magnetic analysis, A and Z limits of $\sim$ 100 and $\sim$ 40 can be obtained. (For details on the current status of such techniques see Ref. 3). This class of particle

identification techniques provides A and Z identification but not separation, hence can be used only to identify new isotopes in addition to providing reaction yield information. They are unsuited for decay scheme or level structure studies which require systems with separation features.

Mass separation has been a powerful technique in the study of nuclei far from stability. Earlier reviews[10-12] on mass separation as applied to such studies provide an introduction and references 13-16 trace major developments in this field. The most significant development has been the establishment of on-line systems that are able to provide mass-separated short-lived isotopes. On-line mass selection systems can be divided into two classes: direct and indirect. Indirect systems are discussed in the following section. With direct systems the reaction products recoil directly into a mass separation system that acts on properties such as charge and energy as well as the mass of the recoiling particles. Three different approaches have been realized: kinematic separators, gas-filled magnetic separators, and combined electric and magnetic separators. The principles have been reviewed and compared with indirect methods by Armbruster.[17]

Kinematic or velocity-filter systems (such as SHIP at Darmstadt) fall in a special class as the major purpose is to deflect the transmitted primary beam from the forward-directed fusion-reaction or evaporation-residue beam in order to greatly reduce the primary-beam induced background at the detection position located in the forward direction. The velocity-filter technique, since it selects particles within a velocity window, does not provide mass or charge separation. Secondary stage

systems would be required for such separations.

Gas-filled magnetic separators (such as JOSEF at Jülich) have a deflection of recoil products which depends on the average charge of the recoiling ion as it traverses the gas-filled magnet field; the deflection depends only weakly on the ion velocity. Moderate mass and charge resolving powers ($\sim$ 10-10^2) can be obtained which are adequate for isotope identification. Combined electric and magnetic field deflections (as with LOHENGRIN at Grenoble) of reaction recoils can provide relatively high resolving power ($\sim 10^3$) for the ionic charge to mass ratio, from which unique mass assignment can be made. With an additional Z-sensitive stage, such as an energy-loss time-of-flight system, adequate Z resolution can be obtained. Both the JOSEF and LOHENGRIN facilities are discussed again in the following section.

III. SURVEY OF ISOL SYSTEMS

A. General Features

The term ISOL (Isotope Separator On-Line) has commonly been reserved for systems in which a laboratory scale mass separator is operated on-line in an indirect but continuous mode.[11] The basic steps involved are the stopping of reaction products, an element selection and ionization process, followed by electrostatic acceleration and mass selection by magnetic deflection. The element selection process and ionization may be done either separately or simultaneously. References 2, 10-13 contain earlier reviews on ISOL systems and refs. 14-16 trace more recent advances. In the present brief survey of ISOL systems, recognition is made of the fact that most of the ISOL systems often do not provide complete isotope separation but instead give some degree of isotope selection. Only for certain classes of elements is it possible to achieve complete isotope separation. Although it would thus be more appropriate to use the general label of mass separator on-line instead of isotope separator on-line, the term ISOL will be retained here due to its common acceptance. The term ISOL will be used in the broader sense, as the direct recoil systems JOSEF and LOHENGRIN, which inherently have no element selection, are included.

Tables 1 and 2 present characteristics of existing ISOL facilities at reactors and accelerators, respectively. Table 3 lists the most recent or especially useful references for each facility; further references from conference proceedings are given in parentheses. The condensation necessary for such tabulation is quite severe and leads to the listing of characteristics in a rather general form. For reactor-based

TABLE 1: CHARACTERISTICS OF EXISTING ISOL FACILITIES AT REACTORS

Name, location (initial operation)	Target and target conditions	Neutron flux at target (cm^{-2} sec^{-1})	Delay time from production to ionization	Type of ion source (temperature)	Elements extracted, with decay products excluded	Approximate overall efficiency
TRISTAN, Ames (Nov. 1956)	^{235}U as UO_2 (0.2g at 600°C)	2×10^{13} th.	12 sec trans.	oscil. elect. (1700°C)	Kr, Xe	10^{-2}-10^{-1}
	^{235}U as stearate (2-4g at 20°C)	3×10^{9} th.	1.2 sec trans.	"	Br,Kr,I,Xe	10^{-3}-10^{-1}
	^{235}U as UO_2 + UC (2g at 1500°C)		1-10^2 sec	oscil. elect. (1500°C)	Zn,Ga,Ge,As,Br,Kr,Rb,Sr, Ag,Cd,In,Sn,Sb,Te,I,Xe,Cs,Ba	10^{-4}-10^{-2}
ARIEL, Grenoble (June 1968)	$^{233,35,38}U$, ^{232}Th (4g UO_2 or stearate)	10^8 14-MeV	4-6 sec trans.	oscil. elect. (1700°C)	Kr,Xe	10^{-2}-10^{-1}
	^{235}U as UC_2 (10g at 20°C)	3×10^{8} th.	"	"	"	"
SOLIS, Soreq (July 1968)	^{235}U as stearate (2-4g at 20°C)	2×10^{9} th.	0.3 sec trans.	oscil. elect. (1700°C)	Kr,Xe	10^{-2}-10^{-1}
	^{235}U as UO_2 (1g at 1800°C)	"	0.1 sec	surface ion. (1800°C)	Rb,Cs;Br,I	10^{-3}
OSIRIS, Studsvik (July 1968)	^{235}U as UO_2 + UC (0.2g at 1500°C)	4×10^{11} th.	1-10^2 sec	oscil. elect. (1500°C)	Zn,Ga,Ge,As,Br,Kr,Rb,Sr, Ag,Cd,In,Sn,Sb,Te,I,Xe,Cs,Ba	10^{-4}-10^{-2}
	^{235}U as UO_2 + UC (2g at 1500°C)	"	"	"	"	"
IALE, Buenos Aires (March 1969)	^{235}U as stearate (14g at 20°C)	5×10^{8} th.	1 sec trans.	oscil. elect. (1700°C)	Br,Kr,I,Xe	10^{-3}-10^{-1}
JOSEF, Jülich* (Nov. 1972)	^{235}U as UO_2 (40mg at 500°C)	1×10^{14} th.	1sec recoil	none - recoil in Torr gas	all fission products (there is no chemical selectivity)	10^{-5}-10^{-4}
SIRIUS, Strasbourg (June 1973)	^{235}U as UO_2 (10mg at 20°C)	5×10^{10} th.	8 sec trans.	hollow cath. (2200°C)	Sb,Sb,Te,I,Xe,Cs,Ba,Ce,Pr + others (survey incomplete)	10^{-4}
	"	"	2 sec trans.	"	"	10^{-5}-10^{-4}
	^{235}U as UO_2 (0.5g at 50°C)	5×10^{11} th	2 sec trans.	"	"	"
SOLAR, Pellman (Jan. 1974)	^{235}U as UO_2 (1g at 1600°C)	5×10^{9} th.	0.1 sec (Sr,Ba: 7 min.)	surface ion. (1600°C)	Rb,Cs;Br,I;Sr,Ba	10^{-5}-10^{-3}
LOHENGRIN, Grenoble* (March 1974)	^{235}U as UO_2 (3mg at 500°C)	5×10^{14} th.	1sec recoil	non - recoil in vacuum	all fission products (there is no chemical selectivity)	10^{-6}-10^{-5}
OSTIS, Grenoble (Oct. 1975)	^{235}U as UO_2 (2g at 1800°C)	3×10^{9} th.	0.1 sec	surface ion. (1800°C)	Rb,Cs	10^{-2}
"ISOL", Mainz (Dec. 1975)	^{235}U as UO_2 (1g at 1800°C)	3×10^{11} th.	0.1 sec	surface ion. (1800°C)	Rb,Cs	10^{-2}

*Facility is often classified as mass analyzer rather than ISOL.

TABLE 2: CHARACTERISTICS OF EXISTING ISOL FACILITIES AT ACCELERATORS

Name, location (initial operation)	General classification of target materials	Particle current and energy	Delay time from production to ionization	Type of ion source (temperature)	Elements extracted, with decay products excluded	Approximate overall efficiency
ISOLDE, Geneva (Oct. 1967)	hydrous oxides of Zr, Ce, Th (room temp.)	4×10^{11} p/sec (600 MeV)	$10 - 10^2$ sec	oscil. elect (1100°C)	Kr,Xe,Rn	10^{-2}-10^{-1}
	molten metals or alloys (600 - 1400°C)	"	$10 - 10^3$ sec	oscil. elect. or surface ion.	Zn,Kr,Rb,Cd,In,I,Xe,Cs,Ba, Sm,Eu,Hg,Tl,Pb,Bi,Rn,Fr,Ra	10^{-4}-10^{-1}
	ThF_4-LiF eutectic (600 - 700°C)	"	$10 - 10^2$ sec	oscil. elect. (1600°C)	I,Xe,Te,Po,At,Rn	10^{-4}-10^{-2}
	Ce, Th ceramic oxides (500 - 2100°C)	"	$10 - 10^2$ sec	hollow cath. (2000°C)	Sb,Te,I,Xe,Cs,Au,Hg, Tl,Pb,Bi,Po,At,Rn,Fr	10^{-4}-10^{-2}
	fine powders of Nb, Ta (2000 - 2200°C)	10^{12} p/sec (600 MeV)	$1 - 10^2$ sec	surface ion. (2800°C)	Rb,Yb	10^{-3}-10^{-2}
	$^{238}UO_2$ in graphite matrix (2000°C)	"	$10^{-1} - 1$ sec	surface ion. (2000°C)	Rb,Cs,Fr	---
	all targets above can be used with ISOLDE II	8×10^{12} p/sec (600 MeV)	---	any of the types above	all 24 elements above are possible with ISOLDE II	---
PINGIS, Stockholm (June 1969)	thin Pt foils (1600°C)	1×10^{13} a/sec (43 MeV)	$10^{-1} - 10$ sec	oscil. elect. (1600°C)	Hg	10^{-3}-10^{-2}
	$^{238}UC_2$ in graphite matrix (1500°C)	"	$10^{-1} - 10^2$ sec	"	As,Br,Kr,Rb,Sr, Ag,Cd,In,Sn,Sb,Te,I,Xe,Cs	10^{-4}-10^{-2}
UNISOR, Oak Ridge (Sept. 1972)	thin metal foils (200 - 1200°C)	10^{13}/sec C,N,O,Ne (60-90 Q^2/A MeV)	$10^{-1} - 10^2$ sec	oscil. elect. (1600°C)	Br,Kr,I,Xe,Eg,Tl,Pb,Bi	10^{-3}-10^{-2}
	thin metal foils with He jet flow system	"	10 - 30 sec (gas flow time)	hollow cath. (2000°C)	Ga,Ag,Sb,Te,Dy	10^{-4}-10^{-3}
"ISOL", Tokyo (Nov. 1972)	thin Cu foils (600 - 1000°C)	5×10^{12} p/sec (52 MeV)	$10^2 - 10^3$ sec	oscil. elect. (1500°C)	Zn	10^{-4}
	thin Cu foils (1400 - 1800°C)	"	10 - 10^2 sec	hollow cath. (2200°C)	"	10^{-3}
BEMS, Dubna (Nov. 1973)	thin metal foils (200 - 1000°C)	10^{12}-10^{13} HI/sec (4-8 MeV/A)	$1 - 10^3$ sec	surface ion. (2700°C)	Rb,Cs,Ba,La,Pr, Nd,Pm,Sm,Eu,Dy	10^{-3}-10^{-1}
ISOCELE, Orsay (Mar. 1974)	molten metals or alloys (700 - 1800°C)	1×10^{12} p/sec (155 MeV)	10 - 10^3 sec	oscil. elect. (1800°C)	Cd,In,Sb,Ho,Er,Tm,Yb, Au,Hg,Tl,Bi,Po,At,Fr	10^{-3}-10^{-2}
	"	3×10^{13} p/sec (200 MeV)	"	"	all 14 elements above are possible with ISOCELE II	---
LISOL, Heverlee (May 1975)	Mo (as filament of ion source)	3×10^{13}/sec ^{14}N (72 MeV)	10 - 10^2 sec	oscil. elect. (1800°C)	In	---
"ISOL", Jyväskylä (Sept. 1975)	thin metal foils (He jet at 80°K)	10^{13}/sec p,d,^{3}He,α (20 Q^2/A MeV)	0.5 - 1 sec (gas flow time)	oscil. elect. (1300°C)	Cu,Zn,In,Sn,Sb,Cs,Ba,Bi	10^{-4}-10^{-3}
	thin metal foils (He jet with NaCl)	"	"	hollow cath. (2000°C)	"	10^{-3}-10^{-2}
"ISOL", Darmstadt (Jan. 1976)	thin metal foils (500 - 1000°C)	10^1-10^{13} HI/sec (4-8 MeV/A)	1 - 10 sec	direct dis. (2000°C)	Br,Kr,Pd,Ag,Cd,In,Sn, Sb,Te,I,Xe,At,Rn	10^{-3}-10^{-1}
	"	"	$10^{-1} - 1$ sec	surface ion. (2000°C)	Rb,Cs,Fr	10^{-1}
"ISOL", McGill (Jan. 1976)	^{238}U and ^{233}Th (1500°C)	10^{12}/sec p,d,^{3}He,α (100 Q^2/A MeV)	10^{-1} sec	surface ion. (2000°C)	Ga,Eb,In,Cs,Ba	10^{-2}-10^{-1}

