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Measuring Difficult Reaction Rates Involving Radioactive Beams: A New Approach

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Abstract: Rates of sub-barrier, radiative capture reactions involving radioactive reactants, needed for understanding various astrophysical explosive scenarios, are often quite difficult to measure directly at relevant stellar temperatures. In general relatively intense radioactive beams (>10^{11}/s) are needed for these inverse kinematic studies, as cross sections are very low. A new production approach is described herein that would supply such required intensities in a relatively straightforward fashion. While this system may have many applications, one area could be increasing our understanding of classical novae and X-ray bursts.

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1. Introduction

A great deal of effort has been devoted to the measurement of the rates of select nuclear reactions over the last 50 years which have clarified significantly the nature of the reactions that occur in stellar environments. However most of these have involved reactants which are radioactively stable. In exploding stellar environments, nuclear reactions occur which involve unstable nuclei as reactants. The rates of these reactions are important to our understanding of the mechanism of these cataclysmic scenarios. Technological advances over the last 10 years now allow us to perform such types of measurements. Direct measurements of such reactions involving radioactive reactants must be performed in inverse kinematics in the case of radiative capture studies. A heavy projectile intercepts a light target such as hydrogen and the reaction products are detected using systems such as a recoil mass separator device. Unfortunately such reactions usually have very small cross sections, which demand using beams of relatively high intensities. For example, a reaction involving a resonance with a strength of 1 meV requires a beam intensity of the order of 10^8 /s to obtain appropriate results in a reasonable period of time (weeks). The properties of the beam are also important as these reactions are usually at energy below the coulomb barrier. Beams of high purity, good emittance and low velocities are required to perform such studies correctly. In general the so-called ISOL approach for the production of these high intensity, pure beams of radioactive nuclei is the desirable method. While this production method has proven to be capable of providing a wide range of such beams, unfortunately some of the most important reactions now require beams which are very difficult to produce by the ISOL method. Following a description of these reactions, a new approach is then described which may lead to the production of required radioactive beam intensities and beam properties.

1.1 Nuclear Astrophysics Rationale

The new production approach described herein (as originally proposed by C.Rubbia [1]), would supply intense radioactive beams in a relatively straightforward fashion. Such a system may have many applications (e.g. nuclear medicine) and one area of particular importance to this conference is nuclear astrophysics. Indeed this approach could be used to increase our understanding of classical novae and X-ray bursts. The radiative capture reactions, namely ^{25}Al(p,γ), ^{30}P(p,γ), and ^{15}O(α,γ)^{19}Ne, are key in our understanding of nova outbursts and/or X-ray bursts and their nucleosynthetic imprints in the Galactic abundances (see recent reviews by Josė, et. al. [2] and Schatz, et al [3] and references herein). The first one is important for the synthesis of ^{26}Al, since it determines the amount of nuclear flow that bypasses ^{26}Al synthesis through the isomeric state, ^{25}Al(p,γ)^{26}Si(β^+)^{26m}Al in a nova explosion. The nuclide, ^{26}Al, is one of few radionuclides that have been observed using orbiting gamma-ray observatories. Hence, reliable predictions of the contribution of novae to the Galactic ^{26}Al content depend critically on this rate. The reaction, ^{30}P(p,γ), determines the path through the Si-Ca region in nova outbursts, and therefore, is crucial in the synthesis of these intermediate-mass elements, and for the location of the nucleosynthesis endpoint in such explosions. Moreover, competition between ^{30}P(p,γ) and ^{30}P(β^+) determines the final amount of ^{30}Si, an important signature that helps to identify presolar meteoritic grains of a likely nova paternity. The $^{15}O(\alpha,\gamma)^{19}Ne$ reaction is believed to be the breakout path of the hot CNO cycle in an X-ray burst leading to the rp process. It is important to our understanding of ignition temperatures for the rp process and to understand the mechanism of X-ray burst to know the absolute value of this rate, rather than an upper limit.

