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Studies of radioactive nuclei and their role in the cosmos

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Producing and accelerating radioactive nuclei in the laboratory provides a unique tool for the study of nuclear reactions involving these isotopes in the energy regime of interest for astrophysics. We briefly review some recent developments with accelerated radioactive ion beams and their impact for astrophysics.

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1. Introduction

Radioactive nuclei play an important role in astrophysics, particularly in stellar explosions where the rates of nuclear reactions can be much faster than the lifetimes of most radioactive isotopes. Select nuclei with longer lifetimes are important in a variety of astrophysical phenomena. The production and acceleration of radioactive nuclei in the laboratory provides a method to allow direct studies of nuclear reactions at well-controlled incident energies that are at or near those of relevance in astrophysical environments. Accelerated beams of radioactive nuclei also allow certain complementary techniques, such as elastic scattering and transfer reactions, that can provide a powerful approach for determining nuclear structure information that is crucial for nuclear reaction rates.

Most species of accelerated radioactive ion beams have typically required substantial development, and progress in experiments has often been linked to breakthroughs in beam development. Following this trend, several recent experimental highlights have come from measurements using recently developed beams of ^{7}Be and ^{26}Al. Recent progress has also included a continued focus on the ^{18}F$(p,\alpha)^{15}$O reaction that is important in the hot-CNO cycle. In this article we briefly review some of the recent measurements of interest to astrophysics using accelerated beams of radioactive ions, in particular focusing on measurements with beams of ^{7}Be, ^{18}F and ^{26}Al. We conclude with a brief outlook for the future.

2. Studies with ^{7}Be

The ^{7}Be isotope plays a crucial role in understanding observations of neutrinos from the solar core and may provide the key to understanding the anomalous primordial abundance of ^{7}Li. Recently these important problems in astrophysics have been addressed using intense beams of ^{7}Be that are available at the Centre de Recherches du Cyclotron at Louvain le Neuve (CRC-LLN) and at the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory (ORNL). The technique used to produce the ^{7}Be beam is similar at both facilities [1]. The ^{7}Be activity is produced via the ^{7}Li$(p,n)^{7}$Be reaction by irradiating a lithium metal target with protons. The long half-life of ^{7}Be ($t_{1/2} = 53$ days) allows a simple chemical separation to be performed offline that substantially enhances the ultimate ^{7}Be beam intensity and the ^{7}Be/^{7}Li ratio. The chemically enriched sample is loaded into an ion source. At the CRC-LLN an ECR ion source is coupled to the CYCLONE cyclotron, while at the HRIBF a cesium sputter source is coupled to the HRIBF tandem accelerator. Beam intensities in each case of about 10^{7} ions/s on target have been achieved using samples containing roughly 0.1 Ci of activity. In the following subsections we briefly describe recent experiments using these beams that are of interest to astrophysics.

2.1 ^{7}Be(d,p)2α and the primordial ^{7}Li abundance

Recent observations of the cosmic microwave background *CMB* have placed strict constraints on the baryonic matter density of the universe [2]. Standard big bang nucleosynthesis (*SBBN*) models using the baryonic density deduced from CMB observations provide reasonable agreement with determinations of the ^{4}He abundance from observations of metal-poor, ionized hydrogen regions and excellent agreement with the deuterium abundance deduced from observations of high red-shift quasars [3]. However, the determination of the primordial ^{7}Li abundance from observations of metal-poor stars [4] is a factor of 2 to 3 lower than SBBN predictions using the baryon density derived from CMB observations [3].

