ACCELERATED RADIOACTIVE NUCLEAR BEAMS
(LOW ENERGY)

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A. Introduction

The possibility of producing and accelerating intense beams of short-lived radioactive heavy ions both for studies of the species themselves and to be used as projectiles in reactions of interest is now considered quite feasible. While several approaches have been used or are proposed for the production of such beams, the two main methods are projectile fragmentation which will result in high energy beams (≥ 100 MeV/u) through the recoiling of the product nuclei, and spallation/fragmentation using intermediate energy protons followed by a post-accelerator stage resulting in low energy (LE) beams (≤ 10 MeV/u). A review of these along with related approaches which are presently in place producing such beams but which are more specific in the type of projectiles produced will be outlined in section B. A review of facilities either operating or proposed will also be given in section B. A number of interesting studies can be performed with such a wide variety of projectiles. Of particular interest here are the kinds of studies that are possible with projectiles classified as low energy (LE) and some of these are presented in section C. The proposed ISAC (isotope separator/accelerator) facility at TRIUMF will be reviewed and a status of the planning presented. In preparation of such a facility and a small test on-line isotope separator was constructed at TRIUMF to initiate a program of developing targets and ion sources of particular usefulness to ISAC. This (TISOL) facility is now operational and a progress report on some of the results relevant to the proposed ISAC facility as well as the possible upgrading of TISOL to a production facility for a full scientific program will be given. Included will be a report on the successful operation of an ECR (electron cyclotron resonance) ion source coupled on-line with an ISOL device for the first time.

B. Methods of Production

The two main approaches to the production of radioactive nuclear beams in general fall into two main categories, namely those that take advantage of the product nuclei recoiling out of the target at an energy close to that of the energy of the projectile used to produce it, and those that produce the desired projectile initially in some thick target followed by its diffusion into a post-acceleration stage to reach the desired energy of interest. Each of these has certain advantages and disadvantages and a thorough exploration of this topic can be found in a recent review by Tanihata.

B.1 Recoil Techniques

There are two main types of recoil techniques considered optimal for the purpose of producing radioactive nuclear beams. These are projectile fragmentation which takes advantage of the fragmentation of very high energy projectiles in their interaction with a thin target, and transfer reactions of rather low energy heavy ions. In the first instance heavy

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ions of energies higher than a few hundred MeV/u and whose nuclear composition is close to the desired radioactive projectile are intercepted by an appropriate target and the recoiling fragments emitted in essentially the forward direction are separated by electromagnetic devices in a recoil separator. Such an approach is best illustrated by the present facilities at Berkeley², GANIL³ and the facility being constructed at GSI/SIS⁴. In the second approach, low energy (30-50 MeV) heavy ions undergo in general a single nucleon transfer reaction and the recoiling product of interest is again captured by electromagnetic devices such as a superconducting solenoid lens to produce a radioactive beam of interest. An example of this leading to the production of a ^8Li beam using a $^9\text{Be}(^7\text{Li}, ^8\text{Li})^8\text{Be}$ reaction⁵ is being implemented at the University of Notre Dame facility⁶; a similar approach is in place at Livermore⁷. Table 1 provides a comparison of the projected yields of these two techniques and some of the expected or proposed properties of these types of facilities are given in Table 2.

