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AN ISOL/POST-ACCELERATOR FACILITY FOR NUCLEAR ASTROPHYSICS AT TRIUMF

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Abstract

A facility to perform measurements of nuclear reaction rates in which one of the reactants is a radioactive species is described. The value of these reactions to the area of nuclear astrophysics is discussed in detail and calculations of expected yields for selected examples are given. This proposed facility is composed of an on-line isotope separator (ISOL) front-end coupled to a booster post-accelerator stage to raise the energy of a radioactive ion beam to sufficient energies (up to 1.5 MeV/u) to perform these studies. The advantages of this approach are presented along with a discussion of the feasibility of not only obtaining the necessary radioactive beam intensities of the important isotopes, but also of achieving the acceleration necessary. Details of one feasible accelerator system are presented.

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1. Introduction

Scientific needs as well as the availability of high current medium-energy proton accelerators have made it reasonable to consider coupling a high-current on-line isotope separator (ISOL) system to a post-accelerator. Such an accelerated radioactive ion beam (RIB) facility could produce beams with currents of up to 100 nA for isotopes close to the valley of stability, accelerate them in several stages up to 1.5 MeV/u (or higher if necessary) and deliver the ions to the experimental areas for use in new types of experimental programs. A general description of such a facility has been presented to some extent in two workshops [1,2], in several publications [3,4], and in proposals to TRIUMF [5,6]. For simplicity, this combined ISOL and accelerator facility is referred to as ISAC.

In this report we will give a summary of the scientific rationale for such a system based upon its requirements in the area of nuclear astrophysics, present arguments supporting this approach for performing these kinds of studies, summarize the desired features of the proposed facility, and explore the feasibility not only of building such a facility but also of performing these kinds of experiments in nuclear astrophysics. An overview of the entire proposed TRIUMF-ISOL facility is given in another contribution [7] to this conference as is the proposed development of new (for ISOL systems) ion source technology, i.e., an Electron Cyclotron Resonance (ECR) source, believed essential to achieve the RIB intensities required here [8]. The construction of the small test ISOL system (TISOL) to be used as a system for developing new target and ion source systems for ISAC is also presented in another contribution [9].

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2. Scientific motivation

2.1 Overview

It will be possible to investigate a large variety of problems in nuclear physics, nuclear astrophysics and condensed matter physics through the use of accelerated radioactive ion beams. These include

- i) nuclear astrophysics (sect. 2.2) [1,2,5]
- ii) reactions involving nuclei in isomeric states
- iii) structure studies of very neutron-rich, light isotopes using reaction spectroscopy
- iv) Coulomb excitation of radioactive isotopes used as projectiles
- v) search for superheavy elements [10]
- vi) studies with polarized radioactive beams [11]
- vii) migration of deeply implanted radioactive isotopes
- viii) lattice dislocation studies via implanted radioactive isotopes (detection, for example, via the Mössbauer effect and perturbed angular correlations)
- ix) deep implantation of radioactive isotopes to simulate and study the behavior of deeply implanted stable ions.

2.2 Radioactive ion beams in nuclear astrophysics

The strongest immediate demand for ISAC comes from the field of nuclear astrophysics [12-18]. It has been suspected for some time that in some stellar environments, especially explosive events, the simple fusion reactions that are occurring involve both stable and unstable nuclei as reactants. This occurs due to the higher temperatures and the very short time scales involved. Thus the well-known CNO-cycle [12] for example, will transform into the hot CNO-cycle starting with the

$^{13}\text{N}(\text{p},\gamma)^{14}\text{O}$ reaction, rather than the ^{13}N ($T_{1/2} = 9.96$ min) decaying to ^{13}C . Fig. 1 displays the hot CNO cycle and the isotopes/reactions involved. This cycle may well be responsible for the production of the very reactive isotopes ^{15}N and ^{19}F from their radioactive progenitors, ^{15}O and ^{19}Ne .

For higher temperatures and densities the isotopes near the proton drip line such as ^{14}O , ^{15}O , ^{18}Ne can capture α -particles via (α,p) or (α,γ) and thus proceed into the $A > 20$ region. From there, by rapid proton capture (rp-process [19]) without a significant backflow via the (p,α) reaction, material can be transformed to isotopes in the iron region and even beyond ($A \approx 100$). This process involves many reactions with radioactive isotopes of which little is known on either the Q -values or the reaction rates.

The validity of the rp-process may well have been supported by the recent observation of the type I X-ray burst. These bursts are believed to occur on the surfaces of accreting neutron stars [13,20-23].

Evidence for the existence of explosive stellar events has been found in the interstellar medium. The presence of radioactive ^{26}Al ($T_{1/2} = 17.35 \times 10^5$ yr) is indicated indirectly by the presence of anomalous amounts of ^{26}Mg in meteoric material [24] and directly by the observation of a γ -ray line from the decay of ^{26}Al [25] (see also ref. [14]). Thus there is a need to explain the production of ^{26}Al . One reaction network that may occur in hot, static hydrogen burning is the MgAl-cycle as displayed in fig. 2. Again many reactions of radioactive isotopes are assumed to take place including the $^{26}\text{Alm}(\text{p},\gamma)^{27}\text{Si}$ reaction starting from the short-lived isomeric state ($T_{1/2} = 6.3$ s) of ^{26}Al .

All reactions in the network are coupled and thus their relative production depends on the rates of all fusion processes.

Examples of some reactions considered important and of high priority for early determination are given in table 1 [6].