A substantial increase in the rate of the ^{7}Be$(d,p)2\alpha$ reaction, previously unmeasured at energies of interest for SBBN ($E_{cm} = 0.1 - 0.6$ MeV), could potentially resolve the discrepancy with the primordial ^{7}Li abundance [3]. A collaboration recently addressed this interesting possibility by measuring the ^{7}Be$(d,p)2\alpha$ cross section in the Gamow window for SBBN using the ^{7}Be radioactive ion beam at CRC-LLN [5]. An isotopically pure beam of ^{7}Be bombarded a 200 μg/cm^2 $(CD_2)_n$ target. Charged-particles were detected using a multi-layered array of silicon strip detectors that provided clean identification of the protons from the ^{7}Be$(d,p)2\alpha$ reaction. An important feature of this measurement was that protons of sufficiently low energy could be detected so that the contribution of the ^{7}Be$(d,p)^8$Be* reaction populating excited states in ^{8}Be up to the broad 4^+ state at $E_x = 11.4$ MeV could be accurately determined for the first time. Previously the contributions of these unobserved states at higher excitation energies had been estimated to increase the astrophysical S-factor for the ^{7}Be$(d,p)2\alpha$ reaction by about a factor of 3 [6]. However, the new measurements of Angulo *et al.* show that these levels contribute only 35% to the astrophysical S-factor and that the rate of the ^{7}Be$(d,p)2\alpha$ reaction at SBBN temperatures is actually significantly lower than previously estimated [5]. The discrepancy in the primordial ^{7}Li abundance thus remains an difficult open question that can not be resolved by the ^{7}Be$(d,p)2\alpha$ reaction rate.

2.2 The ^{7}Be$(p,\gamma)^8$B reaction

Accurate measurements of the flux of neutrinos originating from the decay of ^{8}B in the solar core provide a powerful probe of the properties of the solar interior and of neutrinos themselves [7, 8]. The interpretation of these measurements is hindered by uncertainties ranging from the solar composition (the greatest uncertainty at this point) to the rates of the ^{3}He$(\alpha,\gamma)^4$He and ^{7}Be$(p,\gamma)^8$B nuclear reactions [9, 10]. Nuclear physics laboratories are now aiming to reduce the uncertainties in these two critical nuclear reaction rates, which will help measurements of the solar neutrino flux to provide a significant constraint on solar properties such as the metallicity.

Recent, high precision measurements using ^{7}Be targets have significantly improved our understanding of S_{17}, the astrophysical S-factor for the ^{7}Be$(p,\gamma)^8$B reaction [11, 12, 13, 14]. However, the very precise measurement of Junghans *et al.* [11] dominates global analyses and raises the mean value of the ^{7}Be$(p,\gamma)^8$B astrophysical S-factor by between 6% [11] and 18% [15] depending upon the analysis. Additional high precision measurements to confirm this result are desirable. Since most measurements have used a fairly similar experimental technique, a high precision measurement using a complementary experimental approach would be particularly interesting as a test of systematic uncertainties.

At this point, measurements aimed at a precise determination of S_{17} through the Coulomb dissociation (*CD*) [16, 17, 18, 19, 20] and Asymptotic Normalization Coefficient (*ANC*) techniques [21, 22] deserve mention. A value for S_{17} has also been determined from ANC's extracted from break-up data [23]. A summary of the reported results from these measurements is given in Table 1. All of these indirect determinations are smaller than the precise direct measurement of Junghans *et al.* [11] by between 6% and 22%, but nearly all have uncertainties of about 10%, making it difficult to draw significant conclusions. However, the recent work of the GSI collaboration using the CD technique (Schümann *et al.*) deserves special mention [19, 20]. Their measurement of angular correlations in the break up fragments provide strong evidence against any significant contribution of $E2$ multipolarity gamma rays to the break-up cross section. The careful study of the tracking of the beam and break-up fragments also resulted in an improved efficiency calibration that somewhat changed the energy dependence of the astrophysical S-factor. The continued efforts of the GSI group to improve their understanding of potential systematic uncertainties has resulted in the best determination of S_{17} using an alternate technique to date.

A different approach to determining S_{17} is currently being developed at the HRIBF using a ^{7}Be radioactive ion beam [24]. The ^{7}Be$(p,\gamma)^8$B cross section is being measured directly using an experimental technique similar to that pioneered by the NABONA collaboration [25]. A beam of ^{7}Be from the HRIBF tandem accelerator bombards the differentially-pumped windowless hydrogen gas target. Recoiling ^{8}B nuclei, which emerge from the gas target along the incident beam direction, are separated from the primary beam by the Daresbury Recoil Separator and are identified by a gas ionization counter. Because the systematic uncertainties differ completely from ^{7}Be target experiments, this approach could provide an important result if a precise measurement of S_{17} is achieved.

