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Nuclear transfer reaction measurements at the ESR—for the investigation of the astrophysical $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$ reaction

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Abstract

Astrophysical x-ray bursts are thought to be a result of thermonuclear explosions on the atmosphere of an accreting neutron star. Between these bursts, energy is thought to be generated by the hot CNO cycles. The $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$ reaction is one reaction that allows breakout from these CNO cycles and into the rp-process to fuel outbursts. The reaction is expected to be dominated by a single $3/2^+$ resonance at 4.033 MeV in ^{19}Ne , however, limited information is available on this key state. This work reports on a pioneering study of the $^{20}\text{Ne}(p,d)^{19}\text{Ne}$ reaction, performed in inverse kinematics at the experimental storage ring (ESR) as a means of accessing the astrophysically important 4.033 MeV state in ^{19}Ne . The unique, background free, high luminosity conditions of the storage ring were utilized for this, the first transfer reaction performed at the ESR. The results of this pioneering test experiment are presented along with suggestions for future measurements at storage ring facilities.

Keywords: nuclear astrophysics, storage rings, transfer reactions

(Some figures may appear in colour only in the online journal)

1. Introduction

Space-based x-ray observatories such as Chandra [1] and XMM/Newton [2] have enabled extensive studies of astrophysical x-ray burst events to be made in recent years. Since the first observed event in 1976 [3] a further 91 Galactic sources have been identified as of 2010 [4]. X-ray burst events may be classified as either type-I or type-II events, of these the most common are type-I which are characterized by sudden (of the order seconds) and intense spikes in the emission of x-rays from an accreting neutron star. The x-ray emission is then observed to return to the baseline level over a time period of 10–100 s, with the cycle observed to repeat over a period of a few hours.

In between bursts, energy is thought to be generated by the CNO cycles driven by the in-flow of hydrogen- and helium-rich material from the less evolved companion onto the neutron star. At the extreme temperatures and densities present in the base layers of the accretion disc, it is possible for the nuclear reactions involved in the CNO cycles to occur on timescales of a few seconds, thus, capture reactions on β -unstable nuclei become important. Breakout from these CNO cycles is then able to proceed via reactions on the β -decaying waiting point isotopes ^{14}O , ^{15}O and ^{18}Ne , with the α capture reaction $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$ thought to be the most probable path. This then fuels the rapid proton capture (rp) process leading to the production of heavier isotopes between the line of stability and the proton drip line following a rapid succession of proton capture reactions. As a result of this breakout, nuclei as massive as the Sn–Sb isotopes may be produced [6]. Understanding this breakout mechanism is, therefore, critical for understanding the time structure of x-ray emission in the bursts.

Given its importance in the field of explosive nuclear astrophysics, it is not surprising that great efforts have been made to determine the $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$ reaction rate. Direct measurements, at astrophysically important energies, are not presently feasible due to the limited intensities of radioactive ^{15}O ion beams. Indirect methods have, therefore, been employed. Under x-ray burster conditions the $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$ reaction rate is thought to be dominated by a single $3/2^+$ resonance in the $^{15}\text{O} + \alpha$ system at an energy $E_r = 504$ keV, corresponding to a ^{19}Ne excitation energy of 4.033 MeV. Given the low resonance energy, this state is expected to decay predominantly via γ emission with a small α -branch of the order $b_\alpha \sim 10^{-4}$ predicted by Langanke *et al* [5], where $b_\alpha = \Gamma_\alpha / \Gamma_{\text{tot}} \sim \Gamma_\alpha / \Gamma_\gamma$, and this quantity remains the key unknown now that the γ partial widths Γ_γ are well determined [7, 8].

The $^{21}\text{Ne}(p,t)^{19}\text{Ne}$ reaction has been shown to preferentially populate this key 4.033 MeV level, following the work of Fortune *et al* [9] who utilized a 40 MeV proton beam from the Michigan State University cyclotron and a neon gas target enriched in ^{21}Ne [9]. More recently, Davids *et al* [10] performed the same reaction but instead utilizing inverse kinematics, and again observed the 4.033 MeV state to be strongly populated. In this work, the Big-Bite Spectrometer at KVI was employed to detect tritons in coincidence with ^{19}Ne

or ^{15}O ions following the (p,t) reaction. However, the sensitivity of this method, in the excitation energy region of interest, was limited by a background which was thought to originate from fragmentation reactions on carbon in the solid $(\text{CH}_2)_n$ target. The result of this work was, therefore, an upper limit for the α -branch of the key 4.033 MeV level of $b_\alpha < 4.3 \times 10^{-4}$ [10].

More recently, Tan *et al* [11, 12] made use of the $^{19}\text{F}(^3\text{He},t)^{19}\text{Ne}$ charge-exchange reaction to populate states in ^{19}Ne and then search for the α emission from levels above the $^{15}\text{O} + \alpha$ threshold. In this work α -decay branching ratios were determined through t - α coincidences with a detection system optimized for the detection of low-energy α particles. A value of $b_\alpha = 2.9(21) \times 10^{-4}$ was reported for the key, 4.033 MeV state, however there is significant background in the energy region of interest for this key resonance.

