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Measurement of the p-process branching point reaction ^{76}Se(α,γ)^{80}Kr in inverse kinematics with DRAGON

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The reaction ^{76}Se(α,γ)^{80}Kr has been identified as one of the highest priority measurements for the p-process. The nuclide ^{80}Kr is a branching point of this process and so the relative rates of the ^{80}Kr photo-disintegration reactions will directly affect abundance of the p-nuclide ^{78}Kr. Currently the ^{80}Kr(γ,α)^{76}Se reaction rate is the most uncertain of these reactons. For this reason ^{76}Se(α,γ)^{80}Kr was chosen as the flagship measurement of the DRAGON high mass program, the goal of which has been to expand the capabilities of the DRAGON recoil separator to study beams of mass A > 40. The recent measurement of the ^{76}Se(α,γ)^{80}Kr reaction constitutes the first scientific results of this ongoing program. Here we report on the first two measurements of ^{76}Se(α,γ)^{80}Kr at energies within the 2.0 GK Gamow window, provide a description of the required upgrades to the DRAGON separator, and present results from the high mass commissioning experiments. Plans for future measurements of ^{76}Se(α,γ)^{80}Kr and other p-process reactions will also be discussed.

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1. Introduction

Among the elements heavier than iron, some of the most interesting isotopes also happen to be among the least abundant. These isotopes, known as the *p*-nuclei, are stable isotopes which sit along the neutron-deficient side of the valley of stability. The intriguing aspect of these particular nuclei is that they cannot be produced by either the *s*- or the *r*-process, the two main processes believed to be responsible for creating the majority of the elements heavier than iron. The production of these *p*-nuclides requires a separate astrophysical process, which is commonly referred to as the *p* process [1, 2]. The details of this process are far from understood and it is not yet clear whether it corresponds to a single nucleosynthetic process or whether there are contributions from several independent ones.

Several astrophysical sites have been proposed for the synthesis of the *p*-nuclei but the most studied, and the only one so far that can produce (to some degree) all *p*-nuclei, occurs during core collapse supernovae when the shock-front passes through the O-Ne layer of the massive star [3, 4, 5]. Due to the temperatures involved, pre-existing seed nuclei undergo photodisintegration reactions (hence this process sometimes being called the γ-process). In the beginning (γ,n) reactions dominate, driving the reaction flow along the same elemental chain to less neutron-rich nuclei near the edge of or beyond the valley of stability. However, at some point the (γ,p) and/or the (γ,α) reactions become faster than the (γ,n) reactions and the reaction flow then branches into a new isotopic chain. These *branching points* [6] and the relative rates of all associated reactions are critical nuclear inputs when studying this scenario and its resulting isotopic abundances.

The reaction ^{76}Se$(\alpha,\gamma)^{80}$Kr has been identified as one of the highest priority measurements for the *p*-process [6]. The nuclide ^{80}Kr is a branching point of this γ process and so the relative rates of all of the ^{80}Kr photo-disintegration reactions will directly affect the abundance of ^{78}Kr, one of the aforementioned *p*-nuclides. Of these the ^{80}Kr$(\gamma,\alpha)^{76}$Se reaction rate is currently the most uncertain [6]. It was for this reason that ^{76}Se$(\alpha,\gamma)^{80}$Kr was chosen as the flagship measurement of the DRAGON high mass program, the goal of which has been to expand the capabilities of the DRAGON recoil separator to study reactions using beams of mass A >40.

2. DRAGON

The DRAGON (Detector of Recoils And Gammas Of Nuclear reactions) recoil separator is located at the ISAC facility at TRIUMF in Canada and has been specially designed to measure astrophysically important radiative capture reactions in inverse kinematics. Beams from the ISAC accelerator impinge on the DRAGON windowless gas target which is typically filled with up to 10.5 mbar of either hydrogen or helium. This gas target volume is surrounded by 30 Bismuth Germanate (BGO) detectors to detect the prompt γ rays emitted during the reaction [7]. In addition to providing information about the number and energy of these γ rays, the application of a coincidence requirement (≤ 10 μs separation) between γ rays and the heavy ion events detected at the end of the separator is often used to increase the beam suppression [8].