The first experimental run was conducted in the spring of 2005 using a 120 mCi sample of ^{7}Be to produce a 12 MeV mixed beam of ^{7}Be and ^{7}Li with an average intensity of 1.5×10^7 ^{7}Be/s and a Li/Be ratio of about 7. The beam bombarded the windowless gas target operated at a central pressure of 5.00 Torr. A total of 22 recoiling ^{8}B nuclei were observed in the gas ionization counter at the focal plane of the DRS over a period of 63 hours, implying a total cross section for the ^{7}Be$(p,\gamma)^8$B reaction of 1.07 ± 0.28 μb at $E_{cm} = 1.502$ MeV [26] in agreement with the precise measurement of Junghans *et al.* that when interpolated to this energy gives 0.91 ± 0.03 μb [11].

The uncertainty in the first HRIBF measurement is dominated by the relatively poor ^{8}B counting statistics. Potential sources of systematic uncertainty have been characterized by a variety of independent measurements with both stable ion beams and the ^{7}Be beam. The least well characterized quantities are the beam current integration and recoil transmission, which have uncertainties of about 10% and 5%, respectively. New calibration experiments are currently aimed at reducing these uncertainties. Increasing the beam intensity is also clearly critically needed. About a factor of 4 increase in beam ^{7}Be beam current is expected to be achieved by simply increasing the level of activity and better matching the placement of the ^{7}Be activity in the sample to the geometric sputter pattern of the ion source [27]. At this level, a ^{8}B event rate of 34 (22) counts/day is expected at $E_{cm} = 1.5(1.0)$ MeV, which would allow better than 5% statistics in a 2-week-long experiment. On the other hand, the cross section at $E_{cm} < 0.35$ MeV is at least a factor of 8 smaller, and high precision measurement at energies below the the 1^+ resonance seems unlikely without a substantial advance in beam production.

2.3 ^{7}Be+p scattering

Understanding the structure of ^{8}B and the ^{7}Be$+p$ reaction mechanism is interesting from a nuclear physics perspective since such loosely-bound, light systems provide a laboratory for studying nuclear structure at the extremes of isospin in systems that are sufficiently simple that accurate, sophisticated theoretical calculations are accessible [28, 29, 30]. Theory predicts bound,

Table 1: Summary of S_{17} determined from indirect experimental techniques.

Reference	Technique	$S_{17}(eV \cdot b)$
Kikuchi *et al.* [16]	CD	18.9 ± 1.8
Iwasa *et al.* [17]	CD	$20.6 \pm 1.2_{exp} \pm 1.0_{theory}$
Davids *et al.* [18]	CD	17.8 ± 1.3
Schumann *et al.* [20]	CD	$20.6 \pm 0.8_{stat} \pm 1.2_{sys}$
Azhari *et al.* [21]	ANC	17.3 ± 1.8
Das *et al.* [22]	ANC	20.7 ± 2.4
Trache *et al.* [23]	ANC/CD	18.7 ± 1.9

positive-parity states in ^{8}B from the coupling of one proton and one neutron in p-wave orbitals that have so far not been observed [29, 31]. While the properties of these states are not likely to have a large impact on the extrapolated value of S_{17} at solar energies, they can be important for arriving at a precise quantitative understanding of the shape of the S_{17} over a broad range of energies. Properties such as the *s*-wave scattering lengths have also been shown to be important for obtaining a precise extrapolation of the ^{7}Be$(p,\gamma)^8$B cross section from laboratory to astrophysical energies [30].