TABLE 3: Source References for Existing ISOL Facilities

TRISTAN	Ref. 18 (Also Ref. 13-16)
ARIEL	Ref. 19 (Also Ref. 13)
SOLIS	Ref. 20, 21 (Also Ref. 13-15)
OSIRIS	Ref. 22-24 (Also Ref. 3, 13, 14)
IALE	Ref. 25 (Also Ref. 13)
JOSEF	Ref. 26, 27 (Also Ref. 3, 13, 14)
SIRIUS	Ref. 28 (Also Ref. 14)
SOLAR	Ref. 29, 30
LOHENGRIN	Ref. 31 (Also Ref. 3, 13, 14)
OSTIS	Ref. 32
"ISOL" Mainz	Ref. 33
ISOLDE	Ref. 34, 35 (Also Ref. 3, 13-15)
PINGIS	Ref. 36 (Also Ref. 13, 14, 16)
UNISOR	Ref. 37, 38 (Also Ref. 14, 15)
"ISOL" Tokyo	Ref. 39
BEMS	Ref. 40, 41 (Also Ref. 3)
ISOCELE	Ref. 42, 43 (Also Ref. 14, 15)
LISOL	Ref. 44 (Also Ref. 15)
"ISOL" Jyväskylä	Ref. 45 (Also Ref. 15)
"ISOL" Darmstadt	Ref. 46, 47 (Also Ref. 14, 15)
"ISOL" McGill	Ref. 48

facilities the target and neutron flux are much more specific than is the case for the analogous quantities at accelerator-based facilities. (With the latter the maximum particle currents listed can, for certain targets, greatly exceed the particle current that the target can bear.) General labels are used for ion-source types since the variations within each type class cannot be adequately described in such a table. Only ranges for delay times and overall efficiencies are presented for the elements that have been extracted from a given target and ion source combination. (The overall efficiency for an isotope is defined as the mass-separated fraction of the isotope produced in the target; the delay time is the average time between production and mass separation.)

The overall efficiency for a particular isotope generally depends on both Z (chemical dependence) and $T_{1/2}$ (delay-time dependence) for a given combination of ion-source and target. For isotopes with half-lives long compared to the delay time, the overall efficiency is independent of $T_{1/2}$. The efficiencies given in Tables 1 and 2 refer to longer-lived isotopes of the elements extracted, and the efficiency range listed indicates the variations for different elements and not efficiency differences due to $T_{1/2}$ effects. The realized efficiency decreases rapidly as $T_{1/2}$ becomes progressively small in comparison to the delay time. For certain classes of targets, particularly those from which the reaction products escape by diffusion, the delay time spectrum contains both long and short delay terms. The presence of a short delay term can make it possible to observe an isotope with a $T_{1/2}$ value of the order of 1% of the mean delay time for the element.

In addition to the target dependence, delay times depend on the ionization process and transport times (if the target and ion source are separated by a connecting transport line). In Tables 1 and 2 the dominant delay time feature is indicated when this feature is considered to be transport or recoil. Diffusion or surface desorption times are generally the limiting feature. In the absence of a label, such processes may be assumed to be the dominant feature. For cases with a broad range of available elements, a delay time range is given which spans the various delay times of the different elements. In many cases the delay times given in Tables 1 and 2 are estimated or inferred, as direct measurements have only rarely been made.

Both delay times and element ionization efficiencies can be temperature dependent. Delay times for diffusion targets can often be reduced substantially by increasing the target temperature. The element selectivity in the ionization process is also temperature dependent, especially for ion sources employing surface ionization. Typical operating temperatures of targets and ion sources are indicated in Tables 1 and 2. For cases where the target is contained within the ion source, the same characteristic temperature is listed for both.

B. Discussion of ISOL Systems

The ideal ISOL system would provide rapid, high efficiency production of any desired isotope with both element purity and mass purity. Needless to say no such ideal system exists. However, the ideal features can be approached for a few special classes of elements. Elements that can be easily chemically separated (such as the rare gases) or elements that can be easily ionized in a very selective manner (such as the alkali

metals) come close to satisfying the ideal. For most elements, however, some of the properties of the ideal system must be modified or abandoned. In working systems element purity has frequently been relaxed or abandoned entirely in order to obtain shorter delay times or make available elements that are difficult to ionize. One method of classifying the various operating systems is in terms of the degree of element selectivity obtained.

As stated above, quite pure element selectivity can be obtained with rare gases or alkali metals. Some of the facilities (TRISTAN, ISOLDE, ARIEL, SOLIS) have in the past used systems in which only rare gas reaction products (with traces of other gaseous products) have survived a transfer from target to ion source. The process of surface ionization from hot metal surfaces has been used at many facilities (ISOLDE, SOLIS, BEMS, SOLAR, OSTIS and the ISOL facilities at Mainz and Darmstadt) to selectively ionize alkali metals with high ionization efficiency (by selection of the temperature and choice of ionizing surface). Although a few other systems have been used in special cases to provide element selection, the two groups of elements above can be obtained with higher overall efficiencies (10^{-2}-10^{-1}) and shorter delay times (10^{-1}-10^{1} sec) than the others, hence provide the best examples of systems with clean mass and element separation.

Molten targets (metals, alloys, or eutectic mixtures) have been used frequently at ISOLDE and exclusively at ISOCELE. Many elements have been successfully extracted using either oscillating-electron or surface-ionization ion sources. Overall efficiencies are reasonable (typically 10^{-3}-10^{-2}), allowing adequate production rates. These systems have been especially useful in studying neutron-deficient rare-earth

elements. For the most part, clean element separation is not possible, but the neighboring element contamination can often be controlled by careful selection of target material, temperature and ion source operating conditions. Due in part to the rather large target sizes, but mostly due to the temperature limit imposed by target evaporation, the release times (10^1-10^3 sec) are rather slow, limiting the distance from the line of stability for which such targets can be used.

Diffusion of reaction recoils from solids has been extensively used at many facilities. High temperature ceramic oxides in powdered or sintered form were used at ISOLDE, with diffusion of reaction products into a hollow-cathode ion source. The delay times and overall efficiencies of this system are very similar to those of the molten targets. Faster release times have been obtained with reaction products diffusing from a porous graphite matrix, which has fast diffusion times for many elements at temperatures around 1600° C.

Uranium distributed in a porous graphite base located within the ion source has been used successfully at OSIRIS and PINGIS (and, more recently, TRISTAN and ISOLDE) to produce a wide range of fission products with delay times in the range 10^{-1}-10^2 sec and with reasonable efficiencies. (At ISOLDE the target has been used so far only with a surface ionization source in a test for Cs or Fr isotopes.) The fast diffusion from graphite is the major advantage of this type of target. The different diffusion and ionization properties of different elements can restore some elemental sensitivity (as the ISOLDE use to cleanly extract alkali metals).

Metal foil targets and hot recoil catchers of various types have been used extensively at accelerator-based facilities (PINGIS, UNISOR,

BEMS and the facilities at Tokyo and Darmstadt). In general, the reaction recoils from a thin target pass through a thin window and imbed in a catcher material located either within or very close to the ion source. Recoil catchers of hot porous graphite or metals in oscillating-electron ion sources as well as the Ta or Re surfaces of surface ionization sources have been used. The choice of target and accelerator beam can limit the variety of elements produced. The delay times depend primarily on diffusion times from the recoil catcher, thus depend strongly on its temperature. As in the molten and solid targets mentioned above, control of diffusion temperature and ion-source operating conditions can provide a degree of element selection or enhancement. Except for the special case of selective ionization of alkali metals, however, high element purity cannot be obtained.

Recent progress in solid and liquid targets and their connections with ion sources has been well reviewed by Ravn.[49] In addition to some of the systems outlined above, the very hot powder target of ISOLDE and the very hot rhenium surface-ionization source of BEMS and ISOLDE are discussed by Ravn. The increased element availability and reduced delay times obtained in the systems discussed (which are included in Tables 1 and 2) have to a large extent been accomplished by increased temperature. Higher temperatures make diffusion times shorter and ionization possible for elements that are difficult to ionize. A consequence of the higher temperatures is the reduction in element selectivity, since the easily obtainable elements are still extracted together with the difficult elements. However, the achievement of shorter delay times and the availability of previously unavailable elements are significant accomplish-

ments. In particular, the lack of element purity for a difficult element is a small price to pay for the gain of a non-zero efficiency.

The helium jet transport technique has been used at UNISOR and is used exclusively at SIRIUS and the Jyväskylä ISOL facility. The ionized reaction recoils are stopped in helium where they attach to clusters (natural or added mixtures of traces of relatively large molecules) and are transported from the target chamber into an ion source. The cluster attachement process has no significant chemical selectivity and the reaction products in this gaseous form are delivered directly into the ion source. The operating condition of the ion source provides the only means for element selectivity, which can be minimized by use of plasma-type ion sources. Since the processes of stopping, transporting, and ionizing reaction recoils are essentially chemically nonselective and the delay time is simply a matter of gas flow rate, the overall efficiencies seem to differ by less than an order of magnitude for all reaction products of comparable yield and half-life. For elements difficult to obtain in other ISOL systems without also producing neighboring elements at much higher efficiencies, this aspect of helium-jet ISOL systems is an advantage since contamination from neighboring isobars is thus much less than in other types of ISOL systems.

The remaining ISOL systems in this survey are the direct systems JOSEF and LOHENGRIN. As mentioned in the last section in comparison between direct and indirect ISOL systems, for very short times or for primary yield studies, direct systems have no competition. For half-lives above about 0.1 sec, direct and indirect systems can both be used for nuclear spectroscopic studies. Direct systems have a competitive

disadvantage for elements that have much higher efficiencies in indirect systems. However, the very low efficiency of direct systems is not a disadvantage for the elements that also have low efficiencies in indirect systems. One significant distinction between systems that is not included in the tables lies in the focusing properties of the mass-separated ion beams. With the conventional mass separator of the indirect systems, high mass resolution and good spatial focusing are obtained -- both being highly desirable for many nuclear spectroscopic studies. The LOHENGRIN system provides a sufficiently high mass-resolving power of 200-1000, but the focus of the mass-separated beam occurs on a mass parabola of about 70-cm length. The JOSEF system provides a beam focus about 10 cm in diameter and has a low mass-resolving power in the range 20-80.

The preceeding brief discussion and survey tables can only provide a partial overview of the characteristics of existing ISOL systems. The dramatic growth in ISOL systems and the expansion of elements available can best be seen by comparing with the survey made in 1970 by Talbert.[50] The number of ISOL systems and the number of elements extracted have both more than doubled. Furthermore, the ISOL systems have contributed a very substantial fraction of the $\sim$ 300 new isotopes since 1970, particularly those for which some nuclear structure information has been obtained.

