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β-Delayed proton-decay study of ^{20}Mg and its implications for the ^{19}Ne(p, γ)^{20}Na breakout reaction in X-ray bursts

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Under astrophysical conditions of high temperature and density, such as for example found in X-ray bursts, breakout can occur from the hot CNO cycles into the rapid proton capture process. A key breakout route is via the sequence ^{15}O(α, γ)^{19}Ne(p, γ)^{20}Na. The ^{19}Ne(p, γ)^{20}Na reaction rate is expected to be dominated by a single resonance at 457(3) keV. The identity of the resonance has been under discussion for a long time, with $J^{\pi} = 1^+$ and 3^+ assignments suggested. In this study of the β-delayed proton decay of ^{20}Mg we report a new, significantly more stringent, upper limit on the β-decay branch to this state of 0.02% with a confidence level of 90%. This makes a 1^+ assignment highly unlikely and favours a 3^+ assignment for which no branch is expected to be observed. The 3^+ state is predicted to have a significantly higher resonance strength, and to produce a proportionately higher ^{19}Ne(p, γ)^{20}Na reaction rate in X-ray burst conditions.

1. Introduction

In explosive astrophysical phenomena in which temperatures in excess of 0.5 GK are achieved, such as X-ray bursts, it is possible to breakout from the β-limited hot CNO cycles into the rp process, a series of rapid proton capture reactions synthesizing proton-rich nuclei potentially up to the Sb–Te mass region [1,2]. It is expected that the reaction sequence ^{15}O(α, γ)^{19}Ne(p, γ)^{20}Na provides the main link between the two processes, with its strength determining the conditions for ignition of the X-ray burst and the recurrence rate [3,4]. As such, extensive efforts have been made to determine both the ^{15}O(α, γ)^{19}Ne and ^{19}Ne(p, γ)^{20}Na astrophysical reaction rates (see Ref. [4] for a recent discussion of the former reaction). Under X-ray burst conditions, the ^{19}Ne(p, γ)^{20}Na reaction is thought to be dominated by the contribution of a single low-energy resonance ∼450 keV above the proton-emission threshold energy of 2190.1(11) keV in ^{20}Na [5]. The identity of this resonance, and hence its inferred strength, has remained a matter of intense debate for over two decades. Direct measurements of the strength have been attempted using radioactive beams of ^{19}Ne [6–10], but so far only an upper limit of 15 meV with a 90% confidence level has been determined [10].

Lamm et al. [11] studied the ^{20}Ne(^{3}He, t)^{20}Na charge exchange reaction, and from a DWBA analysis made a 1^+ (spin and parity, J^{π}) resonance assignment for the state at an excitation energy ∼2650 keV in ^{20}Na, pairing it with a 1^+ level at an energy of 3173 keV in ^{20}F. However, Clarke et al. [12] studied both the ^{20}Ne(^{3}He, t)^{20}Na and ^{20}Ne(t, ^{3}He)^{20}F charge exchange reactions and found the angular distributions to be incompatible with these being analogue states. Rather, they noted a good agreement could be obtained with a known 3^+ level at 2966 keV in ^{20}F [12]. Similarly, a study of the ^{20}Ne(p, n)^{20}Na reaction made a 3^+ assignment for the ∼2650 keV state in ^{20}Na [13]. Arguing from a shell model perspective, Fortune et al. [14] pointed out that a large Coulomb energy shift is required for the ∼2650 keV level which can only be achieved for states with a large $2s_{1/2}$ component, and is only satisfied by the 3^+ level in this excitation energy region of ^{20}F. The 1^+ state at 3173 keV in ^{20}F is suggested as having a $(sd)^6p^{-2}$ configuration which would not exhibit a significant Coulomb energy shift, whereas the known 1^+ state at 3488 keV is considered to have much too large a shift relative to the ∼2650 keV level in ^{20}Na [15]. For a 3^+ assignment, Fortune et al. derived a lower limit on the resonance strength of 16 meV [14], tantalizingly close to the experimental upper limit of 15 meV [10]. In contrast, taking a 1^+ assignment, a value for the strength of 6 meV has been estimated [9], which is more clearly compatible with the upper limit