As both the recoils and unreacted beam particles leave the gas target volume the particles of interest (the recoils) need to be separated from the more abundant residual beam. To accomplish this the DRAGON separator uses two magnetic (M) and two electrostatic (E) dipoles, arranged in a MEME configuration. As the momentum distributions of the beam and recoil particles overlap, a single charge state of both particles is selected after passage through the first magnetic dipole. Mass selection (or rather mass over charge, A/q, selection) is performed after the first electrostatic dipole. The second stage of separation functions the same way as the first and provides the additional beam suppression required for the typically low reaction rates of the reactions of interest [7, 8]

In the ^{76}Se(α,γ)^{80}Kr experiment the recoils transmitted through the separator were detected in an ionization chamber [9]. Additionally, a local time-of-flight (TOF) system, consisting of two microchannel plate (MCP) detectors [10], was used to increase the beam suppression through improved particle identification.

3. The DRAGON high-mass program

The DRAGON recoil separator was one of the original ISAC experiments. In the early days of the ISAC facility the accelerator was only expected to provide beams of masses $A \leq 30$ at energies from 150A keV to 1.5A MeV. The DRAGON separator was designed to make optimal use of these beams and thus measurements of reaction rates critical for nova nucleosynthesis have been, and continue to be, at the core of the DRAGON program [11, and references therein].

The first step beyond this mass range for DRAGON was the measurement of ^{40}Ca(α,γ)^{44}Ti. This measurement was made possible by upgrades to the ISAC off-line ion source which enabled the production of $^{40}Ca^{2+}$ ions. Due to the 2+ charge state, these particles could be accelerated as the resulting mass to charge ratio (A/q) was within the acceptance of the ISAC accelerator. One of the challenges in measuring this reaction was that the charge state distribution of the beam and recoils after passing through the DRAGON gas target resulted in an A/q value that was too high to bend through the separator. This was solved by including a retractable silicon nitride (SiN) foil right after the inner gas cell and just before the differential pumping tubes [12, 9]. This acted as a solid state stripper and provided the higher charge states required.

The installation of an ECR charge state breeder for radioactive beams [13] and a multicharge ion source for stable beams [14] at ISAC in recent years has dramatically increased the mass range of beams available. Given the success of the ^{40}Ca(α,γ)^{44}Ti measurement [15] and the considerable astrophysical importance of reactions on nuclei with A $>$ 30 a program was initiated to explore the capabilities of the current DRAGON separator at these masses – specifically in the mass and energy range of interest for the *p* process.

Exploring the parameter space of the masses of interest, available energies, theoretical charge state distributions [16], and required electromagnetic fields, we find that for (α,γ) reactions measurements of up to masses of A $\simeq$ 95 appear possible (given beams of 10^9 pps or greater and cross sections of the order of 1μb or higher).

When exploring the feasibility of *p*-process experiments we currently rely on emperical charge state distribution (CSD) calculations. Using the original SiN stripper foil located just after the target, we found a discrepancy between the calculated [16] and measured CSD for ^{84}Kr and ^{76}Se beams. This discrepancy was greatly reduced when we removed the SiN foil and began using an aluminum foil further downstream, located in a region with less residual gas from the target. While there is still not perfect agreement between our measured CSD and the calculations, it appears that the theoretical rates are now close enough for experiment planning purposes. The actual CSD are typically measured as part of the experiment.

Another concern was whether or not the separator would have sufficient beam suppression at these higher masses. Fortunately, for the reactions we are interested in measuring, the outgoing recoil cone angle is small ($\sim$ 3 mrad) compared to the acceptance of the separator ($\sim$ 21 mrad). GEANT3 simulations indicate that the variable slits located at the focal planes of the separator can be narrowed significantly for such reactions (enhancing beam suppression) without adversely affecting the transmission of the recoils through the separator. These results were tested experimentally in April of 2011 by measuring the resonance strength of a well-known resonance in ^{58}Ni$(p,\gamma)^{59}$Cu for a range of slit widths [17]. We found that, for the slits located after the first electrostatic dipole, the range of slit settings which allowed for full transmission of the recoils matched the slit settings for which the GEANT3 simulation predicted full transmission. These tests were also encouraging in that the amount of unsuppressed "leaky" beam did not overwhelm our end detectors even with the slits at their standard settings.

The measurement of the ^{76}Se$(\alpha,\gamma)^{80}$Kr reaction, to be discussed in the following section, constitutes the first scientific results of this program.