C. Types of Studies Done at ISOL Facilities

No discussion, however brief, would be complete without mention of the types of nuclear spectroscopic studies performed at ISOL facilities. The full range of nuclear detection equipment and techniques has been

employed in on-line measurements of nearly all nuclear structure properties. In the following, this range will be surveyed briefly without specific assignment of techniques to individual facilities, as this would be too involved to attempt here and the present purpose is served by indicating the extent of the ISOL studies. Reference 3 provides examples of the types of studies outlined below.

Reaction cross section and yield measurements of primary and secondary reaction products have been made primarily for spallation and fission, and more recently for heavy-ion reactions. Mass and charge dependences of yields, absolute or relative, have been determined for secondary products at indirect ISOL facilities and for both primary and secondary products at direct ISOL facilities.

Half-life measurements have been made using a variety of techniques, such as multiscaling of α, β and delayed particles (α,p,n) with solid state, scintillation or gas proportional detectors, as well as γ-multispectrum measurements in singles or β-gated coincidence studies. In a few cases nuclear emulsions have been used to determine half-lives.

Mass measurements have been extensively and systematically made at several facilities, mainly by Q_β determinations from either β-singles or γ-gated β spectra using a variety of detectors: plastic scintillators, Si(Li) detectors, magnetic spectrometers, and intrinsic Ge detectors. In addition, a system for direct mass measurements has recently been used on-line at ISOLDE.

Delayed particle (α,p,n) emission probabilities have been determined by direct particle counting and by indirect spectroscopic techniques. Energy spectra of delayed particles have been obtained with ΔE-E tele-

scopes, surface barrier and emulsion detectors for protons or alphas, and with ^{3}He proportional detectors for neutrons. Some delayed-proton spectra in coincidence with γ-rays have been obtained. In some cases delayed particle and γ branching ratios have also been determined.

For detailed decay scheme studies of decay chains, all of the standard nuclear spectroscopic measurements have been made on-line. Besides energy and intensity measurements of α,β,γ, e^- and e^+ transitions, all types of double-coincidence spectra (including three-parameter spectra with time as one parameter) have been used in determining level structures. For cases or systems where element identification is nontrivial, x-ray coincidence spectra have been useful. Internal conversion coefficient determination, γ-γ angular correlation and delayed coincidence measurements have been done on-line to yield transition multipolarities, spins and parities of excited states. Absolute decay rates have been established by ground-state β-branching determinations or other techniques. In these decay studies all manner of detectors have been used on-line: scintillation, solid state, proportional, etc., and magnetic spectrometers or lenses have been successfully adopted for used in the study of short-lived activities.

Some of the most recent types of studies to be made on-line are atomic spectroscopic studies such as hyperfine structure and isotope shift to determine nuclear quantities such as spin, electric and magnetic multipole moments, and nuclear radii. Techniques used include optical pumping, tunable dye laser spectroscopy, atomic-beam magnetic resonance, curved crystal spectroscopy and nuclear orientation. Many of these techniques have been used on-line only in the last few years. As a

class, they constitute the most recent addition to on-line spectroscopic capabilities.

Table 4 presents a summary of possible studies at ISOL facilities. The studies mentioned above which have already been done are included, as well as isotope production and solid-state studies which are only beginning to be done at ISOL facilities. Table 4 clearly shows that not only is a wide range of nuclear spectroscopic studies possible at ISOL facilities, but also an appreciable number of atomic spectroscopic and solid-state studies are feasible.

In concluding the preceeding overview of ISOL systems, the future of such facilities must be addressed. In the preceeding outline, not only was the scope of the facilities and measurement capabilities presented but the rather dramatic rate of progress was also mentioned. Projections into the future could be based upon the expected continuation of such progress. However, even without assuming continued expansion of the field to include more and more elements and isotopes, it is clear that there remain many interesting studies to be made on the nuclei presently available at the existing ISOL facilities. Even studies of gross nuclear properties such as half-lives, Q_β values, and delayed particle emission probabilities are far from complete for the presently available nuclei far from stability. Furthermore, as concerns studies of detailed nuclear properties to deduce the nuclear structures, the vast majority of the presently available nuclei have not yet been studied. Many of the reported studies constitute only partial rather than comprehensive studies. Thus even without the expected increase in the near future of the isotopes available, there remain many years of interesting work to be done at ISOL facilities in the study of nuclei far from stability.

TABLE 4: Summary of Possible Studies at ISOL Facilities

Nuclear Masses

- Direct mass measurements
- Q-values of α decay*
- Q-values of β decay

Delayed-particle Emission

- Neutron or proton* emission probabilities
- Energy spectra of neutrons or protons*
- γ-n or γ-p* coincidences

Nuclear Spectroscopy

- Half-lives of β-decaying isomers
- γ singles and β-gated γ spectra
- e^- singles and β-gated e^- spectra
- γ-γ and e^--γ coincidences
- γ-γ angular correlations
- α spectra*
- α-γ coincidences*
- β spectra
- Absolute decay rates (β and γ)
- Half-lives of nuclear excited states
- Magnetic moments of nuclear excited states
- Search for new nuclides

Atomic Spectroscopy (Dye-Laser or rf studies)

- Nuclear spins
- Nuclear magnetic multipole moments
- Nuclear electric multipole moments
- Hyperfine anomalies
- Isotope shifts
- Isomer shifts

Reaction Yields

- Mass distributions or yields
- Nuclear charge distributions or yields
- Ionic charge distributions

Isotope Production

- Radioisotopes for medical uses
- Exotic radioactive targets for reaction studies

Solid-State Studies

- Measurements of atomic magnetic fields
- Ion implanatation studies
- Low-temperature nuclear orientation studies

*Indicates study not possible for ISOL facilities at reactors.

IV. TRISTAN II AT THE HFBR AT BROOKHAVEN

A. Thermal-Neutron Fission of ^{235}U

Contours of independent fission cross sections in barns are presented in Fig. 2 for thermal neutron fission of ^{235}U. The contours were calculated under the assumption of pure Gaussian charge dispersion with the same Gaussian width of $\sigma = 0.56$ (FWHM = 1.32) for all mass chains.[51,52] The values of Z_p (the most probable charge for a mass chain) were taken from the report of Wahl *et al.*[51] Mass yield values for thermal neutron fission were taken from the compilation of Nethaway and Barton.[52] The odd-even fluctuations in fission yields[53] were not included in the calculation of the contours of Fig. 2. For the low-yield fission products in the valley and on the wings, Fig. 2 slightly underestimates the yields to be expected for the fission-neutron spectrum of the external beam of the HFBR. However, for the present purpose of estimating the quantities of fission products produced with TRISTAN II at the HFBR, the cross-sections of Fig. 2 are quite adequate.

The background for Fig. 2 consists of a section of the chart of the nuclides. As in Fig. 1, the solid squares indicate stable or naturally-occuring radionuclides and the squares contained within the dashed outline are presently known nuclides. The solid outline contains nuclei for which some nuclear structure information exists. Only nuclei with at least a few energy levels known are included within the solid outline; for a substantial fraction of these nuclei the level structure information is far from comprehensive. For example, even such a basic quantity as the β-decay Q-value has not been measured for nearly 40% of these nuclei. For the nuclei lying between the solid and dashed outlines,

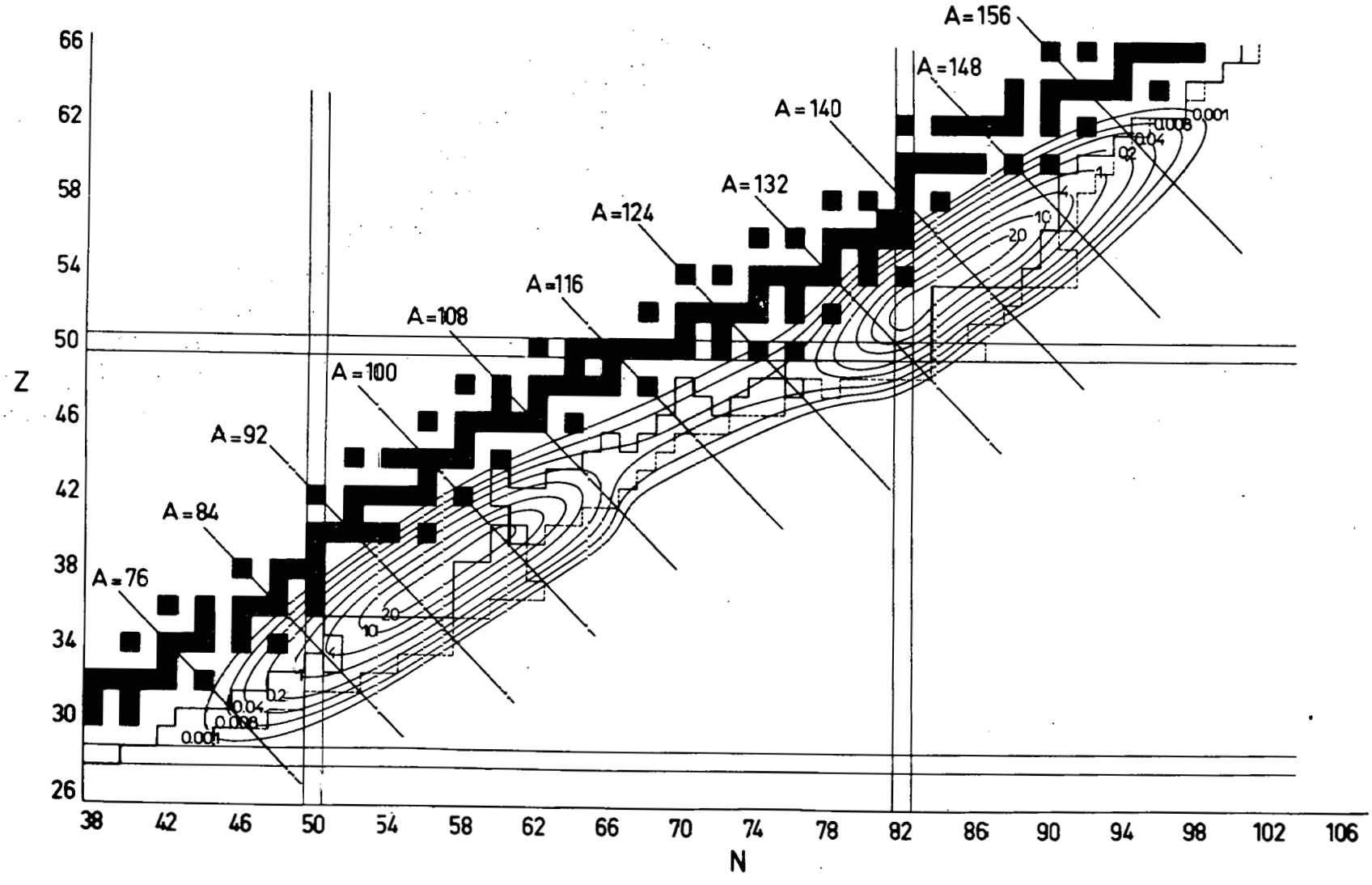

Fig. 2: Contours of independent fission cross-sections in barns for $^{235}U(n_{th}, fission)$.

the present state of our knowledge is extremely poor, with only the half-life and perhaps some γ rays known. Figure 2 makes it very clear that a large number of fission products are inadequately studied.

The half-lives of nuclides in the fission product region are shown in Fig. 3, which also shows the neutron drip line. The half-life contours were calculated from a gross theory of β decay by Takahashi et al.[54] Agreement with experimental values is generally within an order of magnitude for nuclei with half-lives of 10 sec or longer. For half-lives less than 10 sec, the predictions appear to be more reliable and often are smaller than the measured half-lives.[55] Figure 3 shows that the nuclides lying within the dashed outline are expected to have half-lives of about 1 sec or longer. Many undiscovered nuclei (lying outside the dashed line) are predicted to have half-lives of the order of 1 sec; as Fig. 2 shows, many of these nuclei have sufficient fission yield to enable them to be studied with an ISOL system with the capabilities of TRISTAN II.

