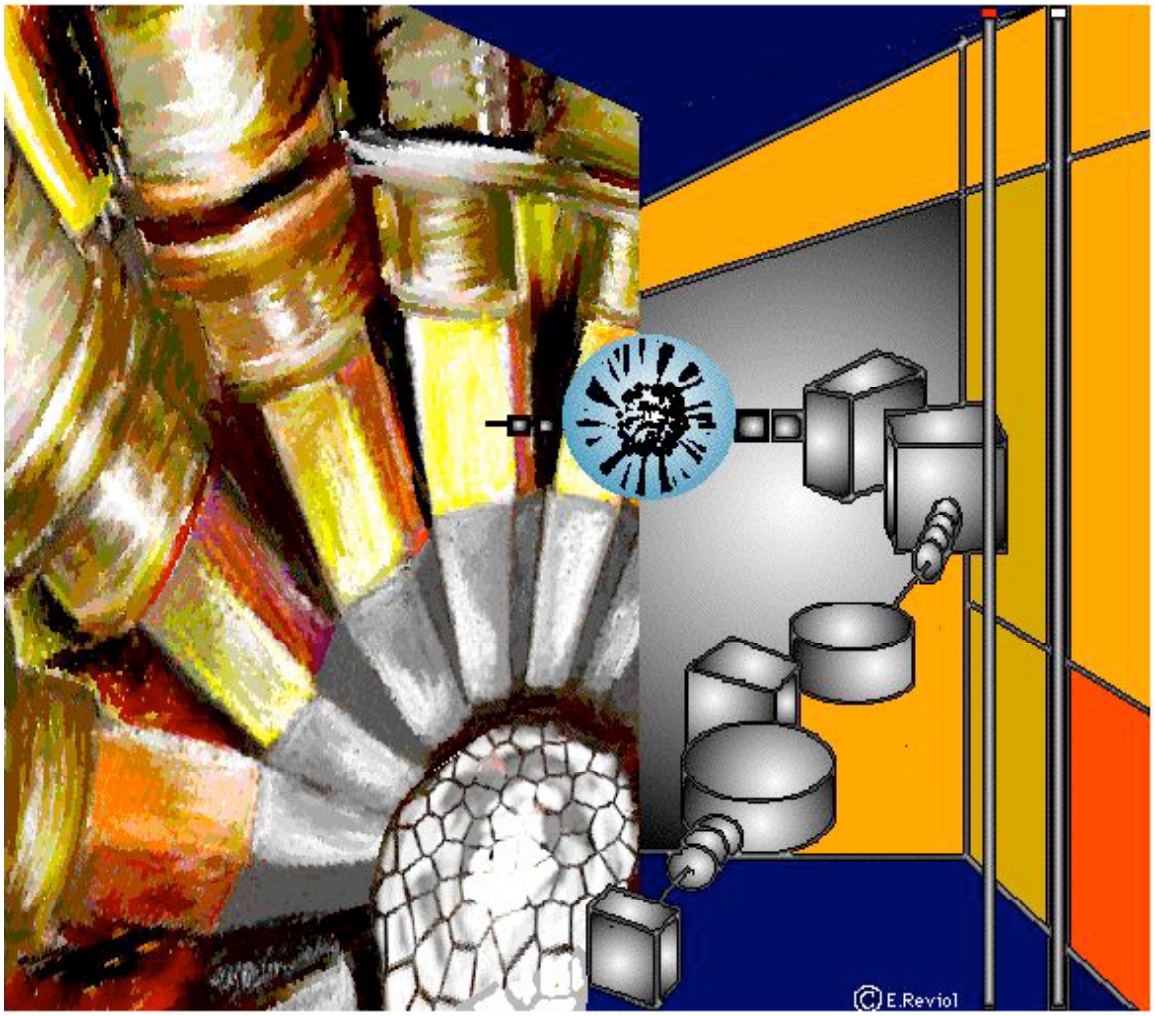
Experimental Program
for an
Advanced ISOL Facility



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Executive Summary

This report summarizes the proceedings and recommendations of the Workshop on the Experimental Equipment for an Advanced ISOL Facility which was held at Lawrence Berkeley National Laboratory on July 22-25, 1998. The purpose of this workshop was to discuss the performance requirements, manpower and cost estimates, as well as a schedule of the experimental equipment needed to fully exploit the new physics which can be studied at an advanced ISOL facility. An overview of the new physics opportunities that would be provided by such a facility has been presented in the White Paper that was issued following the Columbus Meeting. The reactions and experimental techniques discussed in the Columbus White Paper served as a guideline for the formulation of the detector needs at the Berkeley Workshop.

The program of the workshop, which attracted nearly 100 participants, consisted of plenary overview talks followed by shorter technical presentations, as well as parallel sessions of six Working Groups. A Slide Report [1] of the Workshop has been distributed among all the participants. This Slide Report and summaries of the recommendations of the Working Groups, which were prepared by the conveners, served as a basis for the present report.

The Working Groups addressed the detector needs in the following six areas:

- Gamma-ray detectors
- Recoil Separators
- Magnetic Spectrographs
- Particle Detectors
- Targets
- Apparatus for Experiments with Non-accelerated Beams

These Working Groups were charged with the task of specifying the detector needs at the startup of the facility, and identifying the advanced detector systems which require R&D effort before their full capabilities may be realized. They were, furthermore, asked to provide technical specifications, costs, schedule, and the manpower needs for both the R&D and construction phases of these projects. A summary of these recommendations is provided in Table 1 below. The total cost of these detectors is about $40M. This figure represents a preliminary estimate based on the existing devices, and does not include contingency and inflation factors.

[1] Proceedings of the Workshop on the Experimental Equipment for an Advanced ISOL Facility (LBNL-42138), Ed. I-Yang Lee.

To provide further details of the designs, performance characteristics, and the physical sizes of the prototypes of many of these detectors, a listing of the URL links to several laboratories in the U.S. and abroad is given in Appendix A.

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The Editors would like to express their appreciation to Edda Reviol for her artwork that appears on the front page of this report.

Table 1: Phase I: Detector Summary (cost in FY98 dollars)

Instrument	R&D			construction		
	FTE	years	cost [M$]	FTE	years	cost [M$]
Gamma-Ray Detectors						
class 1 (CLOVER)				1	1	2.2
class 2 (TRACKING)	8	2	2.5	8	4	20
Recoil Separators						
Low Energy				2	2	3
High Energy				2	2	3.5
Gas-Filled Separator				2	2	1.5
Magnetic Spectrograph						
Conventional Spectrograph				2	2	3
Large Accept. Spectrograph	2	1				
Particle Detectors						
light charged-particle–CsI				1	1	0.25
light charged-particle–Si	2	2	2.0	1	2	0.5
neutron				1	1	0.5
Non-Accelerated Beams						
laser atom trap				4	3	1.1
ion trap				10	2	1.34
nuclear orientation				2	1.5	0.47
beta–NMR				3	1.5	0.36
decay spectroscopy				5	2	0.95
electron-beam ion trap				2	2	0.45
Special Targets						
gas				1	1	0.5
radioactive targets				2	2	0.5
TOTAL	12	–	4.5	49	–	40.12

1. Introduction

The 1996 Long Range Plan for Nuclear Physics prepared by the Nuclear Science Advisory Committee (NSAC) for the DOE and NSF, recommended the construction of a next generation ISOL (Isotope Separation On-Line) facility in the U.S. In the summer of 1997 a workshop was held at Columbus, Ohio, to discuss the new science opportunities that will be provided by such a facility. The results of this workshop are summarized in the 1997 White Paper "Scientific Opportunities with an Advanced ISOL Facility." As outlined in this report a new ISOL facility with intense, high-quality beams of radioactive nuclei would provide exciting new research opportunities in several areas:

- **The Nature of Nucleonic Matter**
- **The Origin of the Elements**
- **Tests of the Standard Model**

¿From the discussions presented in the White Paper it is clear that experiments addressing questions at this new frontier require not only high-quality beams of short-lived nuclei but also detector systems with high-efficiencies, high selectivity and high-resolutions, since in many cases these exotic beams will have rather low intensities. Only with such powerful detectors can the experiments at an advanced ISOL facility fully exploit the many new opportunities in nuclear physics, nuclear astrophysics and in related fields.

To discuss the experimental equipment needed at an advanced ISOL facility, a workshop was held at Lawrence Berkeley Laboratory on July 22-25, 1998. This workshop attracted nearly 100 participants from the U.S., Europe and Japan. In 25 talks the requirements on several detector systems ranging from ion and atom traps to high acceptance magnetic spectrographs were discussed. This report summarizes the Berkeley workshop and makes a first attempt at defining the detector systems needed:

- Experiments with non-accelerated radioactive beams will explore fundamental symmetries (such as the atomic parity non-conservation in francium atoms), the decay properties of nuclides near the astrophysical rp and r-process paths, and the possible modifications to the shell structure in exotic nuclei through mass measurements and the determination of ground state nuclear moments. The instruments needed to perform these experiments include: atom and ion traps, detectors for decay spectroscopy studies, a low-temperature nuclear orientation facility, and a β-NMR apparatus.

- Nuclear astrophysics experiments with short-lived radioactive beams will enhance studies of nuclear reactions which occur in astrophysical environments such as binary systems (e.g., novae and X-ray bursts) and supernovae. It is in these systems –quiescent stars and in stellar explosions– where the heavier elements, including carbon and oxygen which

form the basis of life, are formed through a series of nuclear reactions. These studies, with beams in the energy range E=0.1-10 MeV/u, require a variety of high-efficiency detection systems, such as recoil separators and high-granularity particle/gamma arrays, to often measure small reaction cross sections in the presence of an unacceptably large background from the radioactive ion beams. For neutron-rich nuclei, the combination of these cross sections and mass and half-lives measured in traps will greatly enhance our understanding of, for example, the reaction path for formation of elements in supernova explosions.