2.3 Stellar reaction rates and specific reactions

2.3.1 Nuclear cross sections

The number of reactions for a certain density and per unit time is given by:

$$\langle \sigma v \rangle (T) = \int_0^{\infty} M(v, T) \cdot v \cdot \sigma(v) \cdot dv \quad (1)$$

where

$\langle \sigma v \rangle (T)$ = stellar reaction rate

$M(v, T)$ = Maxwell-Boltzmann velocity distribution for a temperature, T

$\sigma(v)$ = reaction cross section .

In this integral the strong energy dependence of the Maxwell-Boltzmann distribution and the reaction cross section will result in a narrow energy range (Gamow peak) over which the cross section of a specific nuclear reaction has to be determined to evaluate the reaction rate integral. In most cases this relevant energy range is actually far below the Coulomb barrier. This means that the reaction rates are often dominated by one or more very narrow resonances although, in some cases, a direct capture reaction is important. The latter is normally several orders of magnitude weaker than a resonant reaction. For resonance dominated reactions the integrated strength $\omega \gamma$ at the resonance energy, E_R , is important for the stellar reaction rate, i.e.,

$$\omega \gamma = \omega \frac{\Gamma_i \Gamma_f}{\Gamma} \quad (2)$$

with

$$\omega = \frac{2J_R + 1}{(2J_p + 1)(2J_T + 1)} = \text{statistical factor}$$

and

J_R = spin of the resonance state

J_p = spin of the projectile

J_T = target spin

Γ_i = energy width of incident channel

Γ_f = energy width of final exit channel

$\Gamma = \Gamma_i + \Gamma_f + \Gamma_a + \dots$ = total width of resonant state

and

$$\langle \sigma v \rangle \sim \omega \exp(E_R/kT). \quad (3)$$

For several narrow resonances the total rate is given by the incoherent sum of single resonance rates. These rates are in general difficult to predict accurately due to uncertainties in the nuclear configurations as well as a strong dependence on the (sometimes uncertain) energy of a state.

In general because of the low cross-sections involved experimental determination of these cross-sections or total resonance strengths take considerable periods of time using high intensity/low energy proton (or α) facilities and targets able to withstand the high currents. When using radioactive heavy ion beams the actual laboratory reaction will be inverted. To effect a (p, γ) reaction a hydrogen gas target would be used while for an (α, γ) or (α, p) reaction helium gas will be the target. Highly efficient detectors will be required as discussed below, though the cross sections in explosive stellar burning are somewhat higher than in hydrostatic burning due to the higher temperatures of these events.

2.3.2 Specific reaction yields

To evaluate the feasibility of determining rates of reactions when radioactive nuclei are involved, reaction yields have been calculated [3] using resonance strengths taken from theoretical works or deduced from the isobaric analogue states, and assuming standard conditions of a RIB with 10^{10} ions/s and a target with 10^{18} atoms/cm²; the latter is reasonable for achieving target thicknesses of the order of a few keV in the center-of-mass system.

2.3.2.1 $^{13}\text{N}(p,\gamma)^{14}\text{O}$

There have been three recent theoretical calculations of the cross section for this reaction [26,27,28] using widths Γ in the range of 1.2-2.4 eV for the single resonance expected at 547 keV. This resonant structure as well as the analogue ^{14}N structure is displayed in fig. 3. The total width of the resonance is 38.1 ± 1.8 keV [29]. A recent study of resonant and direct capture in the $^{13}\text{C}(p,\gamma)^{14}\text{N}$ reaction has yielded a spectroscopic factor of $S = 0.45 \pm 0.09$ for direct capture into the 2.31 MeV first excited state in ^{14}N [30]. As the $^{13}\text{C}(p,\gamma)^{14}\text{N}$ reaction is the analogue to the $^{13}\text{N}(p,\gamma)^{14}\text{O}$ reaction, this spectroscopic factor was used in conjunction with the values for the gamma and total widths quoted above to calculate pseudo-experimental S-factor curves for the $^{13}\text{N}(p,\gamma)^{14}\text{O}$ reaction. Table 2 presents the expected yields based upon these estimates, and the standard beam and target parameters given above.

2.3.2.2 $^{19}\text{Ne}(p,\gamma)^{20}\text{Na}$

One broad level at $E_x = 2.890$ MeV [31] determines the stellar reaction rate of $^{19}\text{Ne}(p,\gamma)^{20}\text{Na}$ over a wide range of temperatures. Recent calculations [16] show that this level is probably an overlap of three

narrow ones. Nevertheless, expected reaction rates were estimated taking this level as single [19] and in addition using information on other levels of ^{20}Na . Table 3 summarizes the results given the standard beam/target conditions.

Note that the resonance strengths are estimated using medium strength proton spectroscopic factors. In reality some of the resonance strengths can be higher by a factor of 10^3 and yields correspondingly higher than calculated here. In addition to the resonance yield, the direct capture process has to be taken into account. A typical cross section for proton capture at about 1 MeV/u in this mass region is 1 μb , yielding 36 events/h.

In conclusion, astrophysically important reactions will have absolute yields of $1-10^4$ events/h (into 4π) assuming beam currents of 10^{10} ions/s and thin (relative to the beam energy) targets. Thus a high RIB intensity as well as the use of sensitive detection systems are mandatory to perform such astrophysical measurements.