Before proceeding in the following to describe the TRISTAN facility and make specific predictions of mass-separated fission-product activities available with TRISTAN at the HFBR, a general estimate of activities produced can be made. With a 2 g target of ^{235}U in the H-2 external beam thermal flux of $4 \times 10^{10}/cm^2/s$, the total activity in the target would be 1.1×10^{11} fissions/sec or 3 Curies. For an isotope on the minimum cross-section contour of 1 mbarn shown in Fig. 2, the production rate in the target would be 2×10^5/sec. Even at this minimum rate, mass-separated activities of about 10^3/sec would be available for isotopes with an overall efficiency of about 1% -- more than adequate for the discovery of new isotopes.

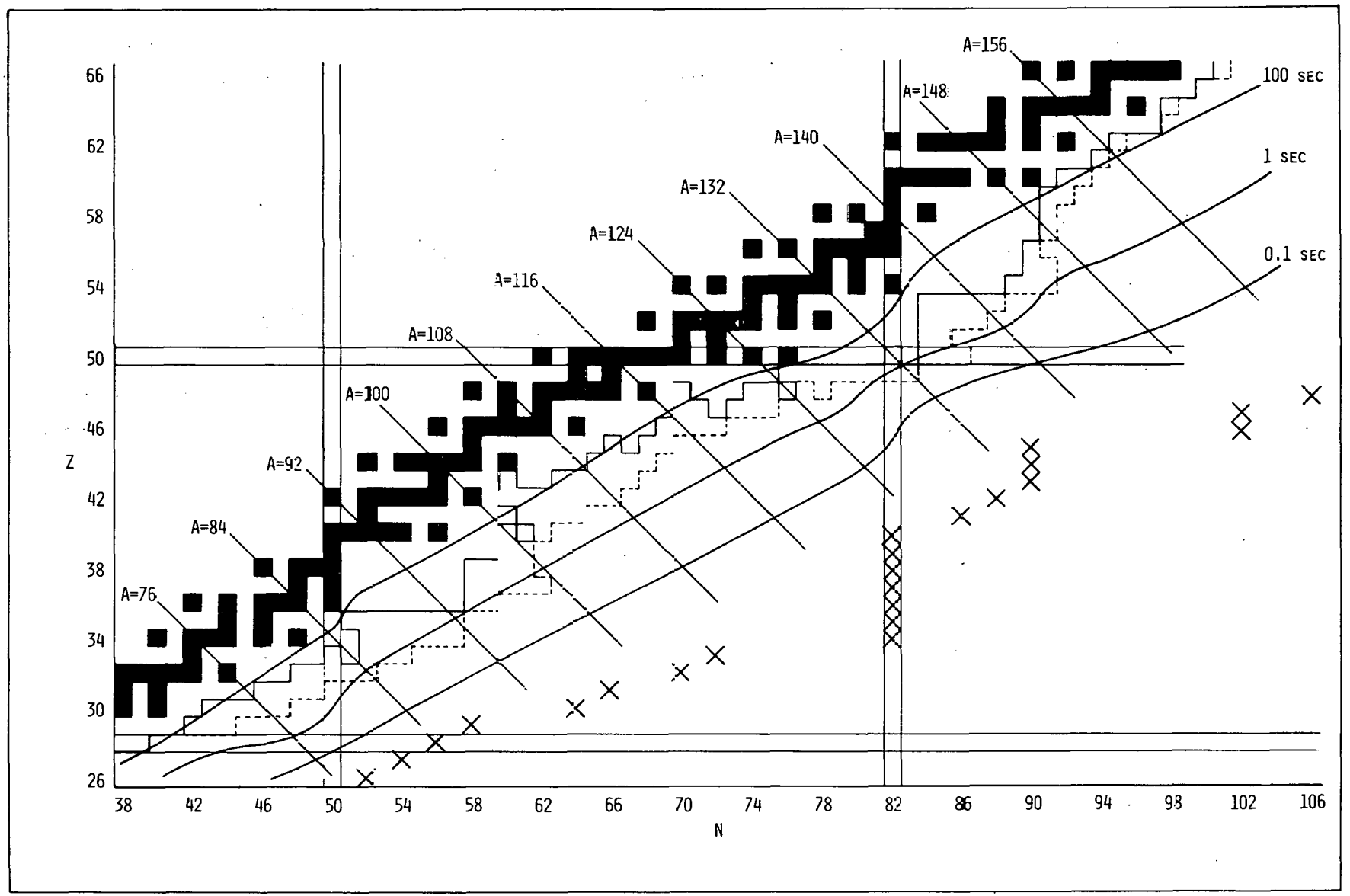

Fig. 3: Contours of half-life predictions and neutron drip-line predictions for neutron-rich nuclei in the fission-product region of the chart of the nuclides.

B. The TRISTAN Facility

Schematic diagrams of the TRISTAN II facility in its present configuration at the ALRR in Ames are shown in Fig. 4 and 5. This configuration is the third in the history of TRISTAN. The two earlier versions of TRISTAN I have been described in detail by McConnell and Talbert.[18] Since most of the operating properties of the separator were unchanged in the conversion from TRISTAN I to TRISTAN II and are well described in Ref. 18, they will not be described here. Pertinent aspects of the present ion-source target configuration are given by Talbert et al.,[56] although a complete report has not yet been prepared. Table 1 lists some of the characteristic properties of the three TRISTAN configurations.

The closeup view of Fig. 6 shows the in-beam ion source of oscillating electron (Nielsen) type with a cylindrical anode made of graphite impregnated on its inner surface with 2g of ^{235}U in the form UO_2. (At the operating temperature of about 1500-1700°C, some of the UO_2 may be converted into UC.[23,24]) The target activity of 0.2 Curies is produced by the ALRR thermal neutron flux of $2.5 \times 10^9/cm^2/sec$. Fission products diffuse from the relatively open-structured graphite matrix into the ion source plasma, where they become ionized, then are extracted from the ion source and accelerated through 50 kV. The 50 kV ions are focused through a 100° electrostatic sector, followed by the 90° mass-separator magnet. At the focal plane of the separator magnet the ions of selected mass pass through a slit and are then directed by a switching magnet to one of the detection stations. Moving tape collectors at each detection station provide isobaric enhancement of the activity of interest.

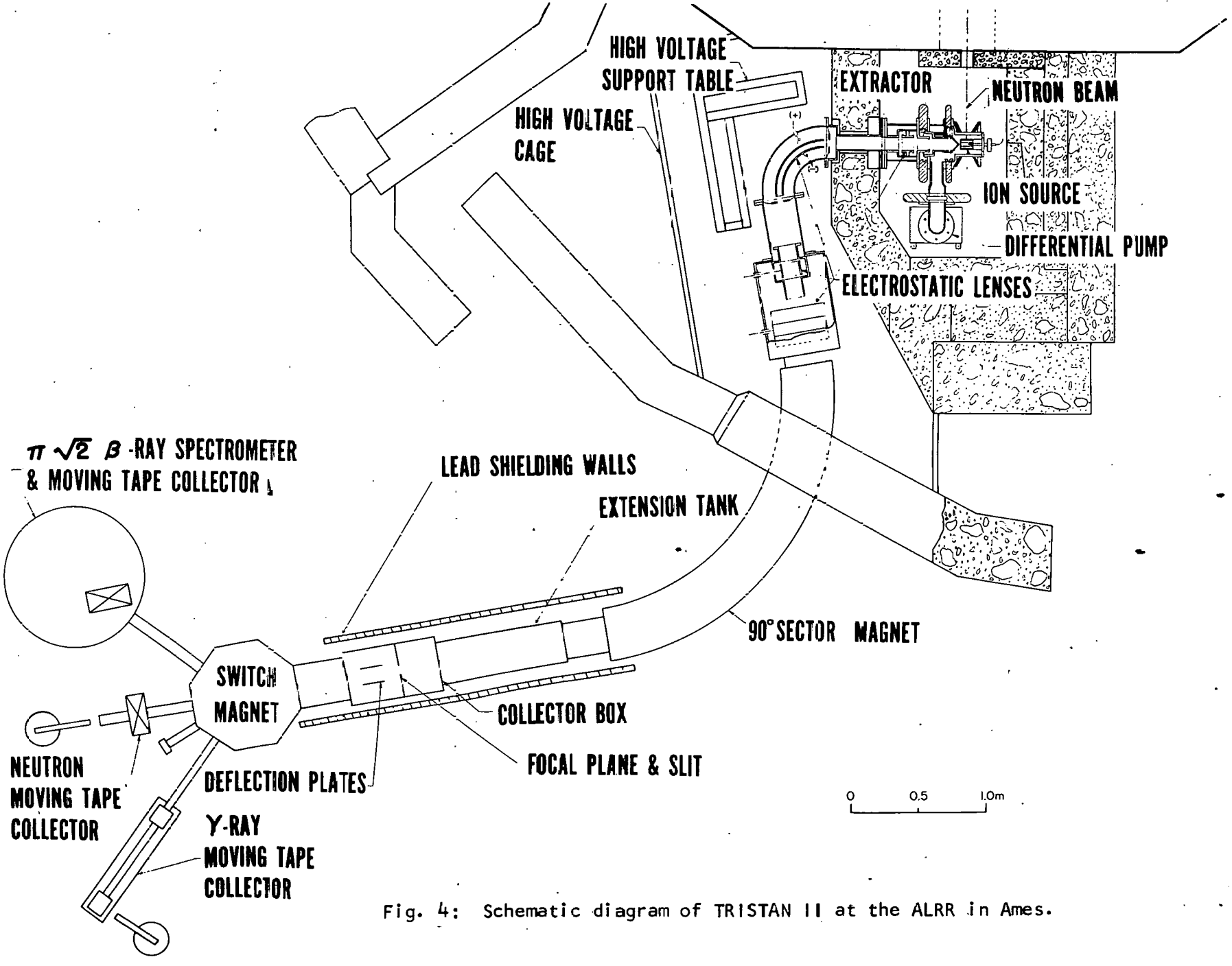

Fig. 4: Schematic diagram of TRISTAN II at the ALRR in Ames.