- Exploring the structure of nuclei in experiments with radioactive ions would allow us to constraint the isospin-dependent terms in the effective interactions for nuclei far from stability. There are indications that the familiar shell structure, which has been very successful in explaining the nuclear properties close to the valley of stability, might be altered as the neutron drip line is approached. Reactions with neutron-rich exotic nuclei might also be a new way to produce and explore very heavy nuclei which are inaccessible with present-day techniques. To perform these nuclear structure studies, a whole spectrum of experimental equipment, each optimized for a specific task, is required. The weakening of the shell structure can be studied through high-resolution mass measurements in ion traps, through measurements of electromagnetic transition matrix elements via Coulomb excitation and high efficiency gamma detector arrays, or through measurements of spectroscopic factors in nucleon transfer reactions using a magnetic spectrograph or a high efficiency Si detector array. Studies of exotic nuclei at the limits of stability require high acceptance recoil mass separators in coincidence with other high efficiency detectors such as gamma or particle arrays to separate and cleanly identify the precious few particles of interest in the presence of a strong primary beam.

The opportunities for advancing our knowledge of the nucleus with beams from an advanced ISOL facility are very compelling. At the Berkeley workshop several working groups were formed with the goal to discuss and define the necessary experimental apparatus, including

- Gamma-ray detectors
- Recoil Separators
- Magnetic Spectrographs
- Particle Detectors
- Targets
- Apparatus for Experiments with Non-accelerated Beams

The reports of these working groups formed the basis of this Report which was prepared by the organizers of the workshop in close collaboration with the conveners of the Working Groups.

Detection systems needed to address the various areas of research as mentioned in the Columbus White Paper are summarized in Table 2.

As outlined in the White Paper, the beam intensities available at a next generation ISOL facility will span a much larger range compared to those of stable beams. While ion beams of certain nuclei near the valley of stability will be produced with intensities of 10^{10}-10^{11} particles/sec, more exotic nuclei located at the limits of stability will be available only with rates of 1-10 particles/sec or less. In addition many of the reactions will be studied in "inverse kinematics", i.e. bombarding a lighter target with a heavier (radioactive) beam. In some cases the beams will also have contaminants from other isobars which are produced with higher yields and can not be completely removed with a high resolution mass separator. The decay of the scattered radioactive beam particles will produce a high background counting rate in particle and gamma-ray detectors.

For these reasons the experimental equipment at a next generation ISOL facility has to fulfill additional requirements. For experiments with low-intensity beams, high efficiency detector systems covering a large fraction of the full solid angle are needed. The inverse kinematics in many of the experiments calls for high granularity detectors to compensate for the large kinematic or Doppler shifts. In order to select a particular reaction of interest in experiments with beams consisting of several isobars, coincident detection of the outgoing particles with good mass and Z identification is required. To handle the high background rate, segmented detector systems are needed.

Some of these experiments and developments have already started at the existing facilities. However, considerable improvement of the detection systems is needed in order to fully exploit the opportunities available at the advanced ISOL facility. In many cases the development and design of these novel detector systems has to start in the near future so that the new devices will be ready for use when first beams from the facility become available. The requirements and designs of various detector systems are discussed in more detail below.

Table 2: Physics topics and required experimental equipment from the 1997 ISOL White Paper

	Physics Topics	Reactions	gamma ray detection	magnetic spectro-graphs and separators	particle detectors	traps etc.	special targets
1.	rapid proton capture (rp process)	transfer, elastic, inelastic, radiative capture, Coulomb dissociation	x	x	x		x
2.	reactions/studies of N=Z nuclei, symmetry studies	transfer, fusion, decay studies	x	x	x	x	
3.	decay studies of ^{100}Sn	decay	x	x	x	x	
4.	proton drip-line studies	decay, fusion, transfer	x	x	x		
5.	slow neutron capture (s-process)	capture	x				x
6.	symmetry studies with francium	decays, traps				x	
7.	heavy element studies	fusion, decay	x	x	x	x	
8.	fission limits	fusion-fission	x	x	x		
9.	rapid neutron capture	capture, decay, mass measurement	x	x	x	x	
10.	nuclei with large neutron excess	fusion, transfer, deep inelastic	x	x	x		
11.	single-particle states, effective nucleon-nucleon interactions	direct reactions, nucleon transfer	x	x	x		x
12.	shell structure, weakening of gaps, spin-orbit potential	mass measurement, Coulomb excitation, fusion, nucleon transfer, deep inelastic	x	x	x	x	
13.	(near) neutron-drip-line studies, halo nuclei	mass measurement, nucleon transfer	x	x	x	x	

2. Gamma-ray Detectors

2.1 Physics Requirements

Just as the study of photon emission played the central experimental role in the unraveling of atomic structure many decades ago, the detection of gamma-ray emission from excited states in nuclei plays a vital and ubiquitous role in nuclear science experiments today. This will most certainly continue to be true at the Advanced ISOL Facility where, after going through so much effort to create rare and exotic nuclear species, it makes sense to have the best and most efficient detection system(s) to catch their "precious gamma-ray signals". It is therefore extremely exciting that, at the time when new and important research opportunities appear at the Advanced ISOL Facility, revolutionary breakthroughs in gamma-ray detector technology seem possible.

2.2 Instruments Needed at the Start up

The working group identified two classes of gamma-ray instrument needs to conduct research at the start up of the new facility.

CLASS 1: A number (∼10-15) of gamma-ray detectors are needed for a wide variety of uses such as deployment at the focal plane of recoil separators, or for magnetic moment measurements. These detectors should be easily movable from one location to another and be flexible enough to be arranged in different configurations. Initially these requirements can be satisfied by using the existing detector systems, such as the segmented CLOVERs currently in use at ORNL, in order to extract significant new physics. However, the second generation of these experiments will certainly benefit from the use of the new type (Class 2) of gamma-ray detectors which are discussed below.

CLASS 2: GAMMASPHERE is an enormously powerful device which, with modest upgrades, will be a state-of-the-art tool for many years to come. To build a spectrometer which has significantly enhanced performance beyond GAMMASPHERE requires the development of new detector, analysis and sorting technologies. It is important that we explore these R&D issues so that we are positioned to build an optimum detector for an ISOL facility. The design requirements for a "next generation" detector include:

(i) High peak-to-total ratio and energy resolution,

(ii) High counting rate capability (there will always be a high background from the radioactive beams),

(iii) High photopeak efficiency for both low and high gamma multiplicity events (because of the low cross-sections and variety of reactions),

(iv) High granularity (because many experiments will involve high recoil velocities. A high granularity will also help to improve the count rate capability),

(v) Modular design for flexibility and portability,

(vi) Compatibility with other auxiliary detector devices, such as a 4π charged particle detector placed inside its cavity (because many experiments require very high selectivity), and

(vii) Capability to provide total gamma-ray energy and multiplicity on an event-by-event basis.

It seems that for the foreseeable future there is no real alternative to using high purity germanium (HpGe) as the basic detector material. However, an entirely new concept of tracking detector array based on highly segmented Ge crystals could provide an enormous performance improvement over the current generation of detector arrays. Such a 4π shell of germanium would be significantly more efficient than the GAMMASPHERE, as the BGO suppression shields can be discarded. The full gamma-ray energy is obtained by summing the interactions belonging to that gamma-ray, identified using the energy-angle relationship given by the Compton scattering formula. High granularity is crucial for many experiments, especially at an ISOL facility where gamma-rays from fast-moving radioactive beams will need precise Doppler corrections. The granularity also distributes the count rate to many individual channels, resulting in a faster counting system. Further, the granularity allows linear polarization to be measured on an event-by-event basis.

Design Options

Since the Class 1 detectors which use existing technology are already available, the discussion below will concentrate on the new Class 2 energy-tracking detector systems. To date a working tracking system has not yet been achieved. However, several possibilities are being aggressively pursued. One concept, called GRETA (Gamma-Ray Energy Tracking Array) builds on the Gammasphere concept of segmentation of large HpGe crystals. About 60 of the present Gammasphere detectors have two-electrode segmentation, an innovation at that time. One possible GRETA design would have a 4π shell of about 100 large HpGe crystals, with a diameter of 7 cm and a length of 8 cm, each with 36-way segmentation. Another concept, called GARBO (GAmma-Ray BOx), using stacks of large-area highly-segmented planar germanium crystals, involves very different technical challenges but may be extremely powerful, especially for low energy gamma-ray spectroscopy.

In the last three years, R&D efforts have been carried out to achieve the "proof of principle" of tracking detector. A 12-segment GRETA prototype detector has been produced and tested. Recently, a 36-segment detector has also been produced. Preliminary studies of the induced signals have demonstrated that a resolution in the range of 2-3 mm is possible. Tracking algorithms have been developed and tracking efficiency has been studied as functions of gamma-ray

energy, multiplicity and position resolution. Simulation studies have also been carried out for the GARBO detector. A prototype detector for the latter has been ordered.

Over the next several years, much research and development is required to bring this promising new technology to fruition. Many questions such as the best packing scheme for the segmented detector, the response of the detectors to neutron damage, and the ultimate efficiency of gamma-ray tracking need to be answered. For the planar design, the problems of edge effects and cooling of the detectors need to be solved. Although the U.S. has presently the lead in the R&D of the tracking technology, the European gamma-ray community has enthusiastically taken up the idea of building a Ge shell based on the concept of tracking and has already put significant money and manpower into investigating this technology. We will make efforts to follow the European development in this area, but we cannot afford to fall behind and let our lead in this field disappear. We must therefore continue to devote considerable effort to advance this technology.

Performance

In all important performance categories the new designs outperform GAMMASPHERE significantly.