B.2 Diffusion Techniques

The second main approach to the production of a wide range of radioactive nuclear beams takes advantage of diffusion of product nuclei from a target generally operated at high temperatures followed by some form of electromagnetic on-line mass/isotope separation and then a booster acceleration stage to attain a final beam energy. In general, two approaches have been used or are proposed by which the desired radioactive species are produced. In specific instances the desired species can be made through the use of an intense beam of low energy protons with the reaction of interest of the (p,n) type. An example of this is best illustrated by the production of a beam of ^{13}N at the Cyclone facility (Louvain-La-Neuve) which has just started operations⁸. A more versatile approach in terms of the availability of a wide range of possible radioactive beams is the use of intermediate energy protons (≥ 500 MeV) and through spallation/fragmentation types of reactions almost all radioactive species can be produced. The use of such energetic protons allows the possibility of using thick targets which in turn leads to rather high intensities of a wide range of final beams. This approach is best illustrated by the proposed ISAC facility at TRIUMF⁹ and the proposed facilities at ISOLDE located at CERN¹⁰, and JHP (Japanese Hadron Project) at KEK in Japan¹¹. This latter approach takes advantage of the well known technology for the production of radioactive beams at on-line isotope facilities, particularly at ISOLDE¹². Again, Table 1 provides a summary of the expected production rates at such a facility while Table 2 indicates where some of these facilities exist or are proposed. A key feature of this approach is the choice of an appropriate booster stage or post-accelerator. While the Cyclone facility takes advantage of the existence of a small cyclotron⁸ to provide the acceleration, most of the larger proposed facilities suggest that the use of a LINAC, similar to that proposed at TRIUMF⁹, is of greater advantage given it has lower injection and extraction losses. This is of some importance given the need to minimize transmission losses of the already relatively low intensity radioactive beams. These LINAC systems generally consist of a first stage, RFQ (Radiofrequency Quadrupole) LINAC which takes the singly charged, approximately 1 keV/u ISOL ion beam up an energy of the order of 60 keV/u. This can be followed then by some combination of stripping process and DT (drift tube) LINAC sections to reach the desired, selectable final projectile energy. In general, the diffusion approach to

the production of radioactive beams leads to beams of relatively low energy, i.e., below 10 MeV/u. This is in contrast to the recoil approach using high energy incident beams which lead to projectiles with energies of the order of 100 MeV/u. Thus these two dominant approaches are rather complementary given that it is expensive to accelerate or decelerate either significantly.

C. Scientific Program with LE Beams

The scientific program is strongly dependent upon the projectile energy and intensity as expected although regardless there is clearly a very wide range of new and novel types of studies which become possible for the first time. Of interest here are studies possible with LE beams. A wide variety of such studies can be found in some of the recent proposals for such ISOL/post-accelerator systems at the proposed ISAC at TRIUMF^{9,13} at the proposed JHP at KEK¹¹, and at the proposed PRIMA facility at ISOLDE in CERN¹⁰. A brief summary of only some of these are included here.

C.1 Nuclear Astrophysics

As is well known, stellar evolution and the subsequent formation of elements are dependent upon a sequence of simple nuclear reactions. Such reactions produce radioactive species which decay given a slow or long time scale. In explosive or high temperature phenomena such as supernovae the time scale is sufficiently short that these reactions involve the radioactive species themselves. While there has been success in developing nuclear reaction networks to help explain stellar processes occurring at low temperatures, it is virtually impossible to make accurate predictions for reactions involving radioactive species. This is due to the fact that such simple reactions, particularly in the low Z region, involve capture into narrow resonances and the related cross section of these are based upon the nuclear structure of the nuclide involved and not on an averaging standard statistical reaction theory. Thus, measurements of the reaction rates themselves are required as is used successfully for stable species. Such reactions must be studied at very low energies below the coulomb barrier and may exhibit cross sections that are quite small, e.g., in the nanobarn region. Nevertheless, estimates of such reactions involving radioactive nuclear beams incident upon He or H gaseous targets have been made^(13,14) and indicate that these are feasible. The forwardly recoiling product nuclei would be detected with standard reaction product technology now in place for similar studies with stable projectiles. A brief list of some of the possible reactions of interest are given in Table 3. A more thorough discussion of the importance of these is given elsewhere^{10,15}. The energy range of interest for these studies is from about 0.2 MeV/u up to about 1.5 MeV/u and beam intensities as low as 10^7 atoms/s can be useful for certain types of reactions.

C.2 Nuclear Physics

The most obvious fact when considering the use of radioactive nuclear beams for nuclear physics is the enormous number of projectiles which become available. In essence, any radioisotope could be used as a projectile to perform nuclear reaction studies. The term 'systematic studies' becomes a gross understatement as one contemplates, for example, the availability of perhaps 35 isotopes of cesium, or 48 species of cesium when isomeric states are considered with which a sequence of reactions can

be studied. Again, the projectile energy and intensity must be considered but clearly such studies as coulomb excitation, nucleon transfer reactions, inelastic scattering, in-beam gamma spectroscopy, and production of very heavy nuclei can be pursued with new vigor into regions previously inaccessible, with very exotic nuclei as projectiles. Some examples of these are given below although more complete descriptions can be found elsewhere^(1,16).