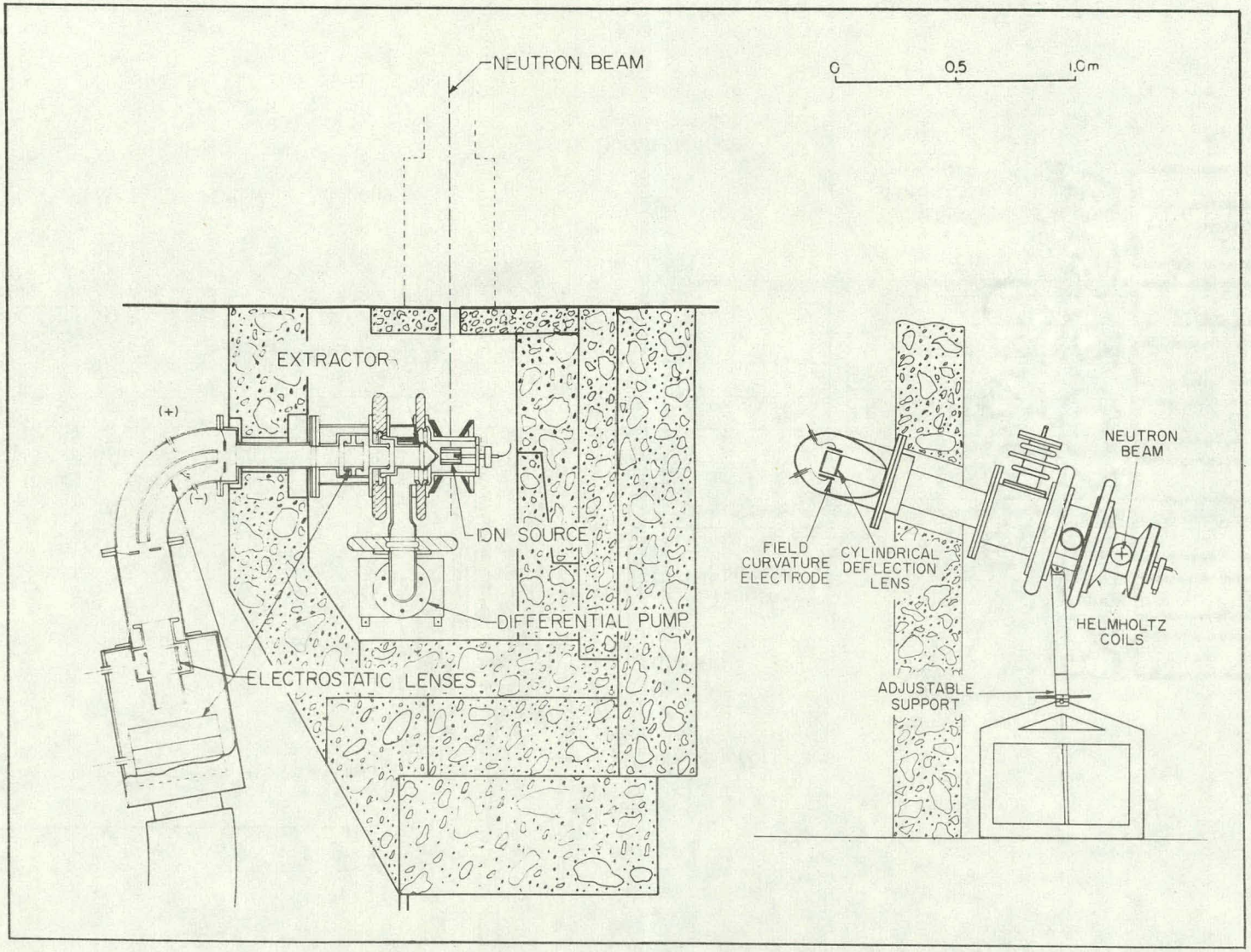

Fig. 5: Close-up and vertical views of TRISTAN II at the ALRR.

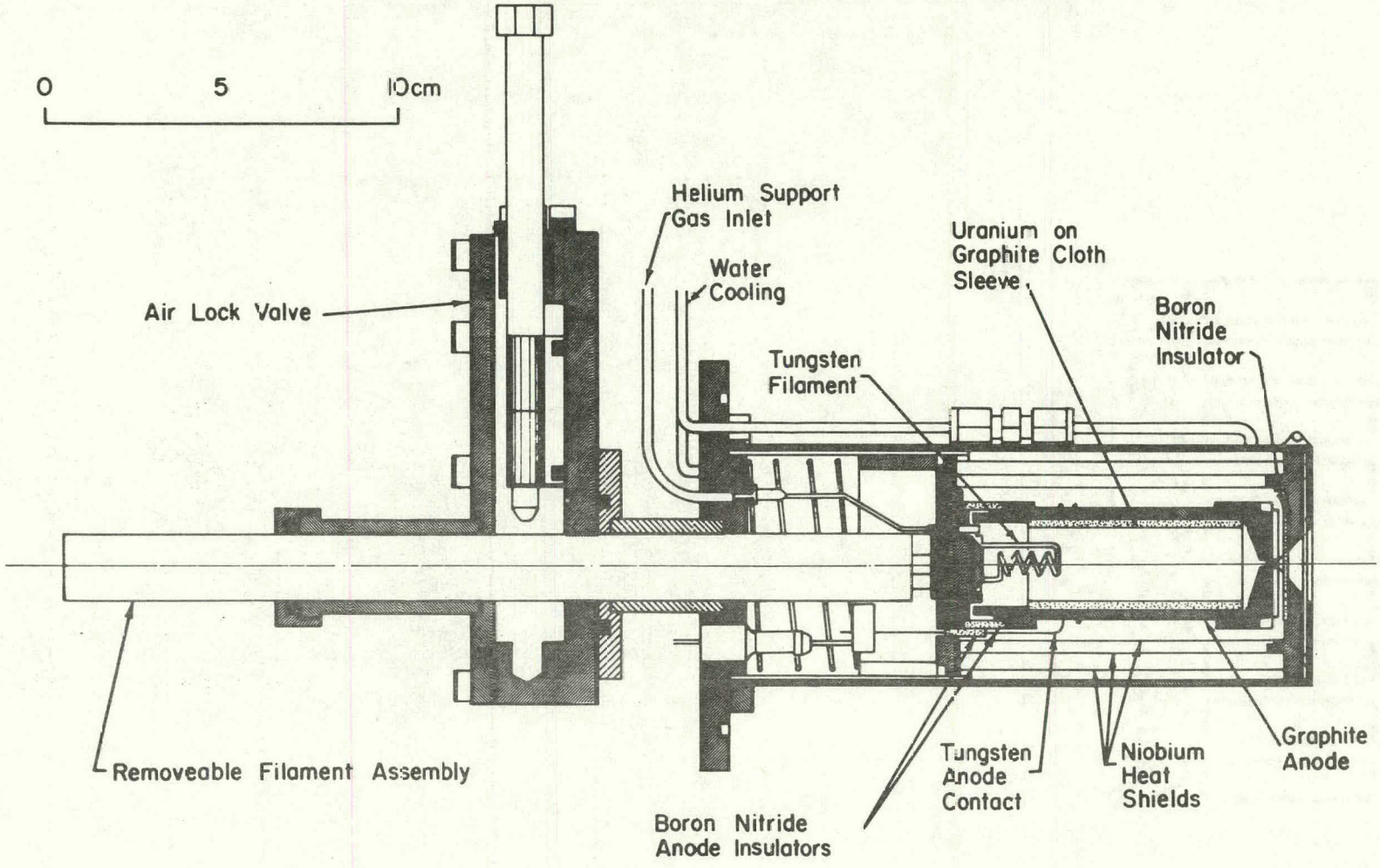

Fig. 6: Details of the in-beam ion source used with TRISTAN II at the ALRR in Ames.

Figure 7 shows a new in-beam ion source presently under construction at the Ames Laboratory. The design is based on the FEBIAD (Forced Electron Bombardment Induced Arc Discharge) ion source of Kirchner and Roeckl.[47,57] The FEBIAD ion source offers many advantages over the conventional oscillating-electron or Nielsen ion source, particularly for ISOL use. Among the advantages are low-pressure operation, very stable discharge conditions, long lifetime and high ionization efficiency.[47,57] In addition, the end cap or outlet plate potential can be selected so as to maximize either resolving power or output intensity.[58] The ion source of Fig. 7 has the same graphite liner impregnated with UO_2 as the presently used ion source of Fig. 6. Since this modification should not affect the high-efficiency characteristics of the FEBIAD concept, it is hoped that higher activities will result when the new in-beam ion source replaces the present one at TRISTAN II at the HFBR.

A schematic diagram of the TRISTAN facility relocated at the HFBR at BNL is shown in Fig. 8. This layout differs significantly from the ALRR layout, as no electrostatic deflection is required before mass separation in the HFBR layout. The magnetic spectrometer shown in Fig. 4 is replaced in Fig. 8 by a planned atomic spectroscopic system using a tunable dye laser. Figure 8 indicates the addition of a second mass line to the facility, which could essentially double the potential use of the facility by allowing simultaneous measurements on two masses. (A second mass line, although also possible at ALRR, was not needed for the scale of the research program at Ames.) Thus the HFBR layout has three distinct differences compared to the ALRR layout: simpler ion optics, a second mass line, and a higher neutron flux (by a factor of 16). The third difference is by far the most advantageous.

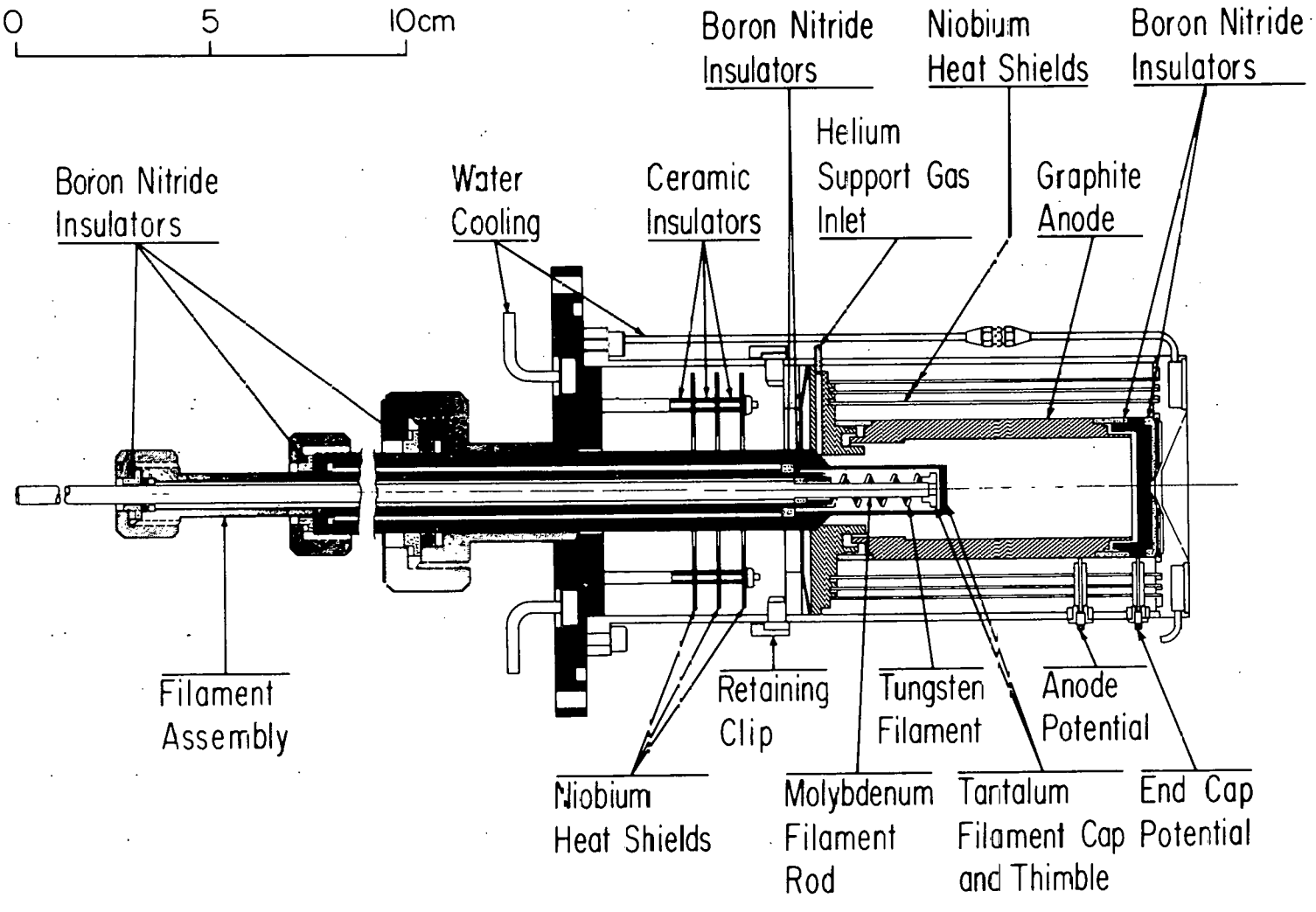

Fig. 7: Details of the modified-FEBIAD in-beam ion source to be used with TRISTAN II.