Characteristic	Tracking Array	GAMMASPHERE
efficiency* at 0.1 MeV	70%	10%
efficiency* at 1 MeV	54%	10%
efficiency** at 1 MeV	30%	8%
efficiency* at 15 MeV	25%	1%
Peak/Total at 1 MeV	85%	60%
position resolution	$\sim$ 2mm	$\sim$ 20mm
radius of target chamber	12cm	18cm
max. count rate (per crystal)	$\sim$ 300 kHz	$\sim$ 10 kHz

*efficiency for events with gamma multiplicity of 1.
**efficiency for events with gamma multiplicity of 25. (Tracking efficiency based on simulation)

This new generation of energy-tracking detector array with its dramatic advantages in performances and its versatility offers an exciting opportunity for the U.S. nuclear science community. These detector systems are not only well suited for gamma-ray work at the Advanced ISOL Facility but they are also the detector of choice for future gamma-ray studies at the existing stable beam facilities. Thus, by building one optimal system the needs of two large communities can be satisfied allowing them both to pursue world-leading scientific research. The mobility of the GAMMASPHERE has already been demonstrated and has shown to be of enormous

benefit scientifically. The same will be true of an energy-tracking array which, due to its smaller physical size compared to the GAMMASPHERE, will be even easier to move. In addition, the modularity of the basic Class 2 detector designs bodes well for their compatibility to other auxiliary detectors.

Cost and Schedule

The necessary Class 1 type detectors (see above) have already been purchased (at a cost of $2M). The cost of a next-generation tracking array is presently estimated to be about $20M. Considering their huge gains in sensitivity, they are extremely cost effective devices and will satisfy a large user base. This means that the cost of these new major gamma-ray detector systems may be shared by a broad physics community and does not have to come solely from the ISOL instrumentation budget.

The next 2-3 years are a crucial time for the R&D in this exciting new field of energy-tracking gamma-ray detector systems . Much work needs to be done to investigate the relative advantages of the different approaches. Results obtained so far confirm the expected gains for these new designs over existing systems. In terms of the manpower, the above R&D tasks require four post-doctoral associates over the next 3 years, in addition to the permanent staff who are already engaged in related activities at various laboratories. The community is optimistic that, given the necessary support, the R&D, design and construction work can be finished prior to the first beams from the Advanced ISOL Facility.

Data Acquisition and Analysis Needs

The data acquisition requirements of the standard Class 1 gamma-ray detectors poses no extra needs beyond present capabilities. The Class 2 energy-tracking gamma-ray detectors, however, require the development of new methods for data acquisition and analysis. Tracking needs the position of the interaction points in three dimensions, obtained from a detailed analysis of the shape of the pulses. This, in turn, requires preamplifiers with faster rise time and digital processing of pulse shapes. Digital processing provides the additional benefit of allowing higher count rate. Currently, intensive R&D work is being carried out and prototype electronics have already been constructed. However, further developments in miniaturization and cost reduction are needed. Field tests of this new approach with the GAMMASPHERE will be performed. This digital approach, when developed, can be used to improve the performance of other detector systems as well. On-line processing of peak shapes and tracking require developments of efficient algorithms and optimal computer connection. In terms of off-line data analysis, the work which is being carried out on new techniques of high-coincidence-fold data analysis indicate that the currently available computer power is adequate.

2.3 Future Gamma-Ray Detector Instrumentation

While LN_2 cooled hyper-pure Ge detectors used in novel configurations are expected to remain the preferred choice for high-resolution gamma-ray spectroscopy for the next decade, developments in other gamma-ray detection technologies should not be neglected. Radiation detectors based on wide band-gap semiconductors such as HgI_2 and CdZnTe, which can be operated at room temperatures have been under intensive development recently. For example, lattice imperfection problems in CdTe crystals have been greatly reduced by alloying it with ZnTe. Also new electrode configurations have been developed to improve the poor charge transport properties of these compound semiconductors. Resolutions as good as 2-4% (at 662 keV) have already been achieved; however, these values are still an order of magnitude lower than what can be obtained routinely with Ge detectors. In addition, there are still problems with growing crystals larger than a few cm^3.

Liquid and compressed rare gases, such as Xe and Ar, as media for the detection of gamma-rays have been studied for nearly 50 years. While such detectors have found applications in particle and astrophysics, the energy resolution obtained cannot compete with Ge. Much effort is currently being placed in the development of liquid Xe time projection chamber technology as a technique to improve the imaging capabilities for experimental gamma-ray astrophysics. Simulations have begun with the aim of deducing the complex histories of gamma-ray interactions and scatterings in the detector volume to within a resolution of $\sim$1mm. Such techniques clearly have an overlap with the new generation of Ge energy-tracking detector system(s) discussed above.

One of the major problems that is often encountered is the task of identifying weakly-produced reaction products by their atomic numbers. This is perhaps best accomplished by detection of their characteristic X-rays. However, to achieve the high energy resolution required to distinguish neighboring elements, we need to cool down the present detectors to liquid nitrogen temperatures. This requirement not only adds to the cost of these detectors, but also prevents deployment of a large number of them in 4π gamma arrays or in confined spaces. Development of new X-ray detectors that can provide adequate energy resolution at nearly room temperatures is, therefore, highly desirable. Several small companies are working to solve this problem and some of their proposed solutions (e.g., Si drift X-ray detectors) are very promising. Further effort is needed to build large-area detectors that may be used in a pixelated X-ray detector array.

3. Recoil Separators

3.1 Physics Requirements

Recoil spectrometers have played a crucial role in many nuclear structure and reaction experiments performed during the last few years: The nearly background-free identification of rare processes (e.g., the production of superheavy nuclei, the study of nuclei which decay via proton emission), or experiments elucidating the structure of drip-line nuclei would have been impossible without these highly selective devices, which can quickly (in a few μs) separate the nuclei of interest from the intense direct beam. There will be an even greater need for these spectrometers at a future ISOL facility, since many of the reactions with radioactive beams will be studied in inverse kinematics (i.e., using a heavy beam incident on a light target), where the separation of the recoil products from the incident beam is more difficult. A great number of the different research areas outlined in the Columbus White Paper requires these highly selective recoil separators. Examples of experiments which require a clean identification of the mass and nuclear charge in the presence of a large background of primary beam particles are:

- Studies of nuclei produced via the rapid proton capture (rp) process,
- Studies of N=Z nuclides up to the doubly magic nucleus ^{100}Sn,
- Studies of the dripline nuclei,
- Production of exotic heavy nuclei.

In a recoil mass separator, the reaction products of interest (and particularly those with the smallest production cross-section) may be separated in mass using ion-optical spatial separation at the focal plane. The mass-separated products may be further identified by measurements of their total energy, energy loss and time-of-flight using a variety of detectors. These detectors may include ionization counters, silicon strip detectors, and microchannel plates. Alternatively, a moving tape transport device in conjunction with other auxiliary detectors such as beta, gamma, and X-ray counters may be used for this purpose.

An ideal recoil separator will have large acceptances in angle, energy, and mass-to-charge ratio. It will reject all primary beam and unwanted reaction channels with excellent mass resolution. It must be of compact design, yet flexible to accommodate many different auxiliary detectors which further enhance channel selection. Many of these detectors will have full 4π solid angle coverage and will be used at the target position or at the focal plane of the recoil separator. Therefore, the separator must be able to operate in different modes or configurations, each optimized for a particular type of experiment.

The ion-optics which governs the properties of these spectrometers prevents the construction of just one ideal spectrometer with superior performance for *all* types of reactions. Furthermore,

from the experience obtained with radioactive beam experiments performed with present-day technologies it has become clear that the technical difficulties associated with these measurements are unique. We, therefore, recommend the construction of three different recoil spectrometers each optimized for specific types of experiments. An alternative would be the modification and upgrade of one or more of the existing separators.

There are two classes of spectrometers which are presently in use at various laboratories throughout the world:

- high resolution spectrometers, which have both good mass resolution ($\frac{M}{\Delta M} \geq 300$), and adequate energy ($\pm 15\%$), angular ($\pm 2°$), and mass-to-charge ($\pm 4\%$) acceptances, or
- gas-filled separators which typically have inferior mass resolutions ($\frac{M}{\Delta M} \leq 50$), but have larger momentum ($\pm 25\%$) and angular ($\pm 5°$) acceptances.

In the following, the requirements of three recoil spectrometers for reaction studies in nuclear astrophysics, for studies of drip-line nuclei, and for the production of very heavy nuclei will be discussed.

3.2 Low-Energy (Astrophysical) Experiments

Since experiments in nuclear astrophysics will likely constitute a considerable fraction of the research program at a future ISOL facility, a dedicated low-energy experimental area (E $\leq$ 2 MeV/u) is planned. Because the distances between the accelerator and this target area are small and no additional stripping is involved, this area will have the highest beam intensities which is essential since the cross sections for many of these processes (e.g., proton or α capture reactions) are very small.

The extreme inverse kinematics of capture reactions with heavy ion beams incident on hydrogen or helium targets (the opening angles are typically less than a couple of degrees), combined with their low cross sections ($\sim \mu$barns) and the similarity of the beam and the recoil momentum (differing only by a few percent), makes these reactions very difficult to measure. However, because of the strong forward-focussing of the recoils, a high collection efficiency is possible.

In addition to the arguments given above there are other reasons for a dedicated astrophysics recoil separator. This device will utilize specialized and complicated equipment at the target area (e.g. gas targets) that are incompatible with the standard equipment like gamma detector arrays and charged particle detectors required at the target areas of other recoil separators. A dedicated separator can be more readily optimized with respect to the detector systems, ion-optic tunes, and slit placement for the highest suppression of scattered beam particles.

The specifications for such an Astrophysics Recoil Separator are as follows:

- High transport efficiency for a relatively small solid angle: Approximately 100% transmission per charge state of the recoils is desired. This requires good vacuum throughout the whole spectrometer.
- High beam purification: Beam rejection of 1x10^{-12} (hopefully 1x10^{-15}) by the ion optics of the separator alone for proton capture reactions over a broad mass range of beams.
- Relatively low mass resolution is required ($\frac{M}{\Delta M} \leq 200$).
- A target chamber capable of accommodating a variety of detector arrays of Si (or other) detectors for (p, p), (p, α), etc. measurements.
- The ability to accommodate gas targets (both jets and gas cell targets).
- The capability of running with different ion optical modes for reactions with different kinematics.
- Careful handling of the beam upstream of the separator is required (e.g., clean beam with small dispersion, no halos etc.)