4. ^{76}Se$(\alpha,\gamma)^{80}$Kr

The first of two planned experimental runs to measure the ^{76}Se$(\alpha,\gamma)^{80}$Kr reaction rate at energies within the astrophysically relevant Gamow window (1.8 - 3.3 GK corresponding to beam energies of 1.0 - 2.3A MeV in inverse kinematics) occurred in December of 2013. Measurements were performed at two energies, E_{beam} = 1.513A MeV ($E_{C.M.}$ = 5.667 MeV) and 1.434A MeV (5.379 MeV), over 7.5 days. The average beam intensity on target was 2×10^{10} s^{-1} of ^{76}Se^{14+}.

The recoils transmitted to the end detector were all in the 25+ charge state. For the highest energy beam (1.513A MeV) the raw beam suppression of the separator (all events in the ionization chamber compared to the total beam on target) was 9.3×10^{8} (Ionization chamber spectra for this condition shown in Fig. 1a). With the coincidence requirement between the reaction γ rays and the events in the end detector applied the beam suppression increased to 1.9×10^{11} (Fig. 1b). The beam suppression increased further to 1.4×10^{14} once software cuts selecting the appropriate time of flight of the recoils through the separator was applied (These events are plotted in red in Fig. 1c and are overlayed on top of an enlarged region from Fig. 1b).

The cluster of recoils in the ionization chamber spectra can be seen just to the upper right of the main locus of points in the coincidence spectra (Fig. 1b) but is seen more clearly once the separator TOF cut selecting for recoils is applied (Fig. 1c). We are confident that these events are due to recoil particles as this locus of red points essentially vanishes if we instead select a separator TOF which is not consistent with recoil events. This clustering of the recoils in separator TOF can be seen in (Fig. 2).

One piece of analysis still outstanding is a determination of the BGO detector efficiency as it is a function of the number and energy of γ events from the radiative capture reaction. This ^{76}Se$(\alpha,\gamma)^{80}$Kr reaction is different from most DRAGON measurements as we are not looking at a single reasonance but rather, due to the high level densities in ^{80}Kr at these energies, we observe recoils from multiple resonances throughout the target volume. Consequently we see γ rays