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found in direct measurements of the reaction. A key aspect in this debate has been the absence of the observation of an allowed Gamow–Teller β-delayed proton branch from the decay of ^{20}Mg that would be expected for a 1^+ resonance assignment [16,17]. The most sensitive limit for feeding of the key resonance (0.1%, corresponding to a $\log ft$ lower limit of 6.24, with no confidence level quoted) was set in the study of Piechaczek et al. [17] measured by implanting ^{20}Mg ions inside a 300 μm thick silicon detector. However, this sensitivity was limited by a high positron background in the energy region of interest. Consequently this still left open the possibility of a weak branch compatible with a 1^+ assignment for a hindered transition [17]. In contrast, a 3^+ transition would be strongly forbidden and would not be expected to be observed.

2. Experiment and results

In the present experiment, the β-delayed proton decay of ^{20}Mg was studied at the Cyclotron Institute at Texas A&M University. A primary beam of ^{20}Ne ions of energy 25 MeV/u was used to bombard a cryogenic ^{3}He target in order to produce ^{20}Mg nuclei through the fusion evaporation reaction ^{20}Ne(^{3}He, 3n)^{20}Mg. The ^{20}Mg recoil ions, produced with an energy ∼380 MeV, were separated from other more intensely produced reaction products using the Momentum Achromat Recoil Spectrometer (MARS) [18]. Typically ∼30 ^{20}Mg ions s^{-1} were transmitted through the slits at the focal plane of MARS, which were set to a narrow range to limit the number of other analyzed reaction products. The analyzed beam consisted of 89% ^{10}C ions, 10% ^{20}Mg ions and 0.5% ^{17}Ne ions, all fully stripped. The analyzed beam was degraded at the focal plane of MARS (details of this procedure are described in Ref. [19]), in order to implant ^{20}Mg ions with a straggling range of ∼18 μm, into the center of a thin (45 μm) double-sided silicon strip detector (DSSD) oriented at an angle of 45° to the beam. The DSSD was segmented into 24 horizontal strips, and 24 vertical strips, of 1 mm pitch. The small thickness and high segmentation of the DSSD minimized the sensitivity to positrons, which have a longer range in silicon (typically a few mm) compared for example to the ∼450 keV protons (range ∼7 μm) emitted from the main resonance of interest. The DSSD was sandwiched between two thicker silicon detectors, 140 μm and 1 mm, also oriented at 45°, which were used to detect positrons and escape protons from higher-energy proton unbound states in ^{20}Na produced in the β-decay of ^{20}Mg ($t_{1/2} \sim 90$ ms). The longer range contaminant ^{10}C and ^{17}Ne ions, were transmitted through the thin DSSD and stopped inside the 1 mm thick silicon detector. The beam was pulsed, with 200 ms of beam on, and 200 ms beam off, with decay data being taken during the beam off period. A total of 3×10^6 ^{20}Mg ions were implanted into the DSSD.

Fig. 1 shows the energy spectrum for the β-delayed proton decay of ^{20}Mg, requiring a multiplicity of one signal above the electronic discriminator threshold (∼300 keV) within both the X and Y strips, and that these signals have ∼ equal energy (within +/−40 keV). These requirements have the effect of vetoing general noise, and background associated with longer range particles, primarily positrons, moving across adjacent strip regions. As can be seen from this spectrum, there is negligible background from positrons in the low-energy region, and almost negligible β-energy summing on the main proton-decay lines, compared for example to Figs. 4 and 3, respectively, in Ref. [17] (note: the main contaminant reaction product implanted in the 1 mm thick silicon detector, ^{10}C, β-decays to the stable nucleus ^{10}B and the β's do not get through the cuts applied to the data, making it a negligible source of background). Instead, the main source of background arises from higher-energy protons associated with the β-decay of ^{20}Mg depositing energy in the DSSD as they escape. To reduce this background from escaped protons, an anti-coincidence for high-energy protons between the DSSD and the two thicker silicon detectors was implemented. On an event-by-event basis it is impossible to completely distinguish between the signals from positrons and protons by a ΔE–E analysis as the direction of particle emission, and the length of path travelled by the particle, in the DSSD is unknown. However, escape protons typically deposit significantly higher energies in the thicker silicon detectors than the positrons. In particular, the escape protons with the highest kinetic energies on average deposit the lowest energies in the DSSD, which is the region critical for the present work. By exploring coincidence events in detail, it was found that an optimal upper-energy