The cost of such a device is estimated to be approximately $3M (including a set of first generation particle detectors but excluding the gas target), based on the costs of the DRAGON Separator which is presently under construction at TRIUMF.

3.3 Experiments at Higher Energies

The large number of experiments utilizing the currently available recoil separators (e.g., at ANL or ORNL) are an indication of the versatility of these devices in many areas of nuclear physics. Especially with new auxiliary detectors, mounted either around the target or in the focal plane area, new insight into the structure of nuclei away from the valley of β stability have been obtained. Based on the experience gained with today's separators a next generation device should meet the following requirements:

- The mass resolution should be better than $\frac{M}{\Delta M} \approx 350$.
- The primary beam hitting the electrodes of the electric dipoles has been shown to be a strong source of scattered beam particles. Installation of a split electrode as has been done for RMS at JAERI or the addition of a momentum separator before the recoil separator as done at the RMS of ORNL greatly reduces this source of background.
- A further background reduction might be possible by using a different ion-optical arrangement, such as a symmetrical arrangement of two recoil separators operated back-to-back (QQED-DEQQ) with an intermediate cross-over between the two magnets. This

intermediate cross-over can be helpful in more than one way. It allows the installation of collimators for background suppression or passive absorbers for differentially slowing down particles with the same m/q but different nuclear charge Z. It might be possible to use an RF resonator in this intermediate focal plane area in order to remove scattered beam particles from the particles of interest by using the pulsed structure of the beam.

- The target and focal plane area should allow the installation of a variety of auxiliary detectors without loss of detection efficiency. Near 4π-coverage at the target and focal plane areas should be possible.

Based on the numbers available from the present operating recoil separators, the cost of a third generation recoil spectrometer is estimated to be nearly $3.5M.

3.4 Experiment Using Gas-filled Magnetic Spectrometers

The use of radioactive ion beams provides an opportunity to considerably broaden our knowledge of exotic heavy nuclei whose existence is due to the quantal shell effects. Experiments with stable beams have given some information about the magnitude of the production yields. Using high-efficiency detection techniques, cross sections down to the picobarn range have been measured.

Experiments with radioactive beams will open completely new regions of the nuclide chart for nuclear structure studies which can not be reached with stable beams. In addition there is the prospect of higher production yields for these heavy exotic nuclei by the use of neutron-rich ion beams. For the study of these low cross section reactions a recoil spectrometer based on the gas-filled magnet (GFM) technique is a viable alternative. While the mass resolution of a GFM is inferior to that of the vacuum devices discussed above, it can very effectively transport the particles of interest, independent of their charge states, to auxiliary detectors (e.g., Si or Ge detector arrays) which would provides the necessary mass information. Other auxiliary devices, such as Penning traps, may also be used at the focal plane to obtain accurate mass information. The large acceptance angle of gas-filled separators requires the close proximity of the target to the first focussing element. This, unfortunately, severely limits the use of auxiliary detectors (such as a Ge detector array or a silicon ball) at the target position .

In principle a gas-filled magnetic spectrometer could be combined with the large acceptance spectrograph discussed in the following section. However, the need for possibly locating a Penning trap in the focal plane makes this combination cumbersome to use. For this reason, and since such a spectrometer can be built with a recycled magnet, it is recommended to have a dedicated gas-filled recoil separator at the new ISOL facility.

The cost estimate for a gas-filled magnetic separator without the focal plane detection system is around $ 1.5M.

4. Magnetic Spectrographs

4.1 Physics Requirements

The high energy resolution achievable with magnetic spectrometers have made these devices important tools for nuclear structure studies with beams of stable particles. Good energy resolution even for systems exhibiting a large kinematic shift will also be a crucial factor for many experiments performed at a future radioactive beam facility. From the 13 regions of the chart of the nuclides listed in the White Paper from the Columbus Workshop, magnetic spectrographs will likely play an important role in at least 7 areas.

There is a close relationship between magnetic spectrographs and recoil separators and, therefore, the question needs to be discussed whether a single device can be designed to operate in more than one mode. For example, a standard magnetic spectrograph can be operated also as a gas-filled recoil separator. The crucial issue is whether such a multi-mode instrument can be highly optimized for both modes, or whether compromises in specifications deteriorate the performance in actual experiments. As discussed in Section 3, it appears unlikely that a combined magnetic spectrograph/gas-filled recoil separator system can be developed without making serious compromises in the performance of the device.

The general types of magnetic spectrographs discussed at the Workshop fall into two distinct categories. One class consists of conventional magnetic spectrographs in which the momentum and possibly scattering angle measurements are made via position-sensitive detectors in the focal plane. The other class comprises very large acceptance devices, with solid angles on the order of steradians, in which the particle energies are usually measured via silicon detectors in the focal plane. The first type generally has better energy resolution, but lower solid angles, than the second type. Designs of both types, in the context of specific benchmark experiments, will have to be investigated in detail to determine what range of reaction kinematics, etc. are better suited to one or the other.

It was the general opinion of the Working Group that an advanced-design, conventional spectrograph should be included in the initial complement of equipment at the new facility. Large acceptance devices, such as solenoids or toroids require much more study and discussion to determine their relative value to the scientific program.

There are currently three proposals for the design and construction of large solid angle "conventional" magnetic spectrographs in Europe. These are VAMOS at GANIL, PRISMA at Legnaro, and MAGNEX at Catania. They have been the basis of the cost estimates given below.

4.2 Conventional Spectrographs – Phase I

The basic requirements of a magnetic spectrograph for an advanced ISOL-type radioactive beam facility are large solid angle, moderate energy resolution, and large energy range. The momentum-bending limit is determined by the most neutron-rich isotopes, such as ^{8}He, in the energy range of 10-20 MeV/u. This spectrograph can be used to study a variety of nuclear reactions. In some cases it would serve as a heavy-ion detector, while in others it would be used as a light-ion detector for reactions with inverse kinematics.

In Table 3 the parameters of the three European projects and the S800 at NSCL are listed. The VAMOS design for the SPIRAL project at GANIL incorporates a Wien filter so that it has two modes of operation: One as a standard magnetic spectrograph and the other as a mass spectrometer. The S800 at NSCL has the largest solid angle of any currently operating standard magnetic spectrograph for nuclear physics (20 msr), combined with a high energy-resolution (10,000). The moderate solid angle, high resolution, and low energy range were optimized for use at relatively high energies, up to 200 MeV/u. The other devices are designed for the lower particle energies appropriate for an ISOL-type facility, and hence have larger solid angles and more moderate resolution specifications. The challenge of these ISOL-type designs is to achieve as large as possible solid angle while simultaneously having reasonable energy resolution and energy acceptance range. Since the cost of a magnetic spectrograph scales with the bending limit, a figure-of-merit for such spectrographs is something like the product of these four parameters.

Listed in Table 4 above are some possible Design parameters that may be taken as goals for a new design for the ISOL facility. In addition to these basic ion-optical specifications, there are other practical considerations. The mechanical layout of the spectrograph must take into account other detectors with which it may be used. It may sometimes be used at back angles with a recoil mass spectrometer at zero degrees, or it may be used in conjunction with large solid angle particle- and/or gamma-detector arrays. Mechanical compatibility with gas targets is also a consideration. Another constraint to be considered is the reaction kinematics. Many reactions at the ISOL facility will be studied with inverse kinematics, i.e. a heavy beam on a light target. This puts additional requirements on the design due to the rapid variation of outgoing particle energy with scattering angle.

Table 3: Summary of the Existing Designs and Specifications

Device	Mode	AE/q^2	Solid Angle (msr)	Energy Resolution	Energy Range	Approx. Cost
VAMOS	QQWD	160	100	∼500	20%	\$3M
PRISMA	QD	70	70	1000	40%	\$2.5M
MAGNEX	QQD	140	53	1000	40%	\$2M
S800	QQDD	800	20	10,000	10%	\$5M

A vertical orientation of the spectrograph, combined with the optical mode listed in Table 4, helps with several of these considerations. The vertical layout makes it more compatible with a variety of other detectors and/or spectrometers. The optical mode specified, which is the same as the S800, decouples the momentum measurement from the scattering angle measurement, as long as the spectrographs is not too close to the zero or 180°. This decoupling appears to be especially useful for inverse kinematics reactions, such as d(^{132}Sn, t)^{131}Sn. In such reactions there is a strong correlation between the scattering angle and the excitation energy spectrum. In fact, at some angles, the excitation energy measurement maps into the scattering angle and the scattering angle maps into the outgoing particle energy.

Table 4: Preliminary New "Conventional" Design with Specifications. Optical mode: vertical orientation, x: point-to-point, y: parallel-to-point.

Device	Mode	AE/q^2	Solid Angle (msr)	Energy Resolution	Energy Range	Approx. Cost
S200	QDD	200	100	1000	40%	$3M

All of the designs listed in Table 3 require particle trajectory measurements to make corrections for aberrations in order to achieve the desired resolution with the full solid angles and energy ranges indicated. These supplemental trajectory angle measurements are also very useful as part of the kinematic correction procedure.

Detailed design studies must be carried out to see if the goal specifications indicated in Table 4 are achievable in a practical device.