3. Experimental approaches to measuring reaction rates

3.1 Nuclear spectroscopy

In rare cases, such as $^{13}\text{N}(p,\gamma)^{14}\text{O}$ (fig. 3) where only a single level in the compound nucleus exists in the relevant energy region, e.g., first excited state in ^{14}O , the relevant quantities $\omega\gamma$ and E_R can be determined, in principle, indirectly via standard nuclear spectroscopy.

A measurement of the excitation energies of the relevant states near the particle threshold combined with the associated reaction Q-value leads to an estimate of each E_R . Under favorable conditions, information on the partial and total width might then be obtained, thus leading to a value of $\omega\gamma$. In the above example, the relevant state was broad enough to

extract a value of $\Gamma = 38.1$ keV from the width of the $^{14}\text{N}(^3\text{He}, t)^{14}\text{O}$ triton-particle group feeding this state [29]. Particle recoil-coincidence techniques will eventually lead to a ratio of Γ_γ/Γ [32] and, since $\Gamma_p \gg \Gamma_\gamma \approx \text{few eV}$, the strength $\omega\gamma = \omega \frac{\Gamma_\gamma \Gamma_p}{\Gamma}$ is thus determined via Γ_γ . Such measurements are rather difficult and time-consuming and thus have not yet been successful for radioactive isotopes. For example, the determination of the 3α [$\alpha(\alpha, \gamma)^8\text{Be}(\alpha, \gamma)^{12}\text{C}$] reaction rate via such indirect measurements took about 12 years. These examples demonstrate that such indirect determination of $\langle\sigma v\rangle$ via individual level structure studies is not a viable solution for the wide field of reactions, in particular for cases where the compound nucleus has a more complex structure and single states cannot be resolved by present techniques. In addition one can never be sure of having not missed or confused states by indirect measurements as recent results on ^{26}Al demonstrate [33,34]. Furthermore, direct capture components or interfering state contributions are impossible to access by indirect spectroscopic means.

3.2 Radioactive beams and radioactive targets

Direct determinations of $\langle\sigma v\rangle$ require either the availability of a radioactive target (RT) or RIB. An important question is then the relative merit of these two alternatives. Suppose, for example, that one has a separated beam of radioactive nuclei and wants to study the reaction $A+x \rightarrow B+\gamma$, where x is a stable nucleus (here mainly protons and α -particles). Should one (fig. 4) collect nuclei A to form a radioactive target and bombard this target with the projectiles x , or should one accelerate the nuclei A and let them impinge on a target of x -type nuclei? If the radioactive nuclei with half-life $T_{1/2}(= \ln 2 \cdot \tau)$ are produced with a rate N_A and form a target of area F (fig. 4a), the total

number of reactions $A(x, \gamma)B$ over the bombarding time T is

$$N(\text{RT}) = \frac{\sigma N_A N_x(b) \tau}{F} [T - \tau + \tau \exp(-T/\tau)] \quad (4)$$

where σ is the reaction cross-section and $N_x(b)$ the beam current. If the radioactive nuclei are accelerated (with a loss factor f) and impinge on a target of $N_x(t)$ target atoms per cm^2 (fig. 4c), the total number of reactions over the time T is:

$$N(\text{RIB}) = \sigma N_A N_x(t) f T \quad (5)$$

For the case of $T_{1/2} \gg T$, both approaches provide the same number of reactions, $N(\text{RT}) = N(\text{RIB})$, for the (mean life) condition

$$\tau = F f \frac{N_x(t)}{N_x(b)} \quad (6a)$$

and this condition is independent of σ , N_A and T . For an order of magnitude estimate, the values $F=1 \text{ cm}^2$, $f=10\%$, $N_x(t) = 10^{19} \text{ atoms/cm}^2$ and $N_x(b) = 100 \text{ } \mu\text{A} = 6 \times 10^{14} \text{ projectiles/sec}$, one finds $\tau=28 \text{ min}$.

In the other extreme case, $T_{1/2} \ll T$, equality of $N(\text{RT})$ and $N(\text{RIB})$ leads to the relation

$$T = \frac{\tau^2}{T - F f N_x(t)/N_x(b)} \quad (7)$$

which requires for $T > 0$ the condition

$$\tau = F f \frac{N_x(t)}{N_x(b)} \quad (6b)$$

which is the same condition as above. Note again that this relationship is independent of σ and N_A . Taking both together, the decision, of which approach to take becomes almost independent of the measuring time. It follows then that for half-lives shorter than about 0.5-1 h, radioactive ion beams are needed (fig. 3-2c), while for half-lives longer than

In the production of an on-line radioactive target is better (fig. 3-2d). This is consistent with other estimates [10,35]. For example, taking $T_{1/2} = 1s$ and $T \gg 1s$ and again using the above values for $F, f, N_X(t)$ and $N_X(b)$, then the ratio of productivity for both approaches is $N(RIB)/N(RT) \approx 10^3$.

The above discussions are based solely on a comparison of productivity for both experimental approaches. However, in the RT-technique there is the problem of the large background due to the "hot" target, in particular for nuclei with short half-lives (see below). This might shift the dividing line between both approaches to somewhat longer half-lives. In summary, for the study of the wide field of reactions induced on nuclei with $T_{1/2} < 1h$ (which is the case for nearly all reactions of astrophysical interest), the radioactive-ion-beam technique appears to be the proper, preferred and indeed the only experimental approach.