The use of the process of Coulomb excitation will provide a wealth of new information on the nuclear excitation of a wide range of exotic nuclei used as projectiles. Bombarding a heavy target with a RNB projectile with energies of a few MeV/u will lead to the direct population of members of the ground state band of the projectile itself. Such processes have reasonably high cross sections and RNB of the order of 10^6 atoms/s should be sufficient. Aside from the standard study of levels populated by E2 transitions in, for example, neutron rich nuclei, information not easily obtainable any other way, the possibility exists for also searching for other interesting excitations such as fast E1 transitions in nuclei such as Be¹¹. The latter possesses the fastest E1 transition known⁽¹⁷⁾.

Nucleon transfer and inelastic scattering reactions, again with exotic nuclei as projectiles, also will be a new way of obtaining information on the relevant excitations within these projectiles. For example, the use of ⁸He as a projectile will allow the possibility of the transfer of up to 4 neutrons, not only a new way of making very neutron rich nuclei, but also to provide spectroscopic information from the transfer itself. Furthermore, the levels in the projectile itself can be studied using inelastic scattering techniques. Beam intensities of the order of 10^{10} atoms/s are probably needed to perform some of the desired studies although low intensities are still quite useful.

Also, the use of some of these exotic projectiles for the production of nuclei far from stability must be mentioned. Depending upon the available energy and beam intensity it is not inconceivable to consider such strange beam/target combinations as a ⁶³Ga beam with a ⁴⁰Ca target to attempt to make isotopes in the 100 Sn region. Even with present technology ⁶³Ga beam intensities of the order of 10^5 atoms/s are available. Alternatively, the study of very heavy elements can be reinvigorated by using the wider selection of very neutron rich projectiles at energies just over the coulomb barrier.

Of course the possibility will now exist to provide a wide range of polarized nuclei for use in various types of studies. With the advent of post-acceleration the possibility of using the tilted foil polarization technique becomes a reality for a wide variety of studies. This is a simple technique and can be used for beams of energies of the order of .5 to 1 MeV/u. As indicated in the PRIMA proposal such beams can be used for beta decay asymmetry studies and measurements of nuclear moments⁽¹⁰⁾.

It should not be ignored that with the presence of an ISOL device on the front end a scientific program similar to that presently pursued at such major facilities as ISOLDE in CERN are still possible. Further, there is also the exciting, possible scientific programs in such important areas as

condensed matter physics, radioisotope production for nuclear medicine applications and ion implantation, which are not mentioned here but should not be overlooked.

D. The ISAC Facility

One of the first facilities proposed of the ISOL/post-accelerator type was the ISAC facility to be located at TRIUMF in Vancouver, Canada. Taking advantage of the intermediate energy (500 MeV), high intensity ($\leq 150 \mu\text{A}$) proton beam, radioactive beams with fluxes approaching 100 nA were predicted. These resultant beams would have had variable energies from 0.2 to 1.5 MeV/u, but with the use of a LINAC as the post-accelerator, this higher limit could be increased to 10 MeV/u relatively easy with well known technology. A schematic representation of the proposed facility is presented in Fig. 1 while a more complete description of the facility can be found elsewhere^(9,13). The project was estimated to cost of the order of \$15M and would be completed in a period of about 4 years. Some of the problem areas identified as requiring additional development included whether cryogenic pumping could be used given the rather hostile environment of the thermally hot targets of an ISOL, whether an ion source could be developed that would exhibit long term but efficient operation and for a wide range of elements of interest to the astrophysics program, whether target systems could be developed which could handle the prospect of proton beam intensities as high as 100 μA , whether these complex systems could easily and efficiently be manipulated remotely given such high radiation fields, whether the acceleration system could be developed to transmit such low intensity, low charge state beams with acceptable losses and for reasonable costs, whether detection systems could be devised to be used in the expected high radiation fields of the projectiles themselves. While a decision to proceed on the construction on the ISAC facility has not yet been finalized, a small test on-line isotope separator (TISOL) was installed at TRIUMF to indeed study some of these areas related to the final facility.