4.3 Very Large Acceptance Options –Phase II

There are other possible geometries for magnetic spectrographs that are quite different from the conventional ones considered above. These alternative geometries provide the possibility for acceptances in the steradian range; i.e., about an order of magnitude more than the conventional designs. The two basic types of these very large- acceptance devices that have been used to some extent in the past are based on solenoidal and toroidal geometries. No detailed design studies for either of these classes of spectrograph have been carried out for charged-particle reaction studies at ISOL facilities. The possibilities of such devices in this context appear to be quite interesting and they are worthy of further study.

a) Solenoidal Geometry

A magnetic solenoid with its axis oriented along the beam direction could serve as a very large-acceptance magnetic spectrograph for low-energy light particles from inverse reactions such as $d(^{132}\mathrm{Sn},p)^{133}\mathrm{Sn}$. In this case the protons of interest are emitted in the backwards hemisphere with energies of 1-10 MeV. The particle energy measurements are done via silicon detector barrels surrounding the beam axis. This type of magnetic spectrograph deserves further study.

b) Toroidal Geometry

Large-acceptance magnetic spectrometers based on a toroidal geometry of six or eight coils surrounding the beam (symmetry) axis have been used in other areas of nuclear physics, but there are no existing devices or design studies for ISOL-type applications. "Orange " spectrometers for electrons have been implemented in many devices in the past. A possible geometry to be studied is one with a detector barrel surrounding the beam axis. The device would have nearly complete azimuthal coverage in either the backward or forward hemisphere, as well as a large energy range. Ion-optical simulations of such a device will have to be carried out to determine the energy resolution and detailed geometrical acceptance. The dependence on the energy and position resolution of the focal plane "barrel" detector will also have to be investigated.

4.3 Cost and Manpower Summary

The estimated costs and manpower needs for a conventional magnetic spectrograph are approximately $3M and about 5 man-years, respectively. This estimate is scaled from the experience with the design and construction of the S800 spectrometer at MSU. In addition, about 2 FTE of effort are needed for preliminary studies of the two large-acceptance, low magnetic rigidity devices mentioned above. At the present time no funds for building a "Phase-II" spectrometer are requested.

5. Particle Detectors

Particle detectors have become an indispensable tool for experimental nuclear physics. With the exception of slow neutron capture and atomic trap studies, particle detectors are needed for all other physics topics mentioned in the White Paper from the Columbus Workshop. The following list identifies some of the applications of the various particle detectors that will be discussed in this Section. The numbers refer to the thirteen categories of physics topics outlined in the White paper.

- *Light Charged Particle Detectors:* Examples are Si, CsI and phoswich detectors needed in fusion, transfer, elastic, inelastic, and decay studies (e.g., topics 1-4, 7,11 in Table 2)

- *Neutron Detectors:* Examples are scintillator detectors needed in fusion, and decay studies (e.g., topics 1-4,12,13 in Table 2)

- *Heavy-Ion Detectors:* Examples are a variety of ionization and avalanche counters and Si detectors needed in fusion, fission, capture, transfer, elastic, inelastic, and Coulomb excitation studies (e.g., topics 1-4, 7-13 in Table 2)

Since the technologies associated with particle detectors are well established, many of the existing detector systems or their analogs may be used for experiments at the start up of the advanced ISOL facility. Nevertheless, several applications require development of new technologies that are discussed in Section 5.2.

5.1 Phase-I Detectors

This section describes the clearly identified and technically feasible particle detectors which would be needed at the start-up of the new facility. The general characteristics and cost estimates for each of these items are provided. Also listed are several detectors which, as they are, can make a significant contribution to the ISOL research effort and, therefore, should be considered as part of the DOE "detector arsenal" for this project.

5.1.1 LIGHT CHARGED PARTICLE DETECTORS A large fraction of the nuclear structure research with large γ detector arrays makes use of coincidence measurements with 4π charged particle detectors for, e.g., channel selection or crude spectroscopy. This type of joint utilization of powerful tools (photon and charged-particle detectors) will certainly continue or expand at a future advanced ISOL facility.

As a prototype of a 4π charged particle detector array, we may consider the Microball which makes use of discrete CsI(*Tl*) scintillator elements. The advantage of this scintillator is that, when properly doped with Tl, the pulse shape can be used for particle identification. The existing Microball could be used at an advanced ISOL facility in conjunction with large γ detector arrays with one major modification. This modification is needed to prevent the vast

majority of the elastically scattered beam particles from stopping within the cavity of the photon detector. Otherwise, an unacceptably large number of background photons from the decay of the scattered radioactive beam particles would impinge on the photon detectors. Replacing the forward rings of the Microball with one or more rings or arrays of detector elements roughly 30 cm downstream would allow sufficient space for shielding of the photon detectors. These replacement arrays could use either pixelated silicon strip (followed by CsI(Tl)) or plastic phoswich detectors. In fact one might need more than one forward array arrangement with more than one technology. However, regardless of the technology employed, the replacement of the forward elements also allows for a significant improvement of the energy resolution in the center of mass system. The resolution in the present device is determined by kinematical broadening. Improving the angular resolution by a finer pixelation of the forward elements is the only way to improve the center of mass energy resolution. This approach also addresses the issue of the large background rate in the particle detectors from β decay of the elastically scattered beam particles, stopped in the absorbers in front of the detector elements. A prototype hybrid detector that consists of six rings of CsI(Tl) detectors at laboratory angles backward of 30°, and double-sided Si strip-detectors (DSSD) covering angles of $\sim 8 - 30°$ will soon allow testing of these concepts at the Holifield Radioactive Ion Beam Facility. The cost to provide the Microball with a new forward pixelated wall using one or more of the technologies mentioned above should be about $250K, including the cost of electronics.

The above general-purpose channel selecting device, which would only have a modest energy resolution, is sufficient for many experiments. On the other hand, a whole class of experiments in the areas of nuclear structure and astrophysics requires detection of light particles with high efficiency, excellent energy (10-20 keV), and good angular resolution. Examples are the inverse kinematics one-neutron and one-proton transfer reactions that probe the single-particle structures of nuclei in the vicinity of shell closures. In a typical experiment, such as the one-neutron transfer reaction $d(^{132}\mathrm{Sn},p)^{133}\mathrm{Sn}$ in the angular range of $\Theta \sim 100°$, an angular resolution of approximately 0.5° is needed to obtain an energy resolution of ∼100 keV. These conditions, as well as the low intensities of exotic beams, would require the availability of large arrays of highly-pixelated Si detectors with good energy resolution.

Another project which could also benefit from a large array of highly-segmented Si-strip detectors is the study of reactions associated with the breakout from the hot CNO cycle and the rp process. These reactions, usually studied at low bombarding energies where the cross sections are quite small, would be impossible without a high-efficiency Si detector array.

Last, but not least, highly-pixelated DSSD detectors are needed at the focal-plane positions of the recoil separators for studies of very proton-rich nuclei that decay by charged-particle emission. These experiments provide a unique tool to establish proton (or alpha) separation energies near the proton drip line. Since emissions of charged particles follow implantation of the recoiling residual nuclei into the DSSD, studies of fast (few μs) emitters require special elec-

tronics that are capable of accurately measuring the energies of the emitted charged particles in the presence of much larger signals associated with the implanted recoiling nuclei.

Much of the cost associated with such arrays is for the development of highly-integrated signal processing chips. While such chips have been used extensively in elementary particle and high energy physics, they have not been used in low and intermediate energy nuclear physics. The number of elements needed for experiments at an advanced ISOL facility may be in the range of several hundred to a thousand. Unfortunately our requirements do not match those of the existing chips and, therefore, a development effort is needed. Requirements for such a chip include: (i) good energy and timing resolution (< 20 keV and < 150 ps, respectively) for low energy protons, (ii) high quality linear digitization (> 12 bits), (iii) on board data sparsification (zero suppression), and (iv) what is perhaps most difficult - the ability to use these chips on a variety of Si arrays of different geometries.

The development of the signal processing chip will take several years and would cost close to \$2M. This estimate is based on the experience with previous chips developed for high-energy physics. The entire cost of providing ISOL with high quality Silicon Strip detectors and the necessary electronics is estimated to be \$2.5M. As the chip development project will require several years, it should start as soon as possible.

5.1.2 NEUTRON DETECTORS Our knowledge of nuclei diminishes as the nuclei under study become more distant from the valley of β-stability. On the n-deficient side, heavy-ion fusion reactions have enabled us to reach or even cross the proton dripline in many instances. Since charged-particle emission dominates the deexcitation of proton-rich compound nuclei, detection of evaporation neutrons provides one of the most effective tools to select very p-rich residues. For example, a combination of n detectors and either a 4π array of charged-particle detectors or a recoil mass separator has provided a very powerful technique for the identification and spectroscopy of $N{\sim}Z$ nuclei. For this purpose, we need to deploy an array of liquid scintillator neutron detectors of approximately 15 cm thickness at forward laboratory angles. To be able to properly identify and discriminate against the much more copious background of γ rays, a target-to-detector distance of $>$20 cm is desirable.

It is generally difficult to produce n-rich nuclei using stable beams and targets. Some of the reactions that have been used to study these nuclei include fission, spallation, projectile fragmentation, transfer, quasi-elastic and deep-inelastic reactions. However, on the neutron-rich side our knowledge is more limited (and the unexplored region much larger) than it is on the n-deficient side. Unfortunately, neutron detectors are of only limited use for channel selection on the n rich side due to their small efficiency. One of their potential uses may be in the area of continuum spectroscopy. Here, short (< 10 cm) detectors could be used in studies determining the extent to which shell structures weaken as the neutron excess increases. This information is contained in the continuum evaporation spectra of moderately ($E^* < 40$ MeV) excited nu-

clei formed by fusion or inelastic scattering reactions. The slope of the continuum spectra are proportional to $(1/g)^{1/2}$ where g is the level density at the Fermi surface.

The costs of these two arrays of BC501A detectors are approximately $500K, including their electronics. This estimate is based on the costs of the DEMON array at Louvain-la-Neuve (Belgium) and recent efforts in the U.S. to build a smaller array to be used for channel selection with the GAMMASPHERE.