3.3 Luminosities of different approaches using

accelerated radioactive ions

Several techniques have been proposed for the production of radioactive ion beams [3-5,36-39]. In comparing the different techniques, the luminosity L is often used as a figure of merit. It is defined as the product of the number of projectiles per unit time, N_p times the number of target atoms per area, N_t . The observed reaction rate, N , is related to the luminosity, reaction cross section σ , and detection efficiency ϵ , by

$$N = L\epsilon\sigma \quad (8)$$

For example, a radioactive ion beam with $N_A = 10^{10} \text{ ions}\cdot\text{s}^{-1}$ and an accelerator transmission factor of $f = 0.10$ provides a beam of $N_p = fN_A = 10^9 \text{ projectiles}\cdot\text{s}^{-1}$. With $N_t = 10^{18} \text{ atoms}\cdot\text{cm}^{-2}$ the

luminosity is $L=10^{27} \text{ cm}^{-2}\cdot\text{s}^{-1} = 1 \text{ mb}\cdot\text{s}^{-1}$. For $\sigma=1 \text{ mb}$ and $\epsilon=10\%$ (see below) one finds $N = 0.1 \text{ events}\cdot\text{s}^{-1}$.

In the conversion method [36-38], primary production reactions with large cross sections and favorable kinematics are used to convert a primary heavy-ion beam into a secondary radioactive ion beam. For example, the reactions $^7\text{H}(\text{Li}, ^7\text{Be})n$ and $^3\text{He}(^{16}\text{O}, ^{15}\text{O})^4\text{He}$ have cross sections in the range of 10-100 mb and emit the radioactive nuclides ^7Be and ^{15}O into a narrow forward cone with energies similar to the primary heavy ion beam ($E \approx 1 \text{ MeV/u}$). The primary and secondary beams are separated from the beam transport systems by using kinematic constraints. For optimum conditions a useful radioactive beam intensity of $N_A \approx 10^6\text{-}10^8 \text{ ions}\cdot\text{s}^{-1}$ is expected [10,37-38] and thus $L = 0.001\text{-}0.1 \text{ mb}\cdot\text{s}^{-1}$. The conversion method suffers from the small conversion factor of 10^{-4} to 10^{-7} for the production of secondary beams. Furthermore recoiling ions at low energies have a large energy spread.

With high energy heavy-ion beams ($E > 100 \text{ MeV/u}$) it is found that many isotopes are produced with large cross sections ($\sigma < 100 \text{ mb}$) via projectile fragmentation [39]. These fragments are emitted into a very narrow cone in the forward direction and have a velocity similar to the primary heavy-ion beam. With a heavy-ion beam intensity of $6 \times 10^{11} \text{ ions}\cdot\text{s}^{-1}$ and a primary target of $7 \times 10^{22} \text{ atoms}\cdot\text{cm}^{-2}$ (i.e. $1 \text{ g}\cdot\text{cm}^{-2}$ of ^9Be), the secondary beam intensity can be as high as $4 \times 10^9 \text{ ions}\cdot\text{s}^{-1}$, indicating a conversion factor of 10^{-2} for radioactive ions not too far removed from the mass of the projectile. Subsequent mass selection and energy spread reduction of the beam can be achieved at the cost of intensity, depending on the beam characteristics desired. For nuclear reactions of astrophysical interest, the final radioactive ion beams may

have to be decelerated to energies around 1 MeV/u causing another reduction in beam intensity. Such techniques are presently being developed at several heavy-ion laboratories. A related approach uses relativistic heavy-ion beams ($E > 1$ GeV/u) to produce radioactive beams by electromagnetic dissociation of the projectile [10].

As indicated a viable alternative is to combine an ISOL device (as the front end) with a booster post-accelerator stage leading to the production of intense RIB [3-5,39]. In this method a thick target ($\approx 6 \times 10^{23}$ atoms $\cdot \text{cm}^{-2}$) is bombarded with an intense proton beam (> 10 μA = 6×10^{13} protons $\cdot \text{s}^{-1}$) of about 200-600 MeV. The radioactive nuclides are produced by spallation or proton-induced fission ($\sigma \approx 20$ mb) at a rate of about 10^{12} ions $\cdot \text{s}^{-1}$. Nuclides are continuously extracted from the target, ionized and mass separated on-line to provide a RIB with characteristics appropriate for studies of astrophysically interesting nuclear reactions. Accelerator systems such as a linear accelerator are able to provide the necessary beam energies ($E \approx 1$ MeV/u) and acceptable energy spreads. These systems have a beam transmission efficiency of greater than 50%, so a luminosity of greater than $L = 5 \cdot 10^{29}$ $\text{cm}^{-2} \text{ s}^{-1}$, sufficient for most applications would be achievable.

Thus the ISOL accelerator (ISAC) approach shows the highest luminosity (about 3 orders of magnitude higher than the best of the others) achievable for radioactive ions.

Similar luminosities could be achieved with the use of a low-energy (50 MeV) proton cyclotron with a high current of, for example, 500 μA . The beam would then intercept a thinner target than used with medium energy protons. Combined with the higher cross sections near stability this would lead to a similar yield of radioactive ions. Subsequently the

radioactive products would have to be released and ionized as with an ISOL as discussed above, followed by an accelerator. Thus it would be the same kind of facility as described here, but with only a limited range of experimental possibilities. For example, nuclei far from stability would not be produced in this approach.