In all of these cases the desired beam, with the intensity required ($\sim10^{9-11}$) to perform the study in a reasonable period of time, is difficult to obtain using the ISOL approach. Either the element is not released sufficiently rapidly by the ISOL thick target or is so reactive that it does not proceed efficiently to the ion source.

2. Experimental Design Overview

The method proposed herein (as originally proposed by C. Rubbia [1]) involves the use of a low Z, ion beam of a few MeV/A, placing this beam into a small (e.g. table top) circular magnetic ring, and allow this circulating beam to continuously intercept an appropriate internal target for the production of the desired radioactive nuclide. The desired product is then extracted using standard ISOL or IGISOL techniques and used as a projectile to induce the desired astrophysics reactions of interest, in inverse kinematics. The intensity of the desired radioactive beams is obtained by controlling and allowing the production beam to intercept the internal target many times. Such an approach has been used for the production of intense X-rays with electron accelerators and synchrotrons (see Y. Mori [4] and references herein). However a key to this for the production of radioactive heavy ion beams is appropriate beam particle cooling or Ionization Cooling [1].

In essence the heavy ion beam loses energy as it passes through the production target, but the ionization losses are recovered using an RF-system with each turn [1]. Transverse emittance is recovered using the RF while longitudinal spread requires an appropriately shaped wedge in the beam. Given the appropriate parameters, beam particles can circulate stably for long periods of time, and intercept the production target for high intensity radioactive products. These products can be captured and extracted from the ring using known ISOL or IGISOL technology as will be described later.

2.1 The Ring

The ring proposed by C. Rubbia et al [1] has a circumference of approximately 4 m., a horizontal Q-value of 1.58, a vertical Q-value of 1.87, an average beta function value of approximately 0.35 m and dispersion at the gas target of 0.15 m (Fig. 1). The gas target is wedge shaped to achieve longitudinal cooling and the average energy loss is 300 keV for light ions. The energy of the ring has to be high enough to keep the ions fully ionized. The loss in the target has to be compensated for with an acceleration system with at least a RF peak voltage of 300 kV. For the reactions proposed by C. Rubbia et al [1] for the production of ^{8}Li and ^{8}B, these parameters result in an average of 10^{12} circulating fully stripped ions with a Laslett tune shift less or equal to 0.25. The Laslett tune shift is a space charge effect which results in the circulating ions undergoing a large number of transverse multiple resonances and will ultimately limit the number of turns any of these ions can make in the ring. A tune shift of 0.25 is sufficiently small to assure that most ions will interact in the gas target well before being lost from the ring.

Y. Mori [4] has proposed using the reaction $^{9}Be(p,n)^{9}B$ with a proton FFAG ring and an internal target for neutron production. The ring would be 10 meter in circumference and the target would be a foil rather than a gas jet. The advantage of an FFAG is the very large transverse and longitudinal acceptance which removes the need of any longitudinal cooling. However, it is not clear that this concept would hold for a more intense ion or proton beam for which the foil heating will be a limiting factor. Furthermore, the produced secondary ions will partly be trapped in the production foil. However, it could be an interesting option to combine the large acceptance FFAG ring with the gas target proposed in [1], especially if the cooling process is less efficient than expected.