This set could be augmented by two other types of devices. One of these is a "neutron wall" of the type recently constructed at MSU. The other is a cryogenic n-calorimeter which is capable of producing spectroscopic information (< 50 keV energy resolution). The former does not require development, but does suffer from a cross-talk problem while the latter requires substantial development and is discussed in Section 5.2.1

A final, but very important issue for neutron detection is *space*. An experimental area should be available with minimal mass close to (within $20'$ of) the reaction area. This requirement for the floor clearance may be partly satisfied by elevating the beam line and creating a pit below it. These considerations have been taken into account for the neutron facility at Louvain-la-Neuve (Belgium).

5.1.3 HEAVY-ION DETECTORS Gas detectors designed for heavy ions are typically insensitive to electrons and, therefore, the additional ionization caused by the beta decay of beam particles should not cause a problem. For example CHICO, a large-area parallel plate avalanche detector built at the University of Rochester, should operate quite well in the radioactive beam environment. On the other hand, decay of the beam particles stopped in the forward hemisphere of this device would generate a large background of γ rays in the Ge detectors surrounding the target. Therefore, for Coulomb excitation, transfer reaction and fission studies with radioactive beams which require a large solid angle coverage by both heavy-ion and photon detectors, one needs a large detector which sits outside of the cavity of the photon array.

One of the interesting problems to study at an advanced ISOL facility is to explore the limits of the nuclear stability due to fission on the neutron-rich side by measuring fission probabilities as a function of excitation energy and isospin. These studies will require nearly 4π coverage of gas counters with moderately good position information. CHICO (mentioned above) has these characteristics, as does another detector presently under construction at ANL with a barrel geometry. One can anticipate It is anticipated that these devices will see significant service in mapping out the fission limits.

It has been predicted that isospin will have an influence on the saddle-to-scission dynamics. One method to investigate this is to study the evolution of ternary fission as a function of isospin. These studies would require specialized light and intermediate mass fragment detectors to be

used in conjunction with the very heavy-ion detectors mentioned above. Fortunately, the technology and many of the detectors already exist. Therefore, while these heavy-ion detectors will be used in many experiments at an advanced ISOL facility, no new single large detector is needed. It is anticipated that the required detectors will be built as needed by individual groups.

5.1.4 OTHER PARTICLE DETECTORS Focal plane detectors for magnetic spectrometers were not explicitly considered by this working group. Design of these detectors must go hand-in-hand with the detailed design of the spectrometers and separators. High-resolution, highly-pixelated Si detectors also will be required at the end of these spectrometers. This highlights not only the need for high-density Si processing electronics, but also for flexibility in the electronics design.

Conversion electron spectrometers, such as a solenoid, might also be needed. Our working group did not address this issue and therefore no cost estimate is provided.

5.2 Phase-II Detectors

This part contains a list of research and development efforts for detectors which are technically feasible and, if the development proves to be successful, would add significantly to the ISOL research program. At this time it is difficult to provide cost estimates for these items. It is our hope that having identified this list, the DOE will encourage the development of some of these technologies in the coming years. The following three items are detector research projects which should be pursued in the near future.

5.2.1 NEUTRON DETECTORS Scintillation detectors for neutrons mentioned in section 4.1 of this report cannot provide spectroscopic quality data. Here we are referring to an energy resolution of better than 50 keV which is needed for, e.g., inverse (d, n) reactions and β-n-γ correlations of neutron-rich nuclei. These experiments are central to the study of the r-process nucleosynthesis which, in addition to decay mode and half-live information, require specific structure data.

A promising candidate for a spectroscopic quality neutron detector is a cryogenic calorimeter which uses the ^{6}Li$(n, t)\alpha$ reaction. The neutron energy and the reaction Q-value (4.8 MeV) are deposited in an absorber composed of a Li salt. This absorber is attached to a Ge thermistor. (Other technologies are available for the temperature transducer.) The measured change in temperature is proportional to the deposited energy. This detector is largely immune to non-neutron background due to the Q-value offset. However, the slow rise times achieved with the existing devices presently limit these detectors to singles measurements.

To obtain the required sensitivity, operating temperatures below 2K are required. The cryogenic operation is not that complex at temperatures above 1K since one can use ^{4}He(l) at a reduced pressure. The principal issue here, as in the case below, is whether an array of such detectors can be constructed and if a double-digit efficiency can be achieved. (Increasing the size of the absorber increases not only the efficiency, but also the heat capacity which reduces the sensitivity.)

5.2.2 CRYOGENIC DETECTORS Cryogenic charged-particle detectors could also play a significant role at an advanced ISOL facility. The advantage of such a detector is that, unlike solid state diode detectors, the intrinsic limitation to the energy resolution is much smaller (meV vs. eV) In solid state diode detectors the pulse height defect due to charge recombination leads not only to a loss of pulse height (proportional to the square root of the energy) but also to a variation in the collected charge and thus poor resolution. For example for heavy evaporation residues of about E/A = 1 MeV, Si detectors cannot achieve better than 1% energy resolution. Charge recombination is even more of a problem for measuring the energy of recoils of charged particle decay. This issue is of relevance for delayed tagging experiments where the resolution of the total decay energy is limited by the resolution of the recoil contribution. For the detection of residues, cryogenic calorimeters should yield resolutions a factor of ten better than can be achieved with Si. For recoil detection the improvement is even larger. The issue again is whether one can built large arrays of these detectors.

5.2.3 STRIP GE DETECTORS The third detector-development project has some overlap with the needs for development of new photon detectors. Intrinsic Si detectors are presently limited to 1-2 mm thickness due to the lack of availability of material with high enough resistivity. These Si-detectors are not thick enough for many low-energy experiments, as protons with energies of 12-15 MeV punch through them. (This is why a forward Si wall in a channel selecting device will have to be followed by a CsI(Tl) wall.) While $\sim$1 cm thick planar Ge detectors have long been used as particle and gamma detectors, pixelated or strip Ge detectors are not in common use. Development and packaging of such detectors would significantly help the research effort at an advanced ISOL facility.

6. Targets

The Working Group on targets discussed the following two topics related to special target needs at the advanced ISOL facility:

(1) A gas target for bombardment with the radioactive secondary beam, and

(2) The use of the un-accelerated secondary beam to produce a radioactive target for bombardment with a high-intensity stable beam from the secondary accelerator.

6.1 Gas Targets

Physics Addressed with Gas Targets

The most urgent need for gas targets has been expressed by groups planning experiments in nuclear astrophysics. Many of the reactions with radioactive beams of interest to the astrophysics community are those necessary for understanding stellar nucleosynthesis. These experiments require pure targets of hydrogen and helium isotopes which will be used in studies of hydrogen or alpha-induced reactions, at energies well below the Coulomb barrier. These capture reactions can most easily be studied in the inverse-kinematics mode utilizing beams of the various exotic nuclei that will be accelerated by the ISOL facility. Examples are proton capture by light nuclei and (d, p) reactions on neutron-rich nuclei. The reverse kinematics reactions result in forward-focussed secondary reaction products with relatively narrow angular and momentum distributions, suitable for either direct detection or detection after a kinematic separator.

Gas Target Requirements

(1) To allow sufficient luminosity for performing these reactions with anticipated radioactive beam intensities, the gas target number density must be greater than 10^{18} cm^{-2}. Present technology allows targets with upwards of 10^{18} cm^{-2}, and new systems will be designed with number densities up to 10^{19} cm^{-2}.

(2) In order to have well-defined geometry for accurate reconstruction of the reaction kinematics, the reaction volume must be small, resulting in a well-defined reaction point. The small reaction volume will also result in reaction products with small emittance which is acceptable for all kinematic separators.

(3) All gas-target arrangements require extensive differential pumping to contain the high-pressure region of the gas target, and to allow the detection/separation apparatus to operate at a high vacuum.

(4) This differential pumping apparatus must be kept as small as possible, to allow placement of the spectrometer or separator close to the target (at a distance less than 60 cm).

(5) The differential pumping apparatus must also be designed so that the detectors or separators have access to the full reaction product angular distribution. The apertures linking the differentially pumped volumes both before and after the target must allow a $\pm$ 2° acceptance. In addition, the differential pumping apparatus must be designed to cover a minimum solid angle around the target, allowing the placement of gamma-ray and particle detectors near the target with a large solid angle acceptance.

(6) A high target purity (impurity level less than 10ppm) is required to allow the measurement of small cross sections: larger cross sections in reactions with small target impurities could obscure detection of the desired reaction. A windowless gas target is preferred. Elimination of windows prevents interfering reactions of the radioactive beam with window materials and provides for cleaner reconstruction of reaction kinematics. Also, for reasons of target purity, solid targets such as $(CH_2)_n$ or gases incorporated in solid matrices are unsuitable.

(7) Required target nuclides for astrophysical measurements are H_2, D_2, ^{3}He, and ^{4}He. In addition, targets of other gaseous elements (N_2, O_2, Ne, Kr, Xe, etc.) will be possible.

With these limitations in mind, a windowless gas target was chosen as the best possibility for fulfilling the requirements.

Windowless Gas Target Design Considerations

The three concepts for a windowless gas target design that were considered were a differentially-pumped gas cell, a differentially-pumped supersonic gas jet target, as well as the idea of plasma confinement of hydrogen or helium at high pressure. The confinement of gas by an envelope of a charged particle plasma seems attractive, but little was known about this technique by the participants in this working group. The discussion in the working group then centered on the choice between a differentially pumped gas cell and a supersonic gas jet target. It is clear that each option has advantages and drawbacks, and in many cases, the choice will be determined by what we want to accomplish and the resources available to us. To make a meaningful comparison of the required pumping speeds and gas loads in order to achieve a target thickness of 10^{18} molecules/cm^2, two designs (a static gas cell and gas jet target) were studied with the same computer program so that all the necessary approximations used apply to both designs.