E. The TISOL Facility

E.1 General Features

As a test system it was considered useful that TISOL incorporate some of the features of the proposed ISOL on the front end of ISAC. Thus, TISOL is a vertically mounted, on-line isotope separator, installed at the end of the medium intensity ($\leq 10 \mu\text{A}$) beam line at TRIUMF. Since installation two different configurations have been developed for the facility depending upon the type of ion source used. Fig. 2 displays a schematic representation of an elevation view of the facility with the heated surface ion source and associated target chamber in place. This system has been described in some detail elsewhere^(17,18). Fig. 3 shows a similar configuration only now with the newly installed and operational Electron Cyclotron Resonance (ECR) ion source in place, along with other modifications to the pumping system and ion transport system. The ECR system consists of a small water cooled, target vacuum chamber in which is located the resistance heated Ta oven and a graphite chamber containing the target material itself. A gas transfer line connected both to an external gas system and the inlet of the ECR source, is also connected to a small opening at the upper part of the oven/target chamber. Nuclear reaction products resulting from the interaction of the proton beam with

the heated target material can diffuse into this opening, but the transfer line is not heated at present so that only gaseous species are expected to reach the ion source. Ions produced in the source are extracted out through a 2 mm hole using a specially shaped extraction electrode (EE) with a 3 mm opening. As before, the accelerating potential at which the target operates is 20 kV. The EE is movable in the transverse direction and is followed by an einzel lens which can operate at voltages up to 15 kV. This is followed by two magnetic quadrupoles (10 cm in diameter), a magnetic steerer, and then the mass analysing, magnetic 90° dipole. The remainder of the system is as before^{7,16}. In addition to the use of 450 l/s turbo pumps common to both configurations, the pumping of the surface target/ion source system is with a CTI-10 cryopump while (15 cm) diffusion pumps are used with the ECR system. The latter were used for economic reasons only. Other aspects of the system, including the control system, beam diagnostic elements, etc., are as described in previous reports.^(17,18)

E.2 Target Materials

Since the last report a series of new target materials have been used successfully to generate a very wide variety of radioisotopic ion beams from both the heated surface and ECR ion sources. In general, these targets have been either metal foils or powders in the form of uniquely prepared pellets. These are placed inside the cylindrical shaped graphite container which, in turn, fits inside the target oven. The targets used have been foils of Ti, Zr, and Nb, and pellets of $\text{UO}_2/\text{graphite}$, ZrC, and SiC. These pellets have been prepared by using an organic adhesive to "glue" the powders and a very slight pressure used to form the powder into a cylindrical shape. Pellets of the order of a few mm in thickness are then sliced. These are heated up to about 2000°C in the target holder under vacuum.

E.3 Ion Sources

E.3.1 Heated Surface

The first ion source to be used successfully and the one for which the greatest number of isotopes have been observed is the well-known heated surface type. The ionizer itself is simply a material with a relatively high work function and the elements ionized are those with relatively low ionization potentials. Such sources are well known and the TISOL source has been described in more detail earlier⁽¹⁸⁾. The TISOL source was operated at temperatures up to about 2000°C and the materials used were primarily Re, and W inside a Ta cylinder. The elements ionized were Li, Na, Al, K, Ga, Rb, Sr, In, Cs, Ba, Yb, and Fr.

E.3.2 ECR

Recently an ECR ion source was used successfully with TISOL leading to the ionization and extraction of radioisotopic beams of Ne, Ar, and Cl. This is the first instance of the coupling of an ISOL device with such a source. General aspects of the design of this source has been described earlier^(19,20) while the specifics of this particular installation and its operation are published elsewhere⁽²¹⁾. Fig. 3 displays an elevation view of the TISOL-ECR configuration while fig. 4 presents a detailed side view of the ECR source itself with the target chamber at its front end. In general, RF waves of 10 GHz at a injected power level of 160 watts are used to provide the power to ionize the gaseous material which reach the plasma chamber of the source. The electrons inside the plasma spiral with

their cyclotron frequency and are contained within the magnetic mirror coils of the source. Since a cooled transfer line was used between the target and the source only noble gases and other gaseous species are expected to be observed. Using a Ti foil target heated up to about 1500°C, ion beams of Ne, Ar, and Cl (as Cl⁺ and HCL⁺) were observed. An extraction potential of 12 kV was used and in this first run a He carrier gas was used although the pressure in the target chamber was only of the order of 10⁻⁵ torr.