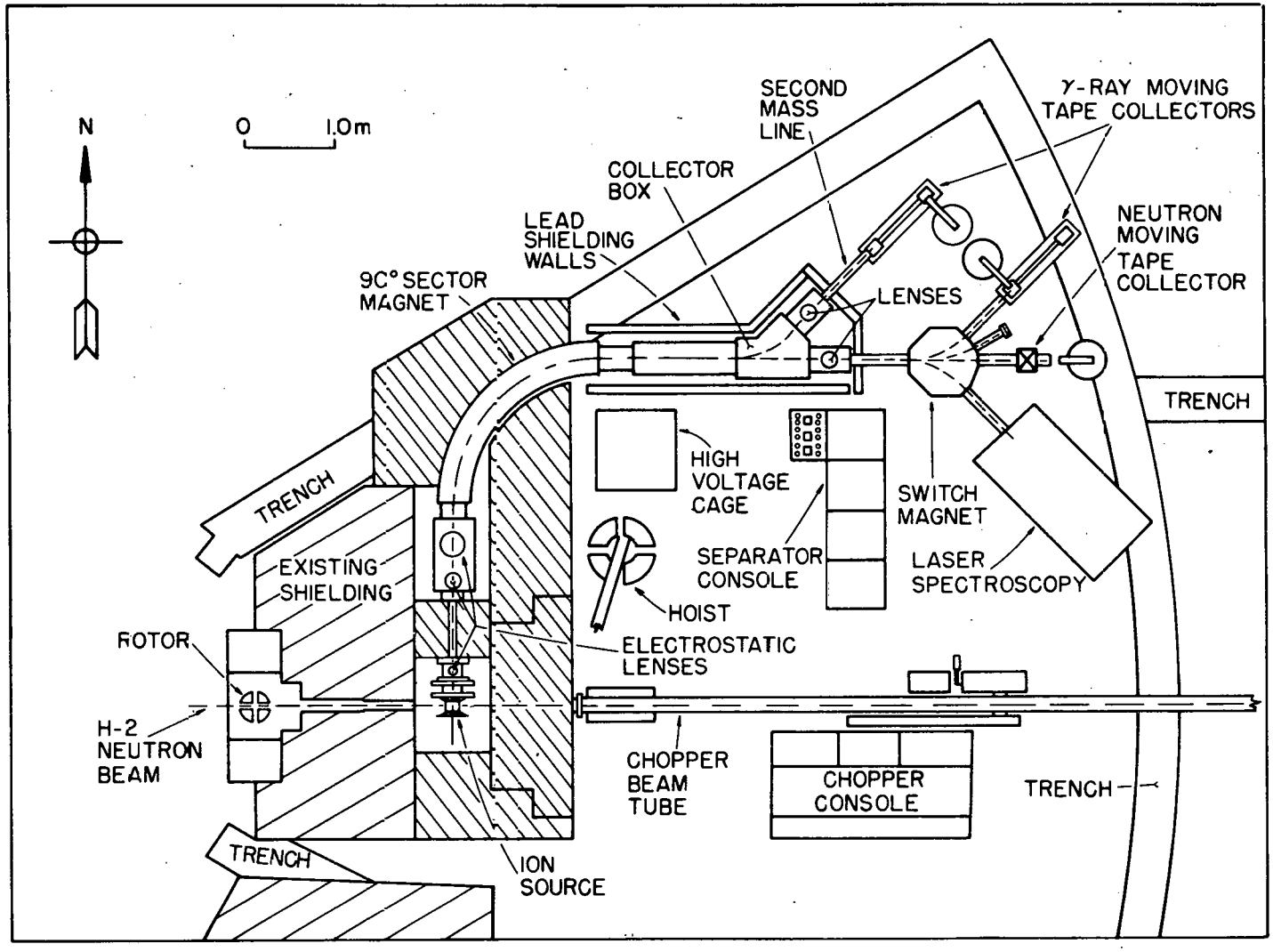

Fig. 8: Schematic diagram of TRISTAN II at the HFBR in Brookhaven.

C. Expected Activities

The overall efficiency of an isotope (the fraction of the isotope produced in the target that is delivered after mass separation to a detection station) must be known to calculate the amount of activity available for study at any mass. For a similar in-beam ion source containing a target of UO_2 in graphite, such efficiencies are known. The OSIRIS facility in Studsvik was the first to develop (in 1970) such a system,[22] which was subsequently improved[23] and has been used extensively ever since. A similar system was also used at PINGIS in Stockholm for the ^{238}U (α, fission) reaction with 43-MeV α-particles;[36] see Table 2 for characteristics. In both cases, a target of UO_2 impregnated graphite was located within an oscillating-electron ion source and overall efficiencies in the range 10^{-4}-10^{-2} were measured.

The overall efficiencies for 18 elements were determined with good accuracy at OSIRIS using longer-lived isotopes ($T_{1/2}$ > 3s) with well-established decay schemes.[23] The same 18 elements have been separated at TRISTAN II; Fig. 9 shows these 18 elements and gives a comparison with TRISTAN I. Such a systematic determination of overall efficiencies has not been made at PINGIS nor with the new TRISTAN II configuration. However, a mass scan at TRISTAN II of β activity was found to agree well with a similar mass scan done at OSIRIS. The OSIRIS and TRISTAN II mass scans are shown in Fig. 10 together with the mass-yield curve for ^{235}U fission. Both mass scans were obtained with a 4π β dectector. For the OSIRIS scan the mass-separated activity was collected for 10 sec then immediately counted for 10 sec;[24] the corresponding times were 30 sec and 30 sec for the TRISTAN II scan, with a 1 sec delay before beginning the

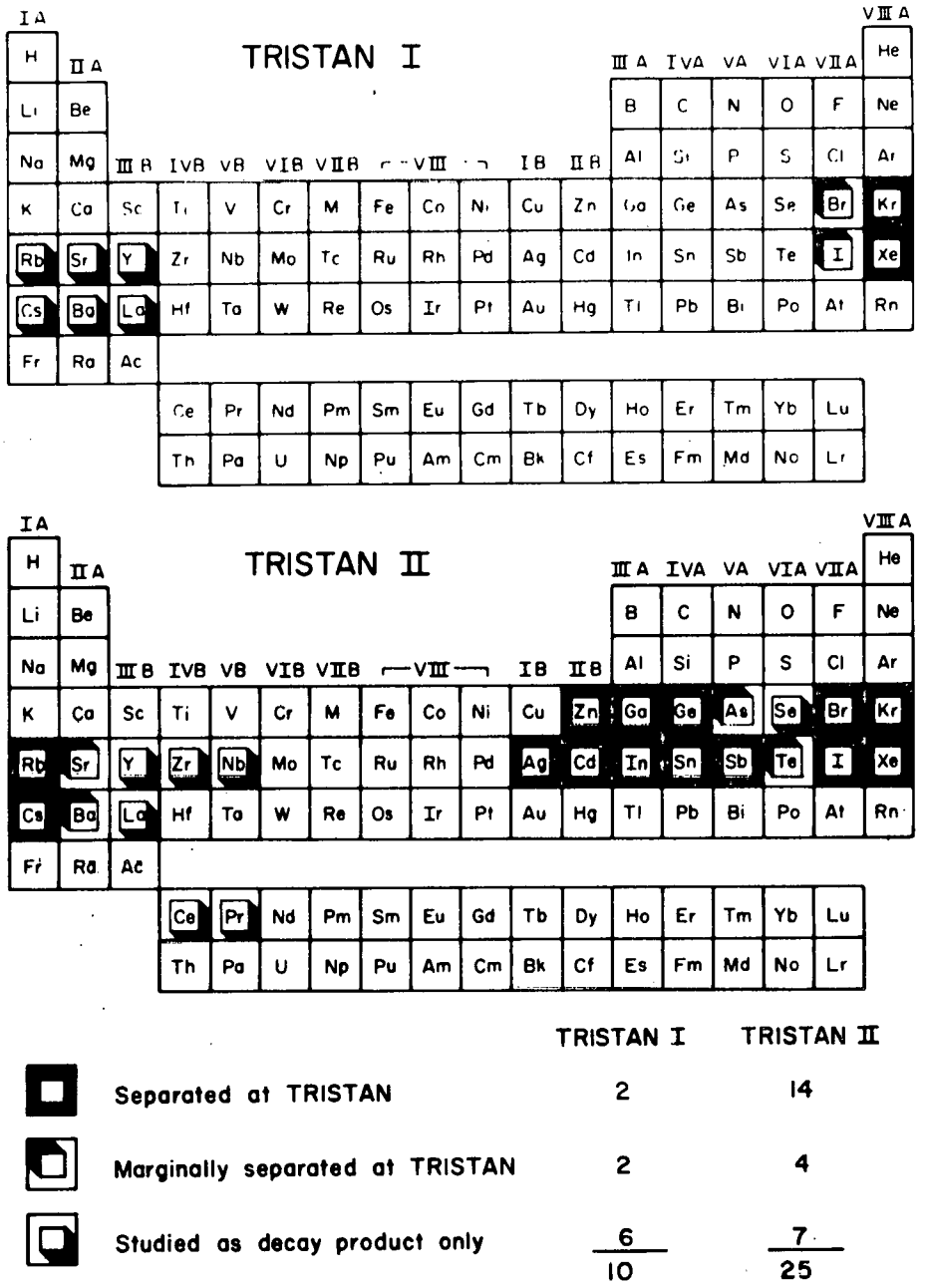

Fig. 9: Periodic table of the elements, showing elements available with TRISTAN I and TRISTAN II.

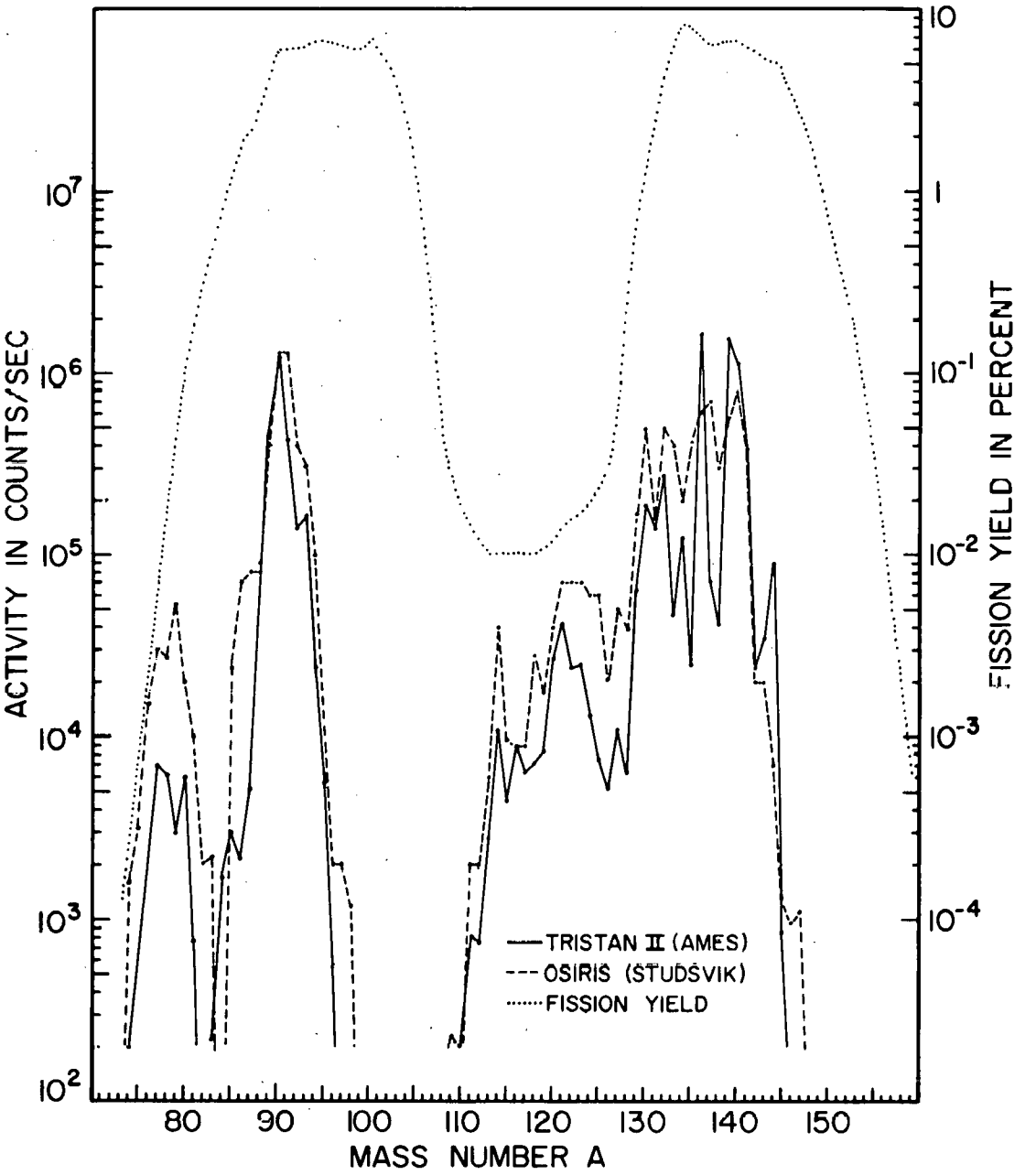

Fig. 10: Mass scans of fission-product activities obtained with 4π β counting at OSIRIS and TRISTAN II in Ames; the mass distribution for thermal neutron fission of ^{235}U is included for reference.

counting. The OSIRIS scan was done with 3 g of U and a neutron flux of 4 x $10^{10}/cm^2/sec$;[24] the TRISTAN II scan was done with about 8 g of U and a flux of 3 x $10^9/cm^2$sec. Although the effect of different time conditions on the various lifetimes renders a detailed comparison meaningless, the general agreement between the two mass scans indicates that the two facilities have quite comparable overall efficienceis for fission products. Thus it is quite reasonable to use the OSIRIS overall efficiency results shown in Table 5 to predict the activities to be expected for the very similar in-beam ion source of TRISTAN II at the HFBR.