Both designs have a 30x30x30 cm^3 box surrounding the central target region - a gas cell or a supersonic jet. The length of the gas cell is 20 cm and the size of the jet is determined by the nozzle's exit shape. The designs of the differential pumping ports depend on the pressure and

differential gas flow regime (absolute pressure). In particular, where the pressure is relatively high (5 Torr) and a large pressure differential must be maintained across the opening, a simple aperture is used. A tube is used to constrict the gas flow at low pressures (in the molecular flow regime). The diameter of apertures/tubes ranging from 1 cm between the high pressure stages to 4 cm between the low pressure stages. Both designs provide a target thickness of approximately 1.8x10^{18} molecules of H_2 per cross sectional area of 1 cm^2.

Discussion and Possible Modifications

One of the main advantages of the gas jet is that it presents a small high-density target volume. While this is clearly recognized, there are situations (i.e., in studies of proton capture using inverse kinematics) where such confinement is not necessary. For many such experiments, especially at low energies, the products are confined to a small narrow cone in the laboratory and the spectrometer opening can be smaller than the 2° requirement set forth in the generic case. This might allow the use of smaller apertures and, therefore, reduce the load on differential pumping stages.

The first volume surrounding the gas-jet target can be kept at a low enough pressure (20 mTorr) so that it can serve as a reaction chamber with a well defined target region. By covering the sides of the volume surrounding the jet with an array of silicon strip detectors, one could study peripheral as well as close collisions of heavy ions bombarding gas targets such as Kr of Xe. The products from binary reactions can be detected with the solid state detectors on both sides of the beam axis, suffering only minimal energy loss and degradation as they exit through the "thin" sides of the target. With the use of high granularity silicon microstrip detectors, one will be able to measure high-quality kinematic coincidence data. Alternatively, the intersection of beam and target can occur with the beam direction along the short dimension. We then have a well defined and small object that can be imaged using spectrographs, if the need arises.

In summary, one should note that especially with the planned ISOL Facility where heavier neutron rich beams become available, the existence of a state-of-the-art gas-jet facility becomes imperative. The studies of (d, p) and similar transfer processes will require a compact clean, and fairly dense target. Such a facility can be constructed at a cost of \$0.5M in a one year period.

6.2 Radioactive Targets

Physics Addressed with Radioactive Targets

There are many radioisotopes with relatively long half-lives of interest to nuclear astrophysics. For example, the reaction rates for radioactive branching points in the slow-neutron capture

(s-) process could be measured using activation techniques if targets containing roughly 10^{14} atoms were available. This same technique could be used to measure reaction rates needed for the study of explosive nucleosynthesis (p- and r- processes). If larger targets could be made ($> 10^{17}$ atoms), more detailed time-of-flight measurements could be made. Very few of these types of measurements have been made due to the difficulties in obtaining suitable targets. Because the isotopes of interest are close to the valley of stability, yields from the ISOL facility are expected to be large and target collection times should be reasonable. Also, some of these isotopes are available from other sources but the capabilites available at ISOL will be invaluable for making the actual targets.

There are many even-even isotopes, with relatively long half-lives, which are two neutrons beyond the most neutron-rich or most neutron-deficient stable isotopes of the given element. Use of targets of these radioactive isotopes with either radioactive beams or high-intensity stable beams can allow access to isotopes further from stability. Binary transfer reactions using neutron-rich radioactive targets can be used to access more neutron-rich isotopes, allowing studies of isotopes important in the r-process. Compound nucleus reactions with neutron-deficient radioactive targets can be used to probe proton-drip- line nuclei more effectively. Calculations indicate that higher production rates of exotic nuclei can be achieved by using the non-accelerated radioactive species from the ISOL primary reaction as a target for irradiation with a high-intensity stable beam. Higher production rates may be achieved when using the radioactive species as a target, rather than as a beam, when the half-life is greater than about one hour.

Radioactive Target Facility Requirements

The facilities needed for the use of radioactive targets depend on whether the target is made by direct implantation into a target backing or is made using radiochemical techniques.

Direct implantation: Making targets by directly implanting the mass-separated, unaccelerated beam into a backing will be most useful for very short-lived isotopes and for targets requiring good isotopic separation and/or high purity. For nuclear astrophysics applications, an isotopic purity of 1 part in 10^5 will usually be sufficient, so it may be possible to extract the isotope of interest at an intermediate location of the full on-line mass separator. In this way, it may be possible to use more than one of the isotopes from the ISOL ion source (one isotope would be implanted while another goes through the entire mass separator and is sent, for example, through the post-accelerator to one of the experimental end stations.

To make implanted targets and to use the short-lived radioactive targets with the other ISOL secondary reaction instrumentation it will be necessary to, a) extract the secondary beam before post-acceleration, b) build low-energy beamlines for efficient transport of the radioactive ions

to the secondary reaction target sites, and c) design and construct the low-energy beamline optics for ion implantation of the radioactive targets. The design and construction of these facilities should be included in the original ISOL facility design.

Targets made off-line: For radioactive targets of isotopes with half-lives greater than about one day, or for those long-lived targets for which the isotopic and chemical purity requirements are not too high and/or for which implanted targets are not practical, it will be possible to collect mass-separated samples after the primary target. These samples can be extracted from the collecting device and purified using radiochemical techniques. The targets can then be placed in the "existing" separator or detector facilities at the end of the ISOL secondary accelerator and bombarded with either ISOL radioactive beams or high-intensity stable beams, or used at other facilities.

Dedicated standard radiochemical laboratory facilities are required, presumably at a cost of approximately $500k.

Some of the longer-lived isotopes could be produced off-line in several ways:

(1) At fission reactors

(2) With neutrons from the ISOL primary target

(3) In the ISOL primary accelerator beamstop (downstream of the primary target)

(4) In the ISOL primary target

(5) In a secondary ISOL target by time-sharing the ISOL primary beam

For options (2) through (5), hot-cell facilities (at a cost of approximately $2M) for the initial separation of the radioactive target material from the beamstop/target will be necessary. In the ISOL primary target design, consideration must be given to having access to these isotope production facilities to allow access to isotopes with half-lives of one month or greater. After initial separation in the hot-cell, radiochemical separations and production of targets could take place in the radiochemistry laboratory facilities mentioned above. Also, in some cases the isotope separator at ISOL would be an invaluable resource for isotopically separating this material and for making implanted targets. The production and use of radioactive target will require 2 FTEs for the duration of ISOL operation.

7 Apparatus using Non-accelerated Beams

7.1 Physics Requirements

Experiments using non-accelerated radioactive ion beams (beam energies < 100 keV) will provide the first opportunities for new and important scientific results at an advanced isotope separation on-line (ISOL) facility. A variety of experiments exploring, for example, atomic parity non-conservation in francium atoms, the radioactive decay properties of nuclides near the astrophysical *rp*- and *r*-process paths, and the breakdown of shell structure in exotic nuclides through mass measurements and the determination of ground state nuclear moments, are envisioned for the low-energy beams available immediately following the primary mass separation stage of an ISOL machine. The instruments needed to perform experiments with non-accelerated radioactive ion beams include: a laser atom trap, an ion trap, detectors for decay spectroscopy studies, a low-temperature nuclear orientation facility, a β-NMR apparatus, and an electron beam ion trap. The performance, cost, design, and manpower needs for each of these instruments are detailed in the following sections.

In considering experiments with non-accelerated beams, the versatility of the primary mass separation facility and the available floor space immediately following the separator should both be given high priority. The capability to provide multiple radioactive beams from the primary mass separator will allow the facility to have maximum physics impact by simultaneously carrying-out both accelerated and non-accelerated radioactive beam experiments. The availability of stable beams is crucial to the on-line development of several instruments described below, and the capability to deliver stable beam "on-demand" is desired. Many of the instruments require dedicated experimental areas, and sufficient floor space (≈ 750 square feet per experiment) behind the primary mass separator will be needed to conduct successful ISOL experiments. A beam switchyard is envisioned that would deliver a non-accelerated beam to each of the dedicated experimental areas. In addition to beam lines for the instruments described below, consideration should also be given to beam-line access for material science experiments and other experimental programs that can make use of the non-accelerated beams.

Some of the instruments for non-accelerated radioactive beam experiments (decay spectroscopy studies, β-NMR with tilted-foil polarization, ion trapping) are also suitable for use behind a recoil mass spectrometer-type device. The cost of duplicating some of the needed instrumentation may require innovative planning of ISOL facility layout or flexible design of the experimental equipment to allow for optimal physics output from these devices.

For many experiments using both accelerated and non-accelerated beams, the beam quality may become an important issue. Therefore, a provision for both primary (following the primary mass separator) and secondary (following the recoil mass spectrometer) radioactive beam handling systems (with radio-frequency quadrupole cooler/buncher and purifying Penning trap

as main components) should be considered.

7.2 Laser atom trap

The measurement of francium atomic parity non-conservation (PNC) and weak interaction studies in radioactive nuclei with $N = Z$ offer exciting opportunities to probe the existence of new physics beyond the standard model, and to measure nuclear anapole moments for a series of isotopes. The laser atom trap is an emerging technology that promises accessibility to pure, highly-polarized, near zero-thickness sources for precise β-decay experiments. The laser trap also provides a laboratory for examining the atomic structure of short-lived radioisotopes. Research and development on atom trapping techniques is underway at several university facilities in the US, and continued support of this effort is required to ensure a successful atom trapping program at a national ISOL facility. The estimated cost of a laser atom trap facility for francium atomic PNC measurements is $800k, where the lasers make up a significant portion of the cost. A common laser facility, designed to take maximum advantage of the expensive lasers required for laser atom trapping and other ISOL experiments, is desired. Such a "laser farm" would distribute laser light through optical fibers to several magneto-optic traps, a general purpose laser spectroscopy area, and possibly for a laser ion source system. With a common laser facility in place, individual magneto-optic traps for weak interaction studies and atomic PNC measurements would be feasible at a cost of $250k each. The manpower requirement for the design, construction, and operation of an individual trap is 2 FTE for 3 years.