E.4 Yields

E.4.1. Experimental Setup
Radioactive isotopes produced in thick targets with the 500 MeV proton beam at TRIUMF, and extracted as isotopically separated ion beams using TISOL were measured using standard radiation detection systems positioned at a fixed collector. Gamma spectra were obtained with a Ge(Li) gamma spectrometer while alpha spectra were detected with a charged particle surface barrier detector. In cases where the half-lives of the species of interest was quite short and a half-life determination was desired, the ion beam could be deflected electrostatically and this process cycled, synchronized with the data acquisition system. All spectra data were collected using a PCA 8000 board (The Nucleus) in a Multiterm AT (IBM clone). Further details of these measurements can be found elsewhere⁽²¹⁾ and a summary of some of these yield data obtained using both the surface source and the newly installed ECR source can be found in Tables 4 and 5. Typical target thicknesses used were in the range of 5-10 g/cm² while proton beam currents of 200-300 nA were utilized.

In addition to the yields themselves from some target materials and the ECR ion source not used before with ISOL devices, some of the other features of these results are the observation of an isotope possessing a half-life of the order of 20 ms, namely ²⁴Na, and also the observation of alpha activities of Fr isotopes, again some exhibiting half-lives in the ms range. This indicates that TISOL can be used for the study of rather short lived species. The observation of isotopes as far from stability as ¹⁵¹In is of interest, as is the good yield of both ²⁰Na, and isotopes of Al for future possible studies at TISOL.

F. Summary and Conclusions

It is now apparent that the field of producing and using accelerated radioactive beams for a wide range of new and exciting studies is beginning and a number of facilities are being planned in several countries around the world. These will take different forms and all will complement each other to provide different approaches to answer the new kinds of questions that can be asked and answered. The proposed ISAC facility proposed to be built at the TRIUMF facility is still awaiting final funding but the small test facility, TISOL, is now operational with a new kind of ion source, an ECR system and a program of testing and development of systems needed in an ISAC facility, located anywhere, is underway. In addition a standard physics program of the type in progress at the ISOLDE facility at CERN is now possible at TISOL.

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Table 1

Comparison of Methods of Producing Intense Radioactive Beams

PRIMARY BEAM	RECOIL		DIFFUSION	
	HEAVY ION	PROTON		
Energy	50 MeV	100 MeV/A	1 GeV/A	20 MeV
Intensity (particles/s)	10^{12}	10^{11}	10^{12}	2×10^{14}
Target thickness (g/cm ²)	10^{-3}	.5	1	10^{-1}
Cross Section (mb)	50	1	1	50
Production Rate (particles/s)	3×10^7	3×10^7	6×10^8	6×10^{10}
SECONDARY BEAM				
Transmission/Losses	10^{-2}	10^{-1}	10^{-1}	10^{-2}
Expected RB Intensity (particles/s)	3×10^5	3×10^6	6×10^7	6×10^8