3.4 Specifications of the TRIUMF-ISOL radioactive beams facility

The discussion above indicates that the ISAC facility is a most promising approach to measure small cross sections of interest to nuclear astrophysics from the point of view of expected yields and experimental conditions. Based upon the requirements for the successful completion of such experiments, a set of specifications has been determined for the ISAC facility and these are listed in table 4 [40]. It is now of importance to consider the feasibility of such a facility from the point of view of producing the required intensities of the isotope of interest as well as a realistic method of accelerating these separated isotopic ion beams.

4. Production of intense RIB for low Z isotopes

4.1 Overview

The goal is to achieve RIB intensities of the order or better than 10^{10} ions $\cdot \text{s}^{-1}$, although some useful studies could be performed with lower intensities. In general such intensities are obtainable from the point of view of production using intermediate energy protons and thick targets, at least for species close to stability. Both calculations and studies elsewhere [41] support this in principle, with yields up to 10^{11} ions $\cdot \text{s}^{-1}$ per μA of incident proton, presently available for selected species. With the possibility of using proton beam intensities over 100 μA at today's meson facilities such as TRIUMF, LAMPF, and SIN, the RIB intensities required should be within reach with technology available

today. However, the isotopes indicated to be of initial interest (see table 1) are ones for which little interest has been shown previously and observed production rates had not been optimized. These could be improved significantly both by more appropriate target selection and with improvements in ion source (IS) technology. In addition questions concerning handling of high power levels and high radiation fields do arise, when proton beam currents as high as 100 μ A into the thick targets used at ISOL proton facilities are proposed.

4.2 Present situation

The radioisotopes of immediate interest are ^{13}N (10 m), ^{14}N , ^{15}O (71 s, 2 m), ^{18}F (110 m), ^{18}Ne (1.7 s, 17 s) and $^{20,21}\text{Na}$ (0.4 s, 22.5 s) as well as isomeric states of ^{26}Al (6.4 s) and ^{34}Cl (32.2 m), although a wide range of similar proton-rich species up to $A \approx 60$ are of great interest [13,19]. The status in terms of present ion beam intensities is summarized in table 5 as taken from Ravn [41]. Clearly none of these at present meets the optimal production rate. The most obvious problem appears to arise from low IS efficiencies for most cases. New approaches in IS technology which could increase such efficiencies, especially for gaseous species, will be presented in a separate contribution to this conference [8]. Some specific cases are discussed below.

4.3 Specific cases

4.3.1 Nitrogen-13

The highest intensity reported to date is $4 \times 10^5 \text{ ions}\cdot\text{s}^{-1}$ (per μ A of incident protons) from a CaO powder target ($6.5 \text{ g}\cdot\text{cm}^{-2}$), operated at 1200°C and with a plasma ion source. The form of the nitrogen is probably as molecular N_2 [41]. The calculated production rate is close to $3 \times 10^9 \text{ ions}\cdot\text{s}^{-1}$ so a significant loss is occurring. One suggestion is

that tantalum (in the diffusion and transfer lines) acts as a collector for nitrogen. Use of other materials may improve the observed rates. Other target materials that are to be tested (on the TRIUMF TISOL test facility [9]) include MgO , BeO , and ^{13}C (as graphite). Molten sodium has excellent thermal properties as a so-called 'heat pipe' capable of handling very high power levels by refluxing [42,43]. Studies are underway with TISOL to determine if such a molten sodium target will indeed release nitrogen [9]. The most obvious method of producing higher yields is with an ECR ion source. Reports indicate ionization efficiencies up to 30% [44]; this development will be discussed elsewhere [8].

4.3.2 Neon-18, neon-19

The highest reported production rate for ^{19}Ne is $3 \times 10^7 \text{ ions}\cdot\text{s}^{-1}$ (per μ A of incident proton) from a MgO powder target ($5.9 \text{ g}\cdot\text{cm}^{-2}$) operated at 1100°C , with a plasma ion source; a value of $6 \times 10^6 \text{ ions}\cdot\text{s}^{-1}\cdot\mu\text{A}^{-1}$ was observed for ^{18}Ne [45]. The most obvious improvements are the use of thicker production type targets as well as new IS technology [8]. Other targets to be studied (on TISOL) are again molten sodium and aluminum carbide. Similar studies with molten cesium have shown that xenon is released efficiently [43]. A molten aluminum target is also under study but it may introduce severe handling problems [46].

4.3.3 Sodium-21

The situation here is that only about $10^5 \text{ ions}\cdot\text{s}^{-1}$ (per μ A of protons) have been observed since the target used (Ta) was selected to produce neutron-rich sodium isotopes; the cross section for ^{21}Na production is of the order of 2 μb . Given the high ionization efficiency for alkali elements with surface sources and a better target such as Hf_3Si_3 (cross section is of the order of mb for sodium production from the

silicon) which is known to release sodium efficiently [47] or perhaps molten aluminum, if developed, the required production rates should be achievable.

4.4 Areas for improvement/developments

A general description of possible systems including targets which might increase the production rates for isotopes from helium to calcium can be found in [45]. The question of handling of high power and high radiation levels will require attention. An increase in the diameter of the target and the beam is an obvious first attempt to keep power densities similar to present levels. Such massive targets would introduce longer holding times but this should not be a problem given that the half-lives of the isotopes of interest are of the order of seconds. A new concept of remote handling of the target/ion source systems is presented in the TRIUMF-ISOL facility proposal [5] and is discussed in a separate contribution to this conference [7].