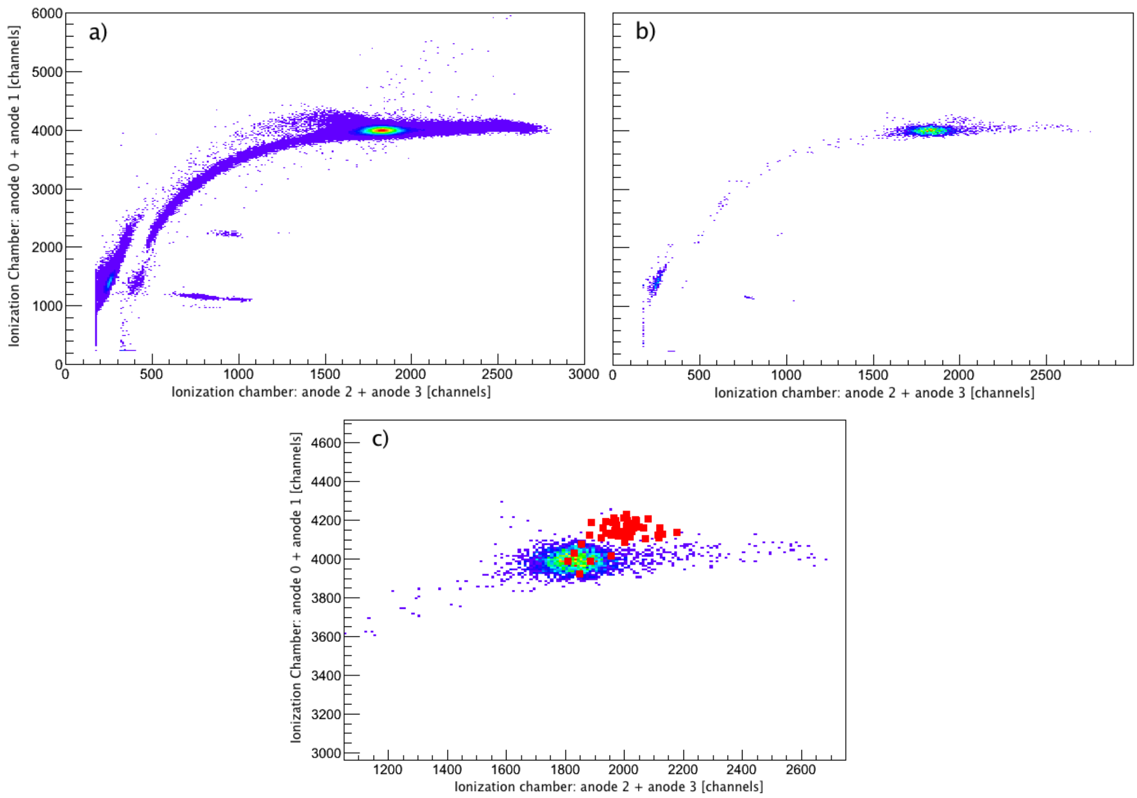

Figure 1: Ionization chamber anode pulse-height spectra for ^{76}Se(α,γ)^{80} Kr for the first of two data sets at $E_{C.M.}$ = 5.667 MeV. The figures show a) all events in the detector (singles), and b) all events passing a coincidence condition between the γ rays and ionization chamber events. In c) events which have a separator TOF consistent with recoil events are plotted in red on top of a zoomed in region of b).

from all possible cascades of all populated resonances. Additionally, the range of energies and potential γ ray multiplicity is larger than previously measured reactions. It is fairly straightforward to determine the maximum and minimum possible BGO efficiencies, but it is a greater challenge to determine a more reasonable uncertainty range. A likelihood analysis comparing a simulated 'average' cascade and the actual energies and multiplicites measured is still in progress.

5. Conclusion

The DRAGON recoil separator has been used to measure cross sections of the ^{76}Se(α,γ)^{80}Kr reaction at two energies $E_{C.M.}$ = 5.667 MeV and 5.379 MeV and preliminary results have been found to be in reasonable agreement with the NON-SMOKER [18] Hauser-Feshbach values. The success of this measurement has opened the door to further *p* process measurements in this mass region. Further measurements of the ^{76}Se(α,γ)^{80}Kr reaction are scheduled for December 2014 and a proposal to measure ^{72}Ge(α,γ)^{76}Se at DRAGON has recently been accepted and is expected to run in 2015.

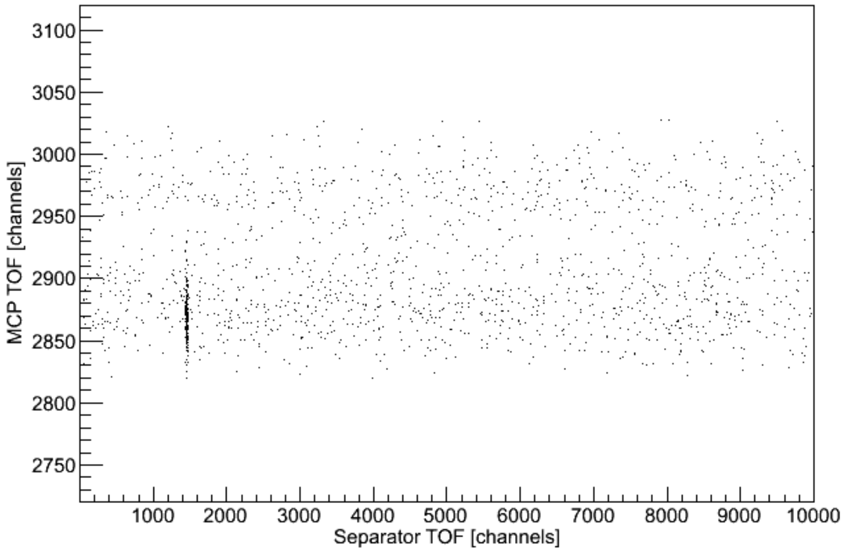

Figure 2: All events in Fig. 1b plotted as their local (MCP) TOF vs separator TOF. "Leaky" beam which passes the coincidence cut has a random time of flight through the separator as the coincidence γ is a room background event unrelated to the passage of the beam through the target. The recoils however all arrive within a narrow separator TOF window as in this case the γ rays and the ionization chamber events are correlated.

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