Figures 11 and 12 present, in different formats, the results of a prediction of expected activities for fission-product nuclei in two mass regions. These two regions were chosen because they lie near single or double shell closure and because good element efficiencies exist in these two regions. Rare-gas or alkali-metal fission products were not included since studies of such products are not anticipated for TRISTAN II at BNL due to past and current comprehensive studies of these products at many ISOL facilities. The left-hand scales in Fig. 11 involve an effective yield which takes into account overall element efficiencies. The effective yield $Y_e(Z,A)$ represents the yield to be expected at a detector station after mass separation. For each nuclide the following expression was used to calculate $Y_e(Z,A)$:

$$Y_e(Z,A) = Y_e(Z-1,A) + \varepsilon(Z)[Y_c(Z,A) - 10\varepsilon(Z-1)Y_c(Z-1,A)] \quad ,$$

where $Y_c(Z,A)$ represents cumulative yield and $\varepsilon(Z)$ is overall efficiency. The $Y_c(Z,A)$ values were taken from the recent compilation by Voigt[59] and the OSIRIS results[23] were used for $\varepsilon(Z)$.

TABLE 5: Overall efficiencies for various elements obtained with old and new target arrangements at OSIRIS.

Element	Mass number measured	Half-life in sec	Overall efficiency in %	
			Old system[a]	New system[b]
Zn	76	5.7	-	2.5
Ga	76	30	-	2.7
Ge	79	19	-	0.29
As	81	28	-	0.016
Br	87	56	0.02	0.040
Kr	91	9.1	-	0.025
Rb	91	58	0.3	0.25
Sr	94	72	-	0.0080
Ag	117	73	1.6	1.5
Cd	119	200	2.4	2.6
In	124	3.2	3.0	2.7
Sn	127	247	0.34	0.30
Sb	133	148	0.45	0.40
Te	135	19	0.06	0.060
I	137	24	0.04	0.090
Xe	139	39	0.008	0.035
Cs	141	25	0.04	0.045
Ba	143	12	0.0014	0.0020

[a] Old system (0.3g) refers to the original UO_2 loading technique.

[b] New system (1.5g) refers to the improved UO_2 impregnating technique; see Ref. 23 of Ref. 16, page 239 for details.

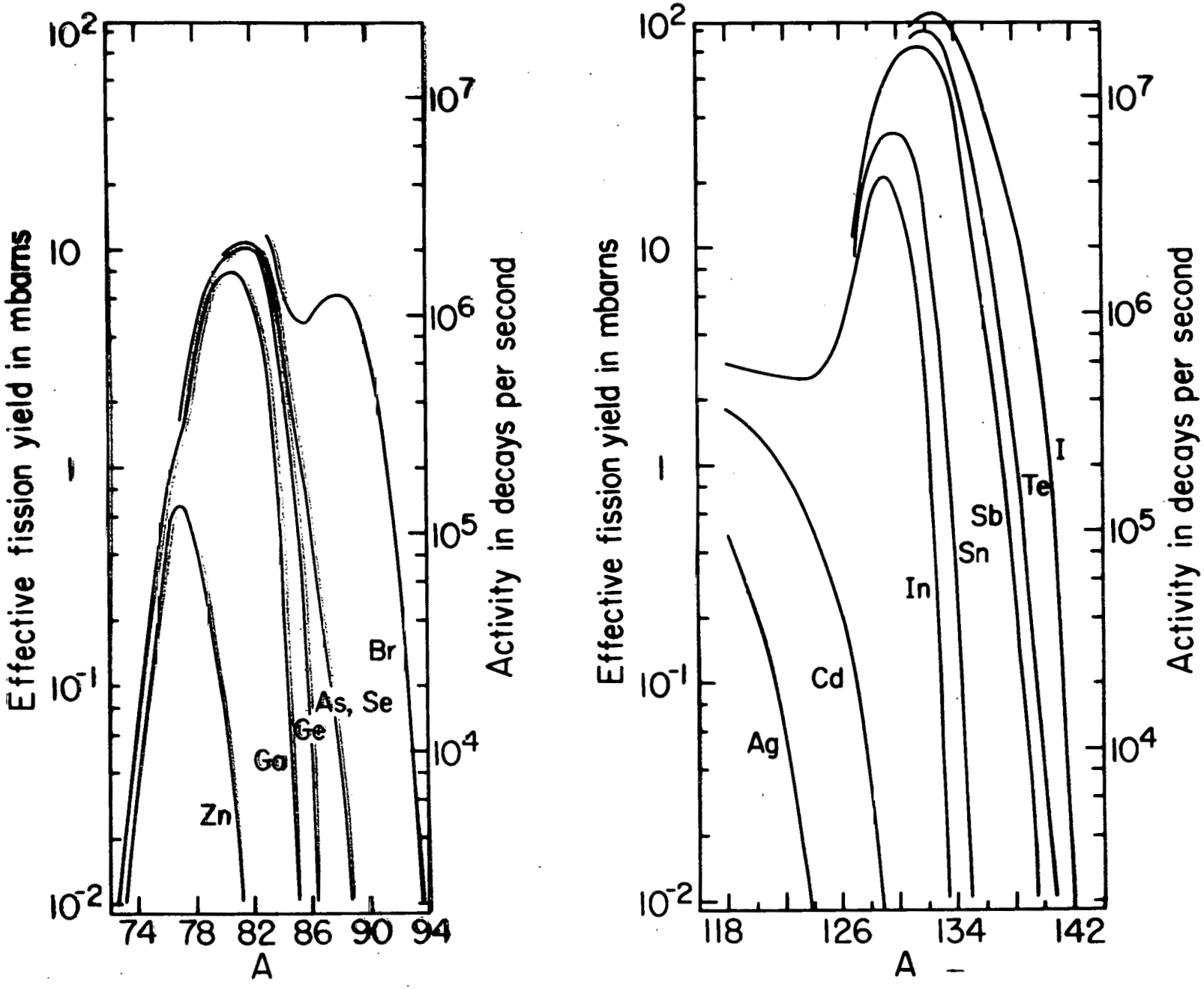

Fig. 11: Effective fission yields calculated with the OSIRIS overall efficiencies (left-hand scales) and saturation activities expected with TRISTAN II at the HFBR (right-hand scales).

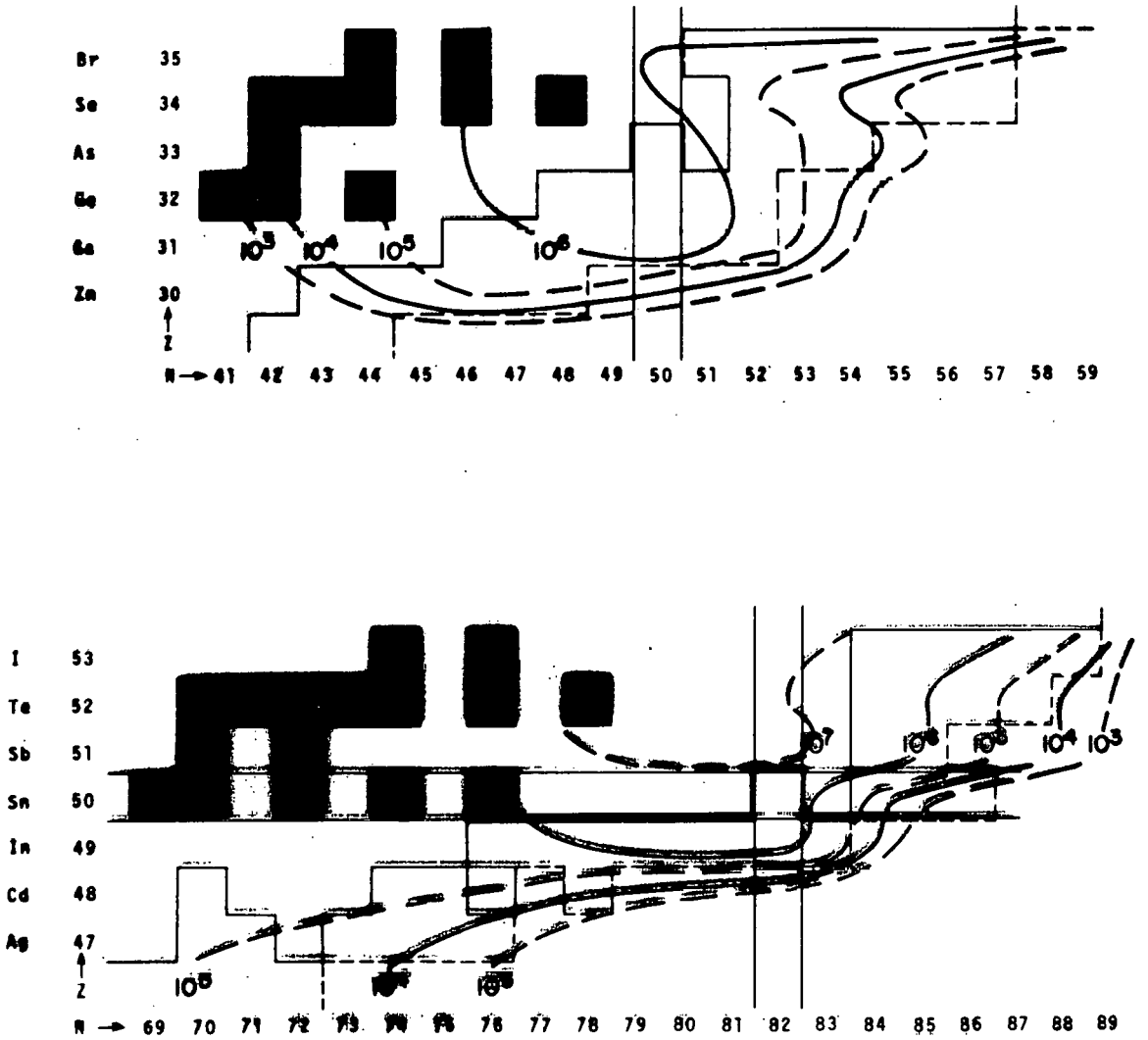

Fig. 12: Contours of saturation activities in disintegrations/sec expected with TRISTAN II at the HFBR, calculated with the OSIRIS overall efficiencies.