5. Acceleration of RIB

Since no ion source is available which delivers high charge state ions with about the same efficiency as singly charged ions, it has been decided [40] to aim for an accelerator with the specifications of table 4 capable of handling the low charge to mass ratio ($q/A \approx 1/60$) and the low incident energy of 1 keV/u. Studies on electrostatic Tandem accelerators were excluded at an early stage since negative ions are not readily available for a great variety of isotopes at ISOL facilities. No provisions have been taken to include an experimental storage ring using internal targets in the accelerator solution, since it can be shown that under all circumstances such a storage ring is inferior in luminosity to the use of external target in the energy range considered here [48].

Thus the investigations concentrated on a cyclotron and a linear accelerator solution, the latter consisting of a Radio Frequency Quadrupole LINAC (RFQ) and a Drift Tube Linac (DTL), either of the room temperature or superconducting variety.

5.1 Cyclotrons

The cyclotron solution [49] would consist of two cyclotrons, either of them normal or superconducting. Stripping would be applied between the machines to increase the charge to mass ratio. The injection into the first cyclotron appears most feasible with lowest losses using a spiral (Belmont-Pasot) system. Prior to injection the beam would be bunched leading to about 25% losses. The beam would have to be operated close to the beta frequency, but the beam separation remains sufficient for a septum extraction. Different methods for adjusting the magnetic field and the frequency for specific ions and energies are feasible, but an adjustment of both at the same time seems to be the most convenient. The extracted energy range of the first cyclotron is expected to be between 0.017 and 0.17 MeV/u, depending on the configuration but with a fixed T/A. The diameter of the first normal-conducting cyclotron would be about 2.5 m (1.5 T field).

The second stage cyclotron could be a normal room temperature sector focussed facility or a superconducting machine. Axial injection would be possible, and the frequency and magnetic field, B, should be variable. The necessary dynamic energy range of about a factor of 10 is considered to be large but not impossible to achieve.

5.2 Linear accelerators

5.2.1 The RFQ

All linear accelerator solutions considered [50,51] consist of a RFQ

LINAC as the first stage. This RFQ would accelerate the singly charged ions from 1 keV/u to between 50 and 100 keV/u, where stripping to a higher charge state can be utilized. The RFQ would consist out of a modulated four-rod structure [50] operating at 23 MHz. To allow for a variable q/m while maintaining a constant injection velocity into the RFQ requires that it be operated with a variable DC bias. In ref. [51] the beam dynamics of such an RFQ has been studied for a 919.7 cm tapered bore configuration operating at 1.5 times the Kilpatrick sparking criterion. A transmission of 86% was achieved for a normalized emittance of $0.46 \pi \text{ mm} \cdot \text{mrad}^{-1}$ ($10 \pi \text{ mm} \cdot \text{mrad}^{-1}$ at 1 keV/u).

5.2.2 Second stage

A stripper positioned at the exit of the RFQ increases the charge to mass ratio of the ion beam. A gas stripper seemed best for this application though a solid state stripper should not be ruled out [50,51]. The gas stripper would lead predominantly to the 3^+ state at 60 keV/u. A beam line of 75 cm in length including two quadrupole magnets between the RFQ and a second stage LINAC was calculated [51] not to deteriorate the beam quality significantly prior to the acceptance in the LINAC.

5.2.2.1 Room temperature Drift Tube LINAC (DTL)

The DTL is of the Wideroe type. The resonators were assumed to be of the RIKEN type [52], but with a constant frequency of 23 MHz due to the RFQ. The LINAC was divided into eight independent powered tanks to allow output energy variation from 1 MeV/u down to 0.265 MeV/amu.

The energy spread at the extraction was calculated to be 1%, but can be reduced by single cavities and debunching lengths to 0.1%. The total power consumption of the room temperature LINAC was calculated to

be about 1 MW or roughly 2 MW of net power. The conceptual design of the RFQ-DTL configuration as proposed in ref. [51] is shown in fig. 5.

5.2.2.2 Superconducting linear accelerators

Recent developments in low frequency, low velocity superconducting RF cavities [53,54] make it feasible to consider a superconducting LINAC following the RFQ stage of the linear accelerator. Such a superconducting solution would reduce considerably the power and amplifier costs necessary in a normal conducting accelerator. In ref. [53] four types of resonators are proposed operating at a frequency of 50 MHz. The first one would accept a $\beta (=v/c)$ of 0.009 (38 keV/u) just sufficient to fit to a small RFQ. The other cavities would accept β values of 0.015, 0.03, 0.048 (105, 419, 1073 keV/u respectively). The combination of these structures potentially not only would accelerate efficiently over a wide range of velocities, but would lead to an accelerator solution with considerably less cost. Continuous energy variation is easily achieved in a superconducting LINAC by controlled phasing of the RF in each cavity. It should be emphasized, however, that detailed beam dynamic calculations have not been performed and focussing problems might make the use of such superconducting cavities impractical.

6. Experimental targets and detection systems for a RIB facility

6.1 Gas targets

For the study of proton- and α -induced reactions on radioactive nuclei, the role of projectile and target nuclei are interchanged with the RIB-approach, i.e. the radioactive nuclei are deployed on ^4He and ^4He targets. To maximize the reaction yield per incident particle, these targets have to be gaseous requiring differentially pumped (windowless) gas target systems. Such systems, including gas recirculation, have been

developed. They are (1) a quasi-static, geometrically extended gas target [55], and (2) a supersonic, quasi-potential jet gas target [56,57]. The latter is of particular importance if the heavy reaction products (recoil nuclei) are to be detected (see below). At present, these supersonic jet systems can provide H_2 and He densities of up to about 10^{17} atoms $\cdot$ cm $^{-2}$. However, for the above studies, higher gas densities are required. Higher densities can possibly be achieved by improvements in the pumping units but, more importantly by cooling the jet gas flow to a low temperature.