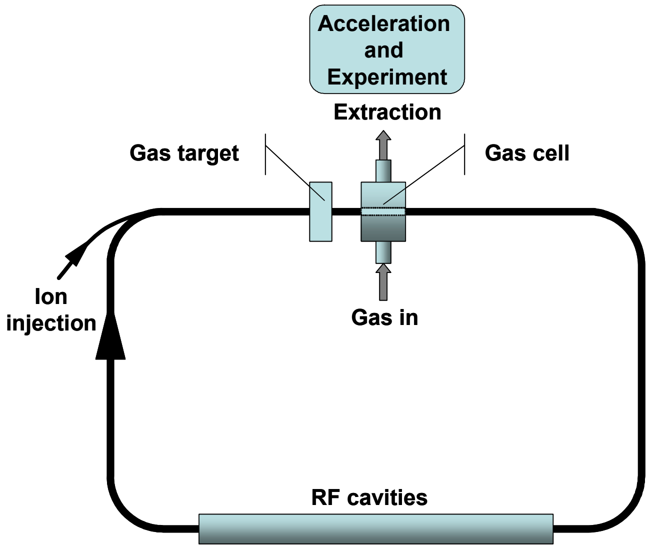

Figure 1: Schematic representation of the described production ring.

2.2 Production Reactions

The production of ^{30}P has been studied in D.J Frantzvog et al [5] using the reaction $^{27}Al(\alpha,n)^{30}P$ over the alpha beam energy range 8.8-15.8 MeV. The study shows an average cross section of several 100 mb which is comparable to the ^{7}Li case in [1]. They also studied the reaction $^{24}Mg(^{3}He,^{2}H)^{25}Al$ in a similar energy range finding a cross section of the same magnitude. The production of ^{15}O has been studied by S. Takacs et al [6] using the reaction $^{14}N(^{2}H,n)^{15}O$ and they found a cross section above 100 mb for the energy region of interest.

The cross sections of interest are a factor of 3-4 larger than those studied in the work by C. Rubbia [1]. Consequently, the ion life time will be smaller requiring a smaller number of ion circulating in the ring for the same average production rate of ions. However, the Laslet tune shifts scales as A/Z^2 so the higher Z projectile nuclei used for our application will suffer a higher tune shift and the number of circulating ions which can be kept stable in ring will be an order of magnitude less compared to [1], approximately 10^{11}.

2.3 Capture Systems

In the work by C. Rubbia [1] it is proposed to use an ISOL type collection target with a hole in the middle for the circulating ion beam. The captured ions will diffuse to the surface of the foils and effuse further to an ion source for re-ionization and acceleration.

The capture system for the ions of interest probably needs to be different from this system as the diffusion of ^{15}O, ^{25}Al and ^{30}P is poor in Ta. We propose to study a gas cell of the IGISOL type [7] for our application. The cell must have a hole in the middle for the circulating beam but filled with He gas, it should be possible to capture the produced ions entering through a thin cell window; extraction then as charged ions. The limitation will be the acceptable collected total charge in the gas cell which will limit the efficiency. It has been shown [8] that at 200 Torr of He gas 10% efficiency can be achieved for up to10^8 ions per cm^3. The efficiency drops drastically above 10^{10} ions per cm^3. The collected ions will have an energy spread between a fraction of a MeV up to several MeV and will consequently stop within a broad depth of the cell. It seems reasonable to expect that up to 10^{10}-10^{11} ions could be extracted from such a system. Note that the ions already are charged making further ionization with some limited efficiency unnecessary. A schematic representation of the system is in Fig.1.

3. Discussion

The beam dynamics of heavy ions in small synchrotrons has been studied in great detail elsewhere, e.g. the GSI facility [9]. However, the high intensities required for our application will require a dedicated machine study. The ring will be larger than the very compact ring proposed in [1] as the A/Q will be larger for some of the proposed ions and as a higher energy will be required to keep the higher Z ions fully stripped.

The production is estimated to exceed the required intensities by several orders of magnitude. The limitations will come from the capture system due to the poor diffusion of many ions in solids and the space charge limits of the gas cell. Further studies to look for other possibilities to collect the ions should be performed; in particular the gas cell developed for the RIA proposal seems interesting.

4. Conclusion

A new production approach is described herein that would produce beams of exotic heavy ion projectiles with required intensities needed for measuring rates of key reaction in nuclear astrophysics in a relatively straightforward fashion. Further research and development studies are still needed to finalize aspects of the approach. This method will also have applications in other areas such as production of radiopharmaceuticals for use in nuclear medicine.

5. References

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