7.3 Ion trap

The precise measurement of ground state masses of nuclear species far removed from the valley of β stability provide critical data for testing the validity of current nuclear structure and astrophysical theories. Coupled to a radio-frequency quadrupole (RFQ) cooler/buncher and purification trap, a Penning trap mass spectrometer is capable of accepting short-lived radioactive nuclei with high efficiency. The Penning trap mass spectrometer also provides the resolution and accuracy required for precise nuclear mass measurements. The implementation of an RFQ cooler/buncher, based on the Paul trap beam collection system originated at McGill University, is underway at Argonne National Laboratory, and the continued support of research and development in the area of ion trap development is necessary for successful ISOL experiments in the future. The cost to instrument a RFQ buncher/cooler + purifier trap + Penning trap mass spectrometer is $700k, and will require a manpower effort of 3 FTE for 2 years for construction and operation.

The ion trap system will be an effective instrument for both non-accelerated radioactive beams and beams produced and separated from a recoil mass spectrometer device. Consideration

should be given for the transport of both types of beams to a single ion trap system, or the development of multiple ion traps. Also, the RFQ buncher/cooler + purifier trap can serve as an excellent beam preparation system for both non-accelerated and accelerated beam experiments at a cost of $250k (in case of accelerated beam, this system should be supplemented with an additional gas chamber, cost of $40k). This implementation should be considered as there are many beam experiments (nuclear orientation, laser spectroscopy, nuclear mass measurements, β decay spectroscopy and testing of Standard Model) that would benefit from the beam purity and emittance offered by this system.

7.4 Nuclear orientation facility

A low-temperature nuclear orientation facility would provide a method to measure ground state magnetic dipole and electric quadrupole moments of nuclides having decay half-lives greater than a few seconds (limited by the nuclear spin relaxation time for a given nuclear species implanted in a ferromagnetic host). The magnetic dipole moment is a probe of the single-particle nature of the nucleus, and can be used to test single-particle states around exotic doubly-magic nuclei (^{100}Sn, ^{132}Sn). Since the electric quadrupole moment is a direct measure of the nuclear shape, one can use this property to track the weakening of shell structure away from the valley of β stability. The instrumentation required for a low-temperature nuclear orientation facility includes a ^{3}He/^{4}He dilution refrigerator with a side/bottom access port for direct beam implantation. Four on-line nuclear orientation facilities exist in the world, and are located at CERN, Studsvik, Louvain-la-neuve, and TRIUMF (under construction). The dilution refrigerator should be equipped with nuclear magnetic resonance coils internal to the cryostat system, and a compliment of moderately efficient ($\approx$ 70% relative to NaI) Ge detectors are necessary to detect γ ray anisotropies. The instrumentation costs for a dilution refrigerator with associated He and high vacuum pumping systems is $400k. The required nuclear magnetic resonance system is an additional $50k. Manpower needs are one FTE for 1.5 years to get the instrument operational. The cost estimate for the nuclear orientation facility would be lowered if existing facilities were utilized. Research and development associated with the nuclear orientation facility would include the development of Si particle detectors with consistent performance at 4 K. This successful development would expand the physics capability of the instrument to include the study of the anisotropic decay of rare particle emissions.

7.5 β-NMR facility

To extend the study of magnetic dipole and electric quadrupole moments to nuclei with half-lives shorter than a few seconds, nuclear magnetic resonance on β-emitting nuclei (β-NMR) can be employed. The β-NMR method requires that a nuclear polarization be induced in the β-unstable nucleus under study. This can be achieved for low-energy radioactive beams using either tilted-foil polarization, or through laser spectroscopy and optical pumping methods. The

tilted-foil technique has been successfully applied to a 60-keV beam of ^{23}Mg at CERN/ISOLDE. The instrumentation employed at ISOLDE included a high voltage platform, a superconducting split-pole magnet, a manipulator for the tilted-foil arrangement, and a pair of β telescope detectors. The high voltage platform provided sufficient acceleration for doubly-charged ions to traverse the tilted-foil stack. Instrumentation costs for a comparable system are $160k, and manpower requirements are one FTE for 1 year.

The major instrumentation cost for a laser spectroscopy system is the purchase of lasers. The implementation of a "laser farm" for the distribution of laser light from a central/common area would significantly reduce the equipment costs of a general purpose laser spectroscopy experimental area. Other necessary equipment, including electrostatic deflectors, retardation/deceleration cells, charge exchange cells, optical detection equipment and associated equipment for β asymmetry measurements would require $200k in funding and a manpower effort of 2 FTE for 1.5 years.

7.6 Decay spectroscopy instrumentation

The experimental determination of β decay half-lives, β endpoint energies, and neutron emission probabilities of very exotic neutron-rich nuclides is essential to the development of network calculations modelling the astrophysical r-process. Beta decay studies of $N = Z$ nuclides up to ^{100}Sn offer a chance to study more extensively superallowed Fermi beta decay, Gamow-Teller decay strengths in proton-drip line nuclei, and unique pairing interactions between protons and neutrons in identical single-particle orbitals. General purpose decay spectroscopy areas should be available to study β decay properties of both primary (non-accelerated) and secondary (resulting from bombarding the target with the accelerated primary) radioactive ion beams. A list of instrumentation required for such studies includes: large volume (clover-type) Ge detectors, low-energy photon (LEPS) Ge detectors, particle detectors (large area Si detectors, double-sided silicon strip detectors, beta telescopes) and associated electronics, neutron detectors, and a total absorption spectrometer. Research and development in high-efficiency neutron detection, segmented planar Ge detectors, and integrated electronics for high channel density Si strip detectors is needed. A moving tape system to transport activities to multiple counting stations and to remove the build-up of longer-lived daughter radioactivity would require funds of $50k and 1 FTE for 0.5 years for implementation.

A perturbed angular distribution system should be constructed for the determination of g factors of excited states populated via β decay. The instrumentation needed includes an activity delivery system, a small permanent magnet arrangement, and a compliment of large volume Ge detectors. Funding support of k$50 (excluding the cost of the Ge detectors) and 1 FTE for 0.5 years is required to design, build and commission the device.

7.7 Electron beam ion trap (EBIT)

The production of highly-charged radioactive ions using an Electron Beam Ion Trap (EBIT) offers a unique opportunity to study ground state nuclear properties such as nuclear charge radius, nuclear magnetic dipole moment, and the distribution of magnetism in the nucleus by observing hyperfine transitions in hydrogen-like ions. Modification of nuclear decay rates (internal conversion rates, electron capture rates, etc.) is also possible through the production of fully-stripped radioactive species. Employed as a beam preparation device upstream from a Penning trap mass spectrometer, an EBIT can provide highly-charged ions for injection into the mass-measuring device, hence increasing the precision of the mass measurement ($\omega_c \propto q$). Development of a new Intense EBIT is underway at Lawrence Livermore National Laboratory. The cost for the device is $400k, and 2 FTEs are required for a 2 year period to construct and operate the instrument.

An EBIT may also provide a method for generating highly-charged radioactive species prior to post-acceleration. Research to study the phase space limitations and extraction efficiency of the EBIT is required. However, the EBIT promises both isobaric separation (production of unique A^{q+}) and small emittance.

Table 5: Summary of the instrumentation needed to conduct ISOL research using non-accelerated beams.

Instrument		FTE	years	cost [k$]
Laser Atom Trap				
	lasers			600
	atomic PNC	2	3	250
	beta decay	2	3	250
Ion Trap				
	beam handler, non-accelerated	2	2	250
	mass spectrometer, non-accelerated	3	2	400
	beam handler, accelerated	2	2	290
	mass spectrometer, accelerated	3	2	400
Nuclear Orientation				
	dilution refrigerator	1	1.5	400
	NMR equipment			50
	particle detectors	1	1	20
Beta-NMR				
	tilted-foil setup	1	1	160
	laser spectroscopy	2	1.5	200
Decay spectroscopy				
	moving tape system	1	0.5	50
	PAD system	1	0.5	50
	neutron detectors	1	1	100
	DSSD electronics	1	1	250
	total absorption spectrometer	1	2	500
EBIT				
	stand-alone trap	2	2	400
	spectroscopy system			50
Total				**4,670**

Appendix A

Suggested URL Links:

Gamma-ray Detectors:
GAMMASPHERE (http://www-gam.lbl.gov) and (http://www.phy.anl.gov/gs)
CLARION (http://www.phy.ornl.gov/hribf/research/equipment/clarion)
EXOGAM (http://www.ganil.fr/exogam)
GRETA (http://radware.phy.ornl.gov/greta/index.html)

Recoil Separators:
FMA (http://www.phy.anl.gov/fma)
RMS (http://www.phy.ornl.gov/hribf/research/equipment/rms)
DRS (http://www.phy.ornl.gov/astrophysics/nuc/rib/drs.html)
DRAGON (http://www.triumf.ca/isac/lothar/recoil/recoil.html)
SHIP (http://www-gsi-vms.gsi.de/ship/home.html)
RITU (http://www.phys.jyu.fi/jyflweb/jyfle.html)
BGS (http://bgsmc01.lbl.gov)

Magnetic Spectrographs:
S800 (http://www.nscl.msu.edu/facility/devices/s800/home.html)
VAMOS (http://www.ganil.fr/vamos/index.html)
PRISMA (http://192.135.29.171/prismaind.html)

Particle Detectors:
Microball (http://wunmr.wustl.edu/∼dgs/mball)
DSSD (http://www.ph.ed.ac.ul/nuclear/silicon)

Apparatus for Experiments using Non-accelerated Beams:
ISAC (http://www.triumf.ca/isac/lothar/isac.html)
ISOLDE (http://www.cern.ch/ISOLDE)
Atom Traps (http://fr.physics.sunysb.edu/francium$_n ews/trapping.HTM$)
$IonTraps$ ($http : //isolde.cern.ch/normal/ISOMAP.html$))