6.2 Detection systems

Radiative capture reactions $A(x,\gamma)B$ are important processes for the formation of most of the elements. They are usually studied in the laboratory by detecting the emitted γ -rays. In the radioactive target approach studies via standard γ -ray spectroscopy are extremely hampered by the radioactive decay of the target itself. For example, 1 μ g targets of ^{22}Na ($T_{1/2} = 2.602$ y), ^{18}F ($T_{1/2} = 110$ min), or ^{13}N ($T_{1/2} = 10$ min) produce a 511- (and 1274-) keV γ -ray flux of $4.8 \cdot 10^8$, $7.3 \cdot 10^{12}$, and $1.1 \cdot 10^{14}$ s $^{-1}$, respectively. To reduce the ^{13}N γ -ray flux to a level of, say, 10^4 s $^{-1}$ requires a 15 cm thick lead shielding around the target. This shielding also reduces the flux of the typical 3-8 MeV capture γ -rays by a factor of 10^{10} . In the RIB approach the beam is stopped in a beam dump far away from the gas target zone and the problem of a "hot" target appears to be absent. In practice, however, interception of the RIB with the apertures of the gas target system as well as divergence of the beam passing through the gas target may lead to non-negligible levels of background radiation at the target area. An ideal detector for γ -ray spectroscopic studies would thus have the following properties:

- i) low sensitivity for γ -rays accompanying β decay;
- ii) high and nearly uniform efficiency for fusion reaction products (γ -rays and/or heavy recoils);
- iii) sufficient energy resolution;
- iv) 4π geometry;
- v) low sensitivity to internal as well as external background.

6.2.1 Threshold detectors

Since the fusion γ -rays are normally of a higher energy (3-8 MeV) than those from radioactive decay, it is possible to use threshold effects (e.g. photodisintegration of nuclei, pair production) for the construction of a suitable detector for radioactive beams. Such a detector based on the photodisintegration of the deuteron (in heavy water) is presented in one of the contributions to this conference [58].

6.2.2 Recoil detectors

Since the recoiling nuclei B of a capture reaction $A(x,\gamma)B$ travel essentially in the same direction as the beam, their direct detection with detectors having up to a 100% efficiency could greatly improve the experimental sensitivity. This approach clearly requires a quasi-point source gas jet target. There are however some obvious problems if a detector is placed in the beam direction. One observes not only the capture products, but also the incident beam (including beam contaminants) the elastic scattering products, and other background events (from multiple scattering processes). These problems have been overcome using detection techniques such as Wien filters plus electrostatic and magnetic deflect ion devices. These and other techniques (i.e. coincidences between capture γ -rays and recoil nuclei B, time-of-flight to identify the recoil nuclei B, etc) are presently being exploited at several

laboratories [59,60]. Such a detector has been shown to have a detection efficiency of 20% for stable nucleus reactions at astrophysically important energies, including the coincidence between the capture γ -rays and the recoiling fusion products [59].

Given then the suppression factors for unwanted events of ref. [59], one can calculate the times necessary to obtain a measurement with 30% statistical error for given beam energies; these are presented in table 6 (target density: 10^{18} cm^{-2} , beam intensity: 10^{10} s^{-1}). As can be seen, the requirements of table 2 and 3 for specific reaction yields can be achieved by such a system. Note that for cross sections down to about 200 nb a γ -recoil coincidence is not necessary. In essence this could be difficult as the γ -ray detector is swamped by γ -rays following β -decay. Such a unit with its ionization chamber will also allow isobaric discrimination of recoil reaction products. This is useful as this sometimes is a problem in on-line isotope separators.

7. Conclusion

It has been shown that a radioactive beams facility as proposed for TRIUMF can meet the requirements necessary to perform nuclear astrophysics measurements and is technically feasible within present technology. Furthermore, it has been shown theoretically that a radioactive beams facility based on an isotope separator is by far the most luminous approach to accelerated radioactive beams, and possibly the only one that can be used to measure most of the astrophysically important cross sections for a great variety of isotopes. The further applications of ISAC in other fields of physics and nuclear physics are obvious and are an added bonus.

Table 1. Some reactions of astrophysical interest [6]

Reaction	$T_{1/2}$ of unstable reactant	Astrophysical interest
$^{13}\text{N}(p,\gamma)^{14}\text{O}$	598 s	hot CNO cycle
$^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$	122 s	rp-process
$^{18}\text{F}(p,\alpha)^{15}\text{O}$	6582 s	hot CNO cycle
$^{18}\text{F}(p,\gamma)^{19}\text{Ne}$	6582 s	hot CNO cycle
$^{19}\text{Ne}(p,\gamma)^{20}\text{Na}$	17.2 s	hot CNO/rp-process
$^{24}\text{Na}(p,\gamma)^{24}\text{Mg}$	22.5 s	NeNaMgAl cycles rp-process

Table 2. Thin target yields into 4π for $^{13}\text{N}(p,\gamma)^{14}\text{O}$

E (CM) (keV)	E (lab, ^{13}N) (MeV)	E/u (^{13}N) (MeV/u)	Yield (h^{-1})
700	9.800	0.754	60-120
547	7.658	0.589	(5-10) $\cdot 10^3$
365	5.110	0.393	20-40
260	3.640	0.280	2-4