The ^{7}Be$(p,p)^7$Be elastic scattering cross section has been previously studied to search for expected positive parity states in ^{8}B [32], but the 0.769-MeV (1^+) and 2.32-MeV (3^+) states have remained the only observed positive-parity, T=1 states in ^{8}B [33]. The ^{7}Be$(p,p)^7$Be elastic scattering cross section has also been used to determine the *s*-wave scattering lengths in ^{7}Be+p [34], but the relatively large uncertainty in the deduced scattering lengths results in the largest source of theoretical uncertainty in extrapolations of the ^{7}Be$(p,\gamma)^8$B astrophysical S-factor in most models [30].

Improved measurements of ^{7}Be+p scattering were recently performed at the HRIBF including the first measurements of the excitation function for ^{7}Be$(p,p')^7$Be* inelastic scattering populating the 429-keV $(1/2^+)$ first-excited state of ^{7}Be [35]. Isotopically pure beams of ^{7}Be^{4+} from the HRIBF tandem accelerator bombarded thin polypropylene targets both with and without a gold backing. Scattered protons were detected in the SIDAR silicon strip detector array [36]. Both ^{7}Be+p elastic and inelastic scattering were easily distinguished by the measured energy of the scattered proton. Differential cross sections were measured at 19 different ^{7}Be bombarding energies corresponding to center-of-mass energies in the range of $E_{cm} = 0.4 - 3.3$ MeV. Data were also collected at 2 different positions of SIDAR, allowing cross sections to be measured at laboratory angles ranging from 14° to 51° (corresponding to $\theta_{cm} = 80^\circ - 152^\circ$ for ^{7}Be+p elastic scattering). Each set of data was accurately normalized based on ^{7}Be+^{12}C and ^{7}Be+^{197}Au elastic scattering. A multi-level *R*-matrix analysis of the combined data set, which includes about 400 data points, is in progress and is expected to yield an improved understanding of the level structure of ^{8}B and the ^{7}Be+p system.

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3. ^{18}F$(p,\alpha)^{15}$O

The ^{18}F isotope was among the first radioactive isotopes that was accelerated with sufficient intensity for experiments [37, 38]. Focus on experiments with ^{18}F has continued over the past decade due to its importance in the hot-CNO cycle that powers novae (e.g., see Ref. [39, 40]). The decay of ^{18}F is the largest source of potentially observable gamma rays at early times after the explosion [41]. The rate of the ^{18}F$(p,\alpha)^{15}$O reaction is one of the most important factors influencing the production of ^{18}F [42]. While our understanding of the ^{18}F$(p,\alpha)^{15}$O reaction rate has continued to improve, significant uncertainties remain due to the potential contribution of low energy resonances as well as to the uncertain interference between resonances [43].

Two recent direct measurements of the ^{18}F$(p,\alpha)^{15}$O cross section have reduced the uncertainty due to interference between $3/2^+$ states in ^{19}Ne. Similar experimental techniques were used in independent measurements at the HRIBF [44] and at the CRC-LLN [45] to measure the ^{18}F$(p,\alpha)^{15}$O reaction cross section at previously unmeasured energies. In both measurements a beam of ^{18}F bombarded thin $(CH_2)_n$ targets and both recoiling reaction products (α and ^{15}O) were detected in coincidence by an array of silicon strip detectors. In the CRC-LLN measurement, the cross section was measured at 6 bombarding energies in the energy range corresponding to $E_{cm} = 400-700$ keV, while 5 bombarding energies in the energy range of $E_{cm} = 663-877$ keV were measured at the HRIBF. Independent R-matrix analyses of the each data set reached similar conclusions, that the well-known 665-keV $(3/2^+)$ resonance must constructively interfere below the 665-keV resonance with other $3/2^+$ states close to the ^{18}F+p threshold (e.g. see Ref. [44]). These measurements have reduced the uncertainty in the ^{18}F$(p,\alpha)^{15}$O by about 37%, but uncertainties remain due to the possible contribution of unobserved levels and the uncertain properties of levels near the proton threshold.