Table 2

Accelerated Radioactive Beams Facilities

PROJECT (LOCATION)	PRODUCTION METHOD	MASS/ENERGY RANGE	STATUS
BEVALAC (LBL, Berkeley)	Fragmentation, Separator	(A < 100) 30-500 MeV/A	Operating
CYCLONE (Louvain)	30 MeV p + (ISOL) + Cyclotron	A ≤ 40 (?) ≤ 110 Q ² /A	Operating
USSR	ISOL + Cyclotron Post-acceleration	A < 230	Proposal in prep.
GANIL (Caen)	Fragmentation, Separators	A < 100 ≤ 50 MeV/u	Operating
JHP (KEK, Japan)	Fragmentation, 1GeVp + ISOL + Post-acceleration	A < 60 1-6.5 MeV/A	Proposed
ISOLDE (CERN/Geneva)	600 MeV p + ISOL + LINAC	A ≤ 40 .3-2.0 MeV/A	Proposed
QSBTS (LNL, Livermore)	Transfer Rxs., Quadrupoles	A ≤ 20 (12 MeV)	(Operating)
RPMS/Al200 (MSU)	Fragmentation, Separators	A < 60 (?) 1200 Q ² /A	Operating Planned
RUTHERFORD LAB (UK)	ISOL + Post-acceleration	not known	Proposal in prep.
SC SOLENOID (UND, South Bend)	Transfer Rxs. Separator	A < 20 (20 MeV)	Operating
SIS 18/ESR (GSI, Darmstadt)	Fragmentation, Storage Ring, Sep.	A < 238 5-500 MeV/u	1990
TRIUMF (Vancouver)	500 MeV p + ISOL + RFQ + LINAC	A ≤ 60 .3-1.5 MeV/A	Proposed

Table 3

Some Reactions of Astrophysical Interest

Reaction	$T_{1/2}$ [s] of reactant	Astrophysical interest
$8\text{Li}(\alpha, n)^{11}\text{B}$	0.84	inhomogeneous big bang
$^{13}\text{N}(\text{p}, \gamma)^{14}\text{O}$	598	hot CN cycle
$^{14}, ^{15}\text{O}(\alpha, \gamma)^{18}, ^{19}\text{Ne}$	71, 122	rp process, hot CNO
$^{17}, ^{18}\text{F}(\text{p}, \alpha)^{14}, ^{15}\text{O}$	65, 6582	hot CNO cycle
$^{17}, ^{18}\text{F}(\text{p}, \gamma)^{18}, ^{19}\text{Ne}$	65, 6582	hot CNO cycle
$^{18}, ^{19}\text{Ne}(\text{p}, \gamma)^{19}, ^{20}\text{Na}$	1.7, 17.2	hot CNO/rp process
$^{21}\text{Na}(\text{p}, \gamma)^{22}\text{Mg}$	22.5	NeNaMgAl cycles, rp process
$^{26}\text{MgAl}(\text{p}, \gamma)^{27}\text{Si}$	6.3	NeNaMgAl cycles rp process

Table 4a

Production Yields (particles $\cdot \text{s}^{-1} \cdot \mu\text{A}$ of proton) at TISOL
(heated surface ion source)

Isotope	Half-Life (sec)	SiC	Nb	Target* Zr	ZrC	UO/C
^8Li	.844	1.1×10^7	7×10^4	-	3.1×10^6	4.0×10^5
^9Li	.177	5.5×10^4	-	-	1.4×10^5	-
^{11}Li	87ms	-	-	-	2×10^3	-
^{20}Na	.446	1.8×10^6	-	-	2.3×10^3	-
^{21}Na	2.25	5×10^7	-	1.5×10^4	5.5×10^4	4.6×10^4
^{24}Na	20.2ms	1.2×10^7	-	-	-	-
^{25}Na	59.6	1.5×10^7	3.2×10^4	7.1×10^5	2.3×10^5	4.6×10^4
^{26}Na	1.07	2.9×10^5	5.7×10^2	1.4×10^3	1.2×10^4	8.5×10^4
^{27}Na	.304	1.7×10^4	-	-	9.8×10^2	3.5×10^3
^{28}Al	134.4	1.6×10^4	-	-	-	-
^{29}Al	393.6	8.3×10^3	-	-	-	-

^{35}K	.19	-	-	-	-	-
^{36}K	.34	-	-	2.1×10^6	-	-
^{37}K	1.23	-	2.3×10^4	7.5×10^5	4.7×10^4	-
^{38}K	458	-	2.4×10^5	2.8×10^5	4.3×10^6	-
^{42}K	12.36h	-	5.0×10^5	7.5×10^5	-	-
^{43}K	22.3h	-	5.4×10^5	2.85×10^5	-	-
^{44}K	1328	-	4.6×10^4	6.3×10^4	4.4×10^4	-
^{45}K	1038	-	7.0×10^3	2.1×10^4	2.2×10^4	-
^{46}K	108	-	9.2×10^2	3.4×10^3	2.4×10^3	-
^{47}K	17.5	-	1.5×10^3	1.0×10^3	-	-