Table 3. Thick target yields into 4π for $^{19}\text{Ne}(p,\gamma)^{20}\text{Na}$

Resonance energy E_{RCM} (MeV)	State energy E_x (MeV)	$E_{\text{R lab}}(^{19}\text{Ne})$ (MeV)	$E/u(^{19}\text{Ne})$ (MeV/u)	ω_γ^a (eV)	Yield (h^{-1})
0.694 ^b	2.890	13.88	0.731	0.004	11
0.770	2.966	15.40	0.811	0.005	13
0.771	2.967	15.42	0.812	0.006	15
0.979	3.175	19.58	1.031	0.002	5
1.292	3.488	25.84	1.360	0.003	6
1.330	3.526	26.60	1.400	0.001	4
1.391	3.587	27.82	1.464	0.007	13
1.485	3.681	29.70	1.563	0.006	11
1.565	3.761	31.30	1.647	0.006	11

a) Ref. [19]

b) See ref. [16]

Table 4. Specifications for an accelerated radioactive beams facility

(i) Beam intensity:	acceptable range, 10^5 - 10^{12} ions·s ⁻¹
(ii) Energy range:	0.2-1.5 MeV/u
(iii) Energy resolution:	<0.1% desirable, <1% acceptable
(iv) Energy increments:	continuous variability desirable, increments <0.25 MeV/u acceptable
(v) Mass limit:	all nuclides up to $A = 60$ ($q = \pm 1$)
(vi) Time structure:	either continuous or pulsed (assuming minimum losses). A microstructure of pulse duration <1 ns may be desirable for some applications.
(vii) Priority items for the future:	higher energy (up to 5 MeV/u), higher mass limit.

Table 5. Present status for isotopes of interest to astrophysics

Isotope	Obs. Prod. Rate ^a (ions·s ⁻¹ ·μA)	Target ^b (g·cm ⁻²)	Calc. prod. rate ^b (ions·s ⁻¹ ·μA ⁻¹)	Ion source type
^{13}N	4.1×10^5	CaO 2.6	6.5	plasma 0.1%
$^{14,15}\text{O}$	—	—	—	—
$^{17,18}\text{F}$	—	—	—	—
^{18}Ne	6×10^6	MgO 3	1.3	plasma 0.7%
^{19}Ne	3×10^7	MgO 3	8.1	plasma 0.7%
^{20}Na	($\approx 10^4$)	Ta 122	4×10^{-4}	SI 50%
^{21}Na	$\approx 1 \times 10^5$	Ta 122	2×10^{-3}	SI 50%
^{25}Al	—	—	0.4	—
^{26}Al	$\approx 1 \times 10^4$	SC ₂ 3.2	1.5	plasma 0.1%
^{22}Mg	$\approx 1 \times 10^3$	SC ₂ 3.2	0.074	SI 0.1%
^{23}Mg	7×10^4	SC ₂ 3.2	0.3	SI 0.1%
^{34}mCl	2×10^5	Ta+Nb 41+22	—	neg. SI —
^{37}K	8×10^7	SC ₂ 3.2	—	—

a) As taken from [41]

b) Calculated using empirical formulation of ref. [61]

c) As taken from [45]

Table 6. Measuring times for 30% statistics ($T_{30\%}$) in a recoil device based on ref. [59] [$\rho=10^{18} \text{ cm}^{-2}/I=10^{10} \text{ sec}^{-1}$]a)

	Reaction cross section σ	Y_{beam} (s^{-1})	$T_{30\%}$
Singles recoil	1 mb	3	3.7 s
counting = 30%	100 μb	0.3	38 s
efficiency	10 μb	3×10^{-2}	7.2 min
	1 μb	3×10^{-3}	2.7 h
	500 nb	1.5×10^{-3}	8.9 h
	300 nb	1×10^{-3}	18.5 h
	200 nb	6×10^{-4}	2 d
γ -recoil	1 μb	2×10^{-3}	1.5 h
coincidence	100 nb	2×10^{-3}	15 h
= 20%	50 nb	1×10^{-4}	31 h
efficiency	10 nb	2×10^{-5}	6.4 d

a) The coincidence setup assumes a zero background while the singles counting assumes background effects, thus longer measuring times.

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Figure captions

1. The hot CNO cycle. Large boxes indicate radioactive isotopes involved, including their half-lives. Arrows indicate different reaction flows (p, γ) and (p, α) as well as the β^+ decays.
2. The reaction networks of the NeNa cycle and the MgAl cycle as proposed for hot hydrogen burning in stellar environments.
3. Relevant level structure of ^{14}O and ^{14}N of importance for the $^{13}\text{N}(p,\gamma)^{14}\text{O}$ reaction.
4. Schematic diagram of experimental techniques for the study of charged particle induced, nuclear reactions involving a radioactive nucleus in the entrance channel. A decision on the most advantageous way of studying such a reaction is found to be only a function of the half-life of the radioactive nuclei. If the half-life is shorter than about 1 h, then the radioactive beam experiment is more advantageous. If it is longer, then a radioactive target experiment may be the preferred method. It should be noted that this conclusion is independent of the reaction cross section and the intensity of the primary radioactive beam.
5. The TRIUMF Radioactive Beams (ISAC) facility as calculated in ref. [51]. A charge state separator is included behind the stripper.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5