4. ^{26g}Al$(p,\gamma)^{27}$Si

Observations of the distribution of the 1.8 MeV gamma-ray from the decay of ^{26g}Al in the Galaxy have provided detailed distribution information on recent ($\approx 10^6$ yr) nucleosynthesis in the Galaxy [46]. Supernovae are believed to be the most important contributor to the nucleosynthesis of ^{26g}Al, and these gamma-ray observations may provide the best information on the frequency and distribution of supernovae in the Galaxy. However, the potential contributions of other sources, i.e. Wolf-Rayet stars and novae, need to be better understood.

Nova models predict ^{26g}Al production that could account for a non-negligible fraction of the observed ^{26g}Al abundance in the Galaxy [47, 48], but the production of ^{26g}Al is sensitive to some uncertain nuclear reaction rates. The ^{26g}Al$(p,\gamma)^{27}$Si reaction that destroys ^{26g}Al in novae has been somewhat uncertain due to the contributions of low energy resonances [49], but recent measurements using an intense beam of ^{26g}Al at the ISAC radioactive ion beam facility have significantly improved our understanding of the ^{26g}Al$(p,\gamma)^{27}$Si reaction rate [50]. The ^{26g}Al beam was produced using a high-power SiC target coupled with a laser/surface ionization ion source that achieved average accelerated beam intensities of more than 2.5×10^9 ^{26g}Al/s on target. The 184-keV resonance that dominates the ^{26g}Al$(p,\gamma)^{27}$Si reaction rate at nova temperatures was studied using the DRAGON facility [51]. The ^{26g}Al beam bombarded a windowless gas target. Recoiling ^{27}Si nuclei were separated from the incident beam by the DRAGON recoil separator and detected in coincidence with capture gamma rays by an array of BGO detectors surrounding the gas target. The relative timing between the recoil and gamma rays, along with the measured energy, allowed the ^{26g}Al$(p,\gamma)^{27}$Si reaction to be cleanly identified. The energy (184 ± 1 keV) and strength ($\omega\gamma = 35\pm7\mu$ eV) of this importance resonance were measured allowing a more accurate determination of the ^{26g}Al$(p,\gamma)^{27}$Si reaction rate at nova temperatures.

The new ^{26g}Al$(p,\gamma)^{27}$Si reaction rate is about 20% less the rate commonly used in nova models implying about 20% greater production in novae [50]. However, some significant uncertainties remain in the production of ^{26g}Al. One of the largest uncertainties arises from the ^{25}Al$(p,\gamma)^{26}$Si reaction rate that can bypass production of ^{26g}Al. Measurements with stable beams have recently shed some light on this important reaction rate, but substantial uncertainties remain [52, 53, 54]. An ^{25}Al radioactive ion beam is currently under development at a number laboratories and would be an important step towards a precise understanding of ^{26g}Al production in novae.

5. Summary and outlook

Accelerated radioactive ion beams provide a unique capability to study nuclear reactions involving radioactive nuclei at low energies that are of interest to astrophysics. Experimental progress in measurements with accelerated radioactive ion beams has generally followed developments in radioactive ion beam production, and recent highlights have focused on measurements using newly developed beams of ^{7}Be and ^{26g}Al. Important progress also continues to be made with well-established radioactive ion beams like ^{18}F. However, the technical challenges in producing and accelerating radioactive ion beams has governed progress.

The development of an experimental technique to achieve efficient production of accelerated radioactive ion beams independent of the chemical properties of the production target or beam species would represent a substantial breakthrough. Approaches are currently under development using ion guides (e.g. see Savard *et al.* [55]) based upon the approach originally pioneered at Jyväskylä, Finland [56] and using a gas-filled, weakly-focusing cyclotron magnet [57]. The U. S. Department of Energy is currently planning a radioactive ion beam facility that may be based on one of these concepts [58, 59]. While the scope has been somewhat reduced and the preliminary engineering design delayed until fiscal year 2011 [60, 61], the planned facility would none-the-less provide an unparallel variety and intensity of accelerated radioactive ion beams with important implications for nuclear astrophysics [62]. However, until such general and powerful techniques become a reality, it is crucial to invest in the development of radioactive ion beam techniques and capitalize on complementary experimental approaches using stable ion beams and fast radioactive ion beams produced by projectile fragmentation.

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