* Target thicknesses - SiC ($6.06 \text{ g} \cdot \text{cm}^{-2}$), Nb ($11.57 \text{ g} \cdot \text{cm}^{-2}$)
 Zr ($6.32 \text{ g} \cdot \text{cm}^{-2}$), ZrC ($14.9 \text{ g} \cdot \text{cm}^{-2}$),
 UO/C ($1 \text{ g} \cdot \text{cm}^{-2}$)

Table 4b

Production Yields (particles $\cdot$ s $^{-1}$ $\cdot$ μ A of proton) at TISOL
(heated surface ion source)

Isotope	Half-Life (sec)	Nb	Target* Zr	ZrC
⁷⁵ Rb	21.4	2.1 x 10 ³	3.1 x 10 ³	1.3 x 10 ³
⁷⁶ Rb	37.0	1.0 x 10 ⁵	8.7 x 10 ⁴	9.5 x 10 ⁴
⁷⁷ Rb	222	4.0 x 10 ⁶	3.5 x 10 ⁶	1.5 x 10 ⁶
^{78m} Rb	345.6	1.2 x 10 ⁷	7.0 x 10 ⁶	1.0 x 10 ⁷
^{78g} Rb	1060	6.9 x 10 ⁶	2.8 x 10 ⁶	7.1 x 10 ⁶
⁷⁹ Rb	1374	1.6 x 10 ⁸	1.0 x 10 ⁸	7.7 x 10 ⁷
⁸⁰ Rb	34	2.9 x 10 ⁷	3.7 x 10 ⁷	2.0 x 10 ⁷
^{81g} Rb	4.58h	5.2 x 10 ⁸	2.6 x 10 ⁸	1.2 x 10 ⁹
^{82m} Rb	6.47h	4.1 x 10 ⁸	2.1 x 10 ⁸	4.2 x 10 ⁸
^{82g} Rb	76.2	8.8 x 10 ⁶	1.9 x 10 ⁷	1.4 x 10 ⁷
⁸³ Rb	86.2d	4.6 x 10 ⁸	-	1.0 x 10 ⁹
^{84m} Rb	1216	2.4 x 10 ⁷	4.8 x 10 ⁷	6.8 x 10 ⁷
^{86m} Rb	61.0	2.5 x 10 ⁵	6.7 x 10 ⁶	6.3 x 10 ⁶
⁸⁸ Rb	1068	2.8 x 10 ⁴	3.3 x 10 ⁶	2.7 x 10 ⁶
⁸⁹ Rb	912	-	3.8 x 10 ⁶	1.2 x 10 ⁶
^{90m} Rb	258	-	7.1 x 10 ⁵	1.5 x 10 ⁵
^{90g} Rb	156	-	5.0 x 10 ⁴	3.0 x 10 ⁴
⁹¹ Rb	58.4	-	1.7 x 10 ⁵	3.7 x 10 ⁴
⁷⁷ Sr	9	-	-	9.0 x 10 ³
^{83m} Sr	4.95	8.9 x 10 ³	6.1 x 10 ³	-
^{83g} Sr	32.4h	1.7 x 10 ⁷	8.5 x 10 ⁶	3.3 x 10 ⁷
^{85m} Sr	4060	5.7 x 10 ⁵	1.9 x 10 ⁶	-
^{87m} Sr	67.6m	1.2 x 10 ⁵	4.3 x 10 ⁵	5.2 x 10 ⁵
⁹¹ Sr	9.5h	-	-	1.4 x 10 ⁵

*Target thicknesses - Nb (11.57 g $\cdot$ cm $^{-2}$), Zr (6.32 g $\cdot$ cm $^{-2}$),
ZrC (14.9 g $\cdot$ cm $^{-2}$)

Table 4c

Production Yields at TISOL
(heated surface ion source)