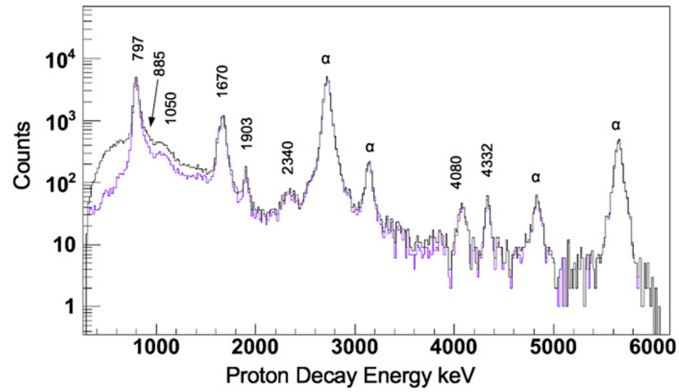

Fig. 1. (Black line) Energy spectrum measured in the DSSD for β-delayed particle decays from ^{20}Mg, with proton-decay energy peaks labelled. The alpha peaks come from known transitions from the β-delayed alpha decay of ^{20}Na produced as a daughter product of the β-decay of ^{20}Mg [26]. (Purple line) Energy spectrum for events in anti-coincidence with high-energy protons from either the 140 μm or 1 mm thick silicon detectors. There is a significant reduction of low-energy signals corresponding to the escape of higher-energy protons from the β-delayed proton decay of ^{20}Mg (see Section 2 for details). Proton transitions are listed in Table 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

Table 1
Table gives the proton-decay energy values for transitions shown here in Fig. 1 for the β–p decay of ^{20}Mg. The excitation energies for ^{20}Na were derived from these proton-decay energy values in combination with the new precise proton threshold energy value [5], and assuming final states in ^{19}Ne as reported in [17]. An approximation symbol denotes a single approximate centroid value obtained here for an energy region with two or more previously known transitions [17] unresolved in the present work.

Excitation energy in ^{20}Na (keV)	Proton-decay energy (keV)	Final state(s) in ^{19}Ne [17]
2647(3)	457(3)[a]	0
2987(2)	797(2)[b]	0
3075(15)	885(15)	0
3860(10)	1670(10)[c]	[d]
4093(5)	1903(5)	0
∼4780	∼2340	238 + 275
	∼1050	1508 + 1536
∼6270	∼4080	0
6522(16)	4332(16)[c]	0
	∼4080	238 + 275

[a] Key astrophysical resonance energy derived here using a precise measurement of the energy difference of this state [23] with respect to the excited state at 2987(2) keV – see text for details.

[b] Precise resonance energy measurement taken from a ^{19}Ne(p, p) resonant scattering study [6].

[c] Proton calibration energies taken from the work of Gorres et al. [16].

[d] This proton line consists of a dominant branch to the ground state and two weaker transitions from the 4093(5) keV excited state in ^{20}Na to the 238 and 275 keV excited states in ^{19}Ne as identified in the p–γ coincidence measurements of Ref. [17]. In the earlier work of Gorres et al. [16], only a single transition was assigned at 1670(10) keV with the other weaker components being unresolved. Therefore in our proton dispersion energy calibration procedure we also used a single centroid value for the peak structure shown in Fig. 1 at 1670 keV.