The first term in the preceeding expression gives the yield due to the mass-separated precursor in the decay chain. The second term gives the extractable fraction of the cumulative yield in the target. The third term is a correction needed because some of the cumulative yield of the precursor does not decay within the target, having been lost as either extracted precursor or pumped out of the ion source as neutral atoms. The factor of 10 in the third term is used to estimate this loss and is based on the observation that only about 1 ion in 10 is extracted for rare-gas fission products introduced directly into the ion source. Since the third term is of second order in efficiencies and is expected to be much less than unity, the estimate given above for this term is adequate for the present discussion. In the right-hand scales of Fig. 11 (and for Fig. 12), the effective yields are converted into activities by selecting a ^{235}U mass of 2g and the 4 x $10^{10}/cm^2/sec$ thermal neutron flux of the H-2 external beam line at the HFBR.

A few comments are in order concerning the independent and cumulative effects on the shapes of the curves in Fig. 11. The curves for Zn and Ag are Gaussian since the efficiencies of their respective precursors were assumed to be zero. The curves for the other elements reflect the mass-separated cumulative effect. The curves for Br and In show clearly separated regions of cumulative and independent domination. The seemingly large shift in the peak of the Br curve is due to the rather sharp increase of efficiency for Br compared to its immediate precursors.

Half-life effects on the activities expected were not taken into account in the preceding calculation because the delay time distributions between production and ionization are not known. The OSIRIS efficiencies,

which were measured in such a manner that only longer-lived activities could be used, should be valid when the half-life is as long or longer than the average delay time. For half-lives short compared to the delay time, however, the predictions shown in Fig. 11 would be too large due to neglect of decay in the target. Delay time distributions have both prompt and slow components, and little is known about the shape of the distributions for such a target system. For elements with efficiencies of 10^{-4}-10^{-3} the delay times may be in the range 10^{1}-10^{3} sec; for elements with efficiencies of 10^{-2}-10^{-3}, the delay time range is probably 1-10 sec.[60] Both target thickness and target temperature affect the delay time distribution of each element. Diffusion times decrease rapidly with increasing temperature, hence slightly higher operating temperatures (1700-1900°C) could cause a significant increase in the efficiency for a very short-lived isotope. For example, it has been observed at OSTIS[61] that the yield of 0.1-sec ^{98}Rb increases by more than an order of magnitude when the temperature is increased from 1700°C to 1900°C. Operating temperatures above the 1500°C of the OSIRIS target could well compensate for possible overestimations of expected activities of very short-lived isotopes given in Fig. 11 and 12 due to half-life effects. Furthermore, the higher ionization efficiencies anticipated with the modified-FEBIAD ion source could also compensate in part for the neglect of half-life effects in the predicted activities.

D. Possible Studies

In spite of the uncertainties in the preceding calculation of activities due to possible half-life effects for the shorter lifetime nuclei, the numbers in Fig. 11 and 12 provide a useful estimation of the activities

available with TRISTAN II at the HFBR. As was previously mentioned in Sec. II.D., detailed decay scheme studies, including coincidence measurements, are possible with activities of 10^3-10^4/sec; singles studies of intense γ rays require minimum rates of $\sim 10^2$/sec; half-life measurements or identification of new isotopes can be made with lower activities provided background rates are low enough. Many nuclei (60-80) lying outside the solid outlines of Fig. 12 might be expected to have activities above about 10^3-10^4/sec, which would be adequate for detailed decay scheme studies. Also, for many of the nuclei within the solid outlines, additional or more comprehensive studies are well worthwhile. A large number (20-25) of new isotopes outside the dashed outlines might be identifiable with activities of about 10^2-10^3/sec.

The preceding estimates of the numbers of nuclei lying outside the solid or dashed outlines of Fig. 12 could be regarded as upper limits since losses due to half-life effects were not included in the estimated activities. The estimate of about 20-25 (for isotopes lying outside the dashed outlines) should be most affected by half-life effects since these nuclei are expected to have short half-lives of the order of seconds.[54] Nevertheless, a substantial number of new isotopes should be available with sufficient activities to permit identification or more comprehensive study. Furthermore, when one considers the diversity of possible studies that could be done with TRISTAN II at the HFBR, one must recognize that many of the previously studied nuclei that lie within the solid outlines have not been sufficiently studied. In particular, atomic spectroscopic studies have been made for very few of the available fission products. This is also true even for the rare

gases, alkali metals and daughters (which were not included in Figs. 11 and 12 since nuclear spectroscopic studies are quite advanced at present for these fission products). Thus, of the nuclei expected to be available with TRISTAN II at the HFBR, a grand total of more than 100 (perhaps closer to 200) would be candidates for one or more of the types of studies listed in Table 4.

With a grand total in the range 100-200, it would be clearly too time consuming to mention all of the studies that would be interesting. Some choice or selection must be made before more detailed comments are given. One consideration to be made in selecting nuclei for study with TRISTAN II is competition from other ISOL facilities engaged in the study of neutron-rich activities. In the following, this consideration for selecting the nuclide regions of Fig. 12 is discussed.

As stated previously, the rare gases Kr and Xe and their daughter activities have been studied for years at TRISTAN I, ARIEL, SOLIS, and IALE (see Table 1). The alkali metals Rb and Cs and their daughter activities are still being studied at SOLIS, SOLAR, OSTIS and the ISOL facilities at Mainz and McGill. Although these studies are not complete (some of the studies have only recently begun), it is clear that investigations of these nuclei at TRISTAN II could not constitute the major thrust of the research program.

The direct ISOL facilities JOSEF and LOHENGRIN must also be considered as possible competitors. In addition to the direct fission-product and microsecond-isomer studies for which these two facilities have no competitors, nuclear spectroscopic studies have been made, but the main concentrations have not been in the nuclide regions of Fig. 12.

At JOSEF, the major concentration in nuclear spectroscopy has been in the nuclear shape-transition region around mass 100, involving primarily Sr, Y and Zr nuclei.[26] At LOHENGRIN, nuclear spectroscopic studies have concentrated in two regions -- near mass 150 (Cs, Ba, La, Ce, Pr) and near mass 100 (Rb, Sr, Y, Zr, Nb),[31] with the later studies often done in coordination with JOSEF.

The SIRIUS facility at Strasbourg could also be considered as a possible future competitor. Although SIRIUS is presently an operating facility, the thrust has mainly been in improving the interconnection of the helium jet and ion source. Identification of the isotopes available and determination of overall efficiencies have been initiated only recently. The goal of the project is to establish a facility for on-line studies of the lanthanide fission products, for which there would be little competition. Thus the emphasis in the research program, which is only beginning to be established, should not involve the nuclides of Fig. 12.

The OSIRIS facility at Studsvik separates the same fission-product elements as TRISTAN II, as the mass scans in Fig. 10 show. An excellent review of the OSIRIS facility and the experimental program was recently given by Rudstam.[24] More than half of the research program has been devoted to systematic studies such as beta decay properties, total decay energies, delayed neutron properties, and independent fission yields. As a consequence, detailed spectroscopic studies have constituted only a relatively minor part of the research program. Of the spectroscopic studies at OSIRIS, the light fission products have nearly been neglected, with one joint experiment (JOSEF, LOHENCRIN and OSIRIS)

published. Several spectroscopic studies of the heavy fission products have been made in the region near Z=50, extending up to doubly magic ^{132}Sn. (See Ref. 24 for the list of reports on nuclear spectroscopic studies at OSIRIS.) In addition to continuing the present projects, future plans at OSIRIS involve projects to expand the range of elements processed. Even if the number of elements available at OSIRIS does not expand, with the elements now available at OSIRIS (and TRISTAN II), to quote Rudstam in Ref. 24, "The field is still far from being fully explored, and we forsee a long period of fruitful research."

From the preceding brief discussion of areas of concentration at other ISOL facilities engaged in the study of fission products, it should be clear that the nuclide regions shown in Fig. 12 are the regions in which TRISTAN II would have minimal competition. This statement is particularly true for nuclear spectroscopic studies, as only a minor part of the research program at OSIRIS has involved studies in this region. Although such studies in the nuclide regions of Fig. 12 have been shown to have minimal competition, the question of whether these nuclei are worth studying should be addressed.

For the light fission-product region of Fig. 12, the nuclear structures of the nuclei near the N=50 shell could be systematically explored. Although the nucleus ^{78}Ni, which is expected to be doubly magic, is beyond reach, nuclei with a few particles or holes relative to a ^{78}Ni core could be studied. For the N=50 isotones, proton particle states could be explored in nuclei with three or more protons beyond the Z=28 shell, i.e. ^{81}Ga, ^{82}Ge, ^{83}As, etc. Neutron hole states in the N=50 shell and neutron particle states beyond N=50 could be studied in

odd-A nuclei of Ge and Se. The behavior of collective states in even-even nuclei on either side of the N=50 shell could be systematically studied. For the low-lying levels in even-even Ge, Se and Kr nuclei, the trends near N=50 would reveal whether the closed shells at N=50 and Z=28 affect the level spacings in the same manner as closed shells do nearer stability. Nuclear structure studies in the light fission-product region of Fig. 12 would allow our knowledge of the structure of nuclei around the N=50 and Z=28 shells, which was obtained near stability, to be extended towards ^{78}Ni. This could thus shed light on the unanswered question of whether these magic numbers remain magic as ^{78}Ni is approached.

For the heavy fission-product region of Fig. 12, both the Z=50 shell, N=82 shell and doubly magic ^{132}Sn regions could be systematically studied. The nuclei near ^{132}Sn are especially interesting. As Fig. 12 indicates, activities should be sufficient to study level structures of the single neutron-hole nucleus ^{131}Sn and the single proton nucleus ^{133}Sb through the decays of ^{131}In and ^{133}Sn, respectively. It might also be possible to study levels in both ^{132}Sn and ^{133}Sn through the decays of ^{132}In and ^{133}In, respectively, if the activities realized are not too far below the upper-limit estimations of Fig. 12. The proton-hole nucleus ^{131}In, however, seems to be beyond reach through the decay of ^{131}Cd. In terms of "valence" nucleons or nucleon holes relative to ^{132}Sn, possible studies could involve the following nuclei: valence-0 ^{132}Sn, 2 or 3 of the 4 valence-1 nuclei, 4 or 5 of the 8 valence-2 nuclei, 6 or 7 of the 12 valence-3 nuclei, 8 or 9 of the 16 valence-4 nuclei, etc. Thus at least half of the low-valence nuclei near ^{132}Sn

could be systematically studied with TRISTAN II at the HFBR. Of the 21-25 nuclei listed above as possible, some nuclear structure information exists, particularly for the proton-particle neutron-hole nuclei nearer stability. As ^{132}Sn is approached, the information becomes more scarce, with most of the existing information coming from studies at OSIRIS. Comprehensive studies have not been made for the large majority of these nuclei. TRISTAN II and OSIRIS both have the opportunity to make substantial contributions to our knowledge of nuclear structure in this especially interesting region.

In addition to shell-model oriented studies in the heavy fission-product region of Fig. 12, collective properties of even-even nuclei could also be explored with TRISTAN II. Even-even isotopes of Cd, Sn, Te and Xe, whose expected activities can be obtained from Fig. 12, could be studied. Also, even-even Ba and Ce isotopes would be available. A large number of these nuclei have not yet been studied in sufficient detail to provide the information needed to test the collective models. In addition to the behavior of collective states as the two shells Z=50 and N=82 are approached, trends in collective behavior as the nuclei approach the nuclear shape-transition regions below the Z=50 shell and above the N=82 shell could be systematically mapped.

In the preceding discussion of interesting studies to be made with TRISTAN II for the nuclide regions of Fig. 12, the emphasis was directed towards nuclear structure studies. In addition to the nuclear spectroscopic and atomic spectroscopic measurements required to obtain the nuclear structure information outlined above, many other interesting studies would clearly be possible for the nuclei in Fig. 12, as a glance

at the possible studies in Table 4 shows. Although the other types of studies could also be discussed in some detail, the preceding limited discussion is sufficient to indicate the large number of interesting studies of the nuclei far from stability that would be possible with TRISTAN II at the HFBR.

VI. ACKNOWLEDGEMENTS

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Certainly the most important acknowledgements to make are to those who brought TRISTAN II from conception into production at Ames. Gusta Rudstam and his team at OSIRIS provided us with all the information we requested, thus assisting indirectly in the design of our in-beam ion

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