2. Experimental details

In order to measure this tiny α -decay branch, it is desirable to perform such a measurement in an environment which would yield negligible background in the energy region of interest while still maintaining the large luminosity required. Such a setup is possible with a heavy-ion storage ring, where protons for the target material are provided by an ultra-pure hydrogen gas-jet target. Given that the $^{21}\text{Ne}(p,t)^{19}\text{Ne}$ reaction has previously been shown to strongly populate the key 4.033 MeV level it would be desirable to make use of a recirculated beam of, stable, ^{21}Ne ions. Unfortunately, insufficient quantities of enriched ^{21}Ne material were available for beam production. Thus the $^{20}\text{Ne}(p,d)^{19}\text{Ne}$ reaction was instead employed as a proof-of-principle experiment to explore whether transfer reactions can be used as a spectroscopic method and to explore this reaction as a means of accessing the key resonance in ^{19}Ne .

A schematic of the experimental setup is shown in figure 1. A $50 \text{ MeV u}^{-1} \text{ }^{20}\text{Ne}^{10+}$ beam was delivered by the GSI accelerator system and injected into the experimental storage ring (ESR) where up to 2×10^8 ions were accumulated, with electron cooling utilized to reduce the momentum spread of the beam and, therefore, increase the lifetime of the beam within the ring. The beam then passes through the hydrogen gas-jet target (of thickness $10^{13} \text{ atoms cm}^{-2}$) about 10^6 times per second. Energetic deuterons from the resulting $p(^{20}\text{Ne},d)^{19}\text{Ne}$ reaction were then identified using two double sided silicon strip detectors, arranged as a ΔE -E telescope, and placed within a specially constructed detector pocket. Excitation energy spectra could then be constructed by gating on deuteron events in the particle ID spectra and then making use of the segmentation afforded by the DSSD detectors in order to determine polar angles. The corresponding heavy-ion is then detected with an array of six silicon pin diode detectors, placed 8 m downstream of the target and within the UHV of the ESR, for more information on this detector see [14]. Then by investigating deuteron–heavy-ion coincidences, where the complementary heavy-ion is detected in the downstream pin-diode detector array (see figure 1), the α -

Figure 1. Schematic of the experimental setup employed at the experimental storage ring (ESR). Figure is taken from [13].

branch of states above the α particle emission threshold may be determined.

3. Results

Figure 2 shows a sample (singles) ^{19}Ne excitation energy spectrum, from the ground state up to approximately 4.4 MeV, obtained in the present work from around 6 h of beam on target, with the arrows above the data indicating the energies of known ^{19}Ne states. Several ^{19}Ne states have clearly been identified, including the key, astrophysical level at 4.033 MeV showing the feasibility of transfer reaction studies on the storage ring. While the 4.033 MeV state is populated fairly strongly compared to neighbouring levels it is not as preferentially populated as in (p,t) studies [9, 10] which would remain the best approach for a full experimental study. The energy resolution may be estimated by determining the FWHM of the 2.795 MeV peak, which is known to be a singlet. The value of ~ 260 keV is comparable to the ~ 180 keV figure expected from Monte-Carlo simulations [13].

4. Conclusion

In summary, we have shown that transfer reactions on heavy ion storage rings can be used as a method for spectroscopic studies in an essentially background free environment. For the population of the key astrophysical resonance in ^{19}Ne an approach based on the $p(^{21}\text{Ne},t)$ reaction mechanism looks most feasible.

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Figure 2. ^{19}Ne excitation energy spectrum obtained for a single pocket position. The red line is the total fit to the data while the arrows above the data represent the literature values for known ^{19}Ne states, in this excitation energy region, from [15]. This figure is taken from [13].

References

- [1] Zezas A *et al* 2007 *Astrophys. J.* **661** 135
- [2] Ajello M *et al* 2008 *Astrophys. J.* **673** 96
- [3] Woolsey S E and Taam R E 1976 *Nature* **263** 101
- [4] Jose J and Iliadis C 2011 *Rep. Prog. Phys.* **74** 096901
- [5] Langanke K *et al* 1986 *Astrophys. J.* **301** 629
- [6] Schatz H *et al* 2001 *Phys. Rev. Lett* **86** 3471
- [7] Kanungo R *et al* 2006 *Phys. Rev. C* **74** 045803
- [8] Mythili S *et al* 2008 *Phys. Rev. C* **77** 035803
- [9] Fortune H T, Nann H and Wildenthal B H 1978 *Phys. Rev. C* **4** 18
- [10] Davids B *et al* 2003 *Phys. Rev. C* **67** 065808
- [11] Tan W P *et al* 2007 *Phys. Rev. Lett.* **98** 242503
- [12] Tan W P *et al* 2009 *Phys. Rev. C* **79** 055805
- [13] Doherty D T 2013 *PhD Thesis* University of Edinburgh
- [14] Mutterer M *et al* 2015 *Phys. Scr.* **T166** 014053
- [15] Ouellet C and Singh B 2013 *Nucl. Data Sheets* **114** 209