Isotope	Half-Life (sec)	Target* UO/C (1)
Rb-79	1.374E+03	2.90E+04
Rb-80	3.400E+01	3.70E+04
Rb-86M (6-)	6.102E+01	7.40E+06
Rb-89	9.120E+02	1.90E+07
Rb-90M (4-)	2.580E+02	1.50E+07
Rb-91	5.840E+01	1.40E+07
Rb-92	4.500E+00	6.80E+05
Rb-93	5.860E+00	6.20E+05
Rb-94	2.780E+00	3.40E+05
Rb-95	3.840E-01	2.80E+04
Rb-96	1.990E-01	7.60E+03
Rb-97	1720E-01	2.00E+03
Rb-98	1140E-01	1.00E+02
Ga-79	2.630E+00	1.50E+03
Ga-80	1.670E+00	7.10E+02
In-122a	1.500E+00	1.80E+04
In-122b	1.030E+01	3.30E+04
In-122c	1.080E+01	1.60E+05
In-124G	3.210E+00	2.80E+04
In-124m	2.400E+00	5.60E+04
In-126G	1.500E+00	9.60E+03
In-126m	1.450E+00	9.30E+03
In-128G	9.000E-01	9.80E+02
In-128m	9.000E-01	1.30E+04
Cs-124g	2.650E+01	6.00E+04
Cs-126	9.840E+01	5.7E+05
Cs-128	2.34E+02	1.99E+06
Cs-130	1.500E+03	4.57E+06
Cs-139	5.562E+02	1.33E+07
Cs-140	6.370E+01	2.51E+06
Cs-141	2.494E+01	3.15E+06
Cs-142	1.780E+00	6.02E+04
Cs-143	1.780E+00	6.69E+04
Cs-144	1.020E+00	1.41E+04
Cs-145	5.900E-01	5.61E+03

*Target thickness - 1 g $\cdot$ cm $^{-2}$

Table 5

Production Yields with ECR at TISOL (Ti target - 5.45 g/cm ²)			
Isotope	Half-life (sec)	Production Yield (particles/s/ μ A of protons)	Comments*
²³ Ne	37.24	1.1 x 10 ⁵	
²⁴ Ne	202.8	2.7 x 10 ⁴	
³⁴ Cl	1920	2.7 x 10 ⁴	as Cl ⁺ ion
³⁴ Cl	1920	9.6 x 10 ⁴	as HCl ⁺ ion
³⁸ Cl	2234	8 x 10 ⁴	as Cl ⁺ ion
³⁵ Ar	1.77	7.2 x 10 ⁴	
⁴¹ Ar	1.83h	4.5 x 10 ⁶	
⁴³ Ar	110.1	1.2 x 10 ⁴	as Ar ⁺⁺ ion

* unless indicated all observed species are singly charged

Figure Captions

1. A schematic representation of the proposed ISAC (isotope separator and accelerator) facility at the intermediate energy (500 MeV) proton facility, TRIUMF. Included is a possible experimental system which could be used to measure the reaction products arising from the interaction of the low energy radioactive beam such as ¹⁵N with a hydrogen gas target.
2. A schematic representation of the elevation view of the TISOL facility, located on beam line 4A at TRIUMF. The front end of TISOL shows the configuration for a heated surface ion source, situated in the target/ion source (TIS) vacuum chamber.
3. This figure is similar to figure 2 except the new ECR ion source is situated at the front end. In this configuration the target chamber is separated from the ion source.
4. This is a schematic, detailed representation of the newly installed ECR system at TISOL. The ion source is the large chamber on the left while the target chamber is on the right.

The ISOL / Post - Accelerator

Fig. 1

- 1 TIS Box
- 2 Faraday Trunk
- 3 Faraday Cup
- 4 Wire Scanner
- 5 Magnetic Quadrupoles
- 6 Analyzing Magnet
- 7 Analyzing Slits
- 8 Electrical Quadrupoles
- 9 Electrical Bender
- 10 Electrical Steering

Fig. 2

Fig. 3

- SAMARIUM COBALT
 - IRON
 - INSULATOR
 - COPPER
- SCALE IN CENTIMETERS