Low-energy $^{23}$Al $\beta$-delayed proton decay and $^{22}$Na destruction in novae

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The radionuclide $^{22}$Na is a target of $\gamma$-ray astronomy searches, predicted to be produced during thermonuclear runaways driving classical novae. The $^{22}$Na$(p,\gamma)^{23}$Mg reaction destroys $^{22}$Na during a nova, hence, its rate is needed to accurately predict the $^{22}$Na yield. However, experimental determinations of the resonance strengths have led to inconsistent results. In this work, we report a measurement of the branching ratios of the $^{23}$Al $\beta$-delayed protons, as a probe of the key 204–keV (center-of-mass) $^{22}$Na$(p,\gamma)^{23}$Mg resonance strength. We report a factor of 5 lower branching ratio compared to the most recent literature value and discuss possible interpretations of the results. This is the first reported scientific measurement using the Gaseous Detector with Germanium Tagging (GADGET) system.

Radionuclides are now routinely observed astronomically using space-based gamma-ray observatories capable of detecting their characteristic emission lines. For example, $^{26}$Al ($T_{1/2} = 0.72$ Ma) and $^{60}$Fe ($T_{1/2} = 2.6$ Ma) live long enough to migrate from the stellar events producing them before they decay and manifest as diffuse emission across the Milky Way. Attempts have been made to benchmark nucleosynthesis in massive stars and their supernovae using the relative amounts of observed $^{26}$Al [1–5] and $^{60}$Fe [6], but such benchmarks can only be applied by considering all possible sources in aggregate. More stringent constraints on astrophysical models of particular events can be derived using shorter-lived nuclides that manifest as localized sources such as $^{44}$Ti ($T_{1/2} = 59$ a), which has been observed in the 350-year-old Cas A core-collapse supernova remnant [7–11] and the younger remnant of Supernova 1987A [12]. Similarly, the detection of $^{22}$Na ($T_{1/2} = 2.6$ a) from a classical nova explosion has been a long sought constraint [13–18]. Observations with previously and currently deployed instruments may have been on the cusp of detecting $^{22}$Na [19–23], and more sensitive future missions are being planned [24]. Accurate model predictions of $^{22}$Na nucleosynthesis in novae are needed to estimate the detectability distance and for comparison to past searches and future observations.

The $^{22}$Na yield predicted by nova models is sensitive to the thermonuclear rates of the reactions associated with explosive hydrogen burning on the surface of a white-dwarf star accreting hydrogen-rich material from a binary companion star [18, 25]. This has motivated the development of innovative experimental nuclear physics techniques, providing rates to improve predictions of the $^{22}$Na yield [26–39]. While $^{22}$Na is being produced during the thermonuclear runaway driving a nova, the $^{22}$Na$(p,\gamma)^{23}$Mg reaction is actively destroying it. The $^{22}$Na yield is related inversely to the reaction rate and, in particular, to the strength of a single resonance at a center-of-mass energy of 204 keV. Two direct measurements ([27, 28] and [36, 37]) of the resonance strength using proton beams and radioactive $^{22}$Na targets have yielded values that differ by a factor of 3.2, which results in a factor of $\approx 2$ variation in the expected $^{22}$Na yield from classical novae [36]. Another way to determine the strength is to combine measurements of the proton branching ratio $\Gamma_p/\Gamma$ of the resonance with its lifetime $\tau$ and spin. The most precise literature values [34, 38] for these quantities yields a strength that is consistent with that from Refs. [27, 28]. It may be tempting to consider this the conclusive arbiter for the two inconsistent directly-measured values, but it would be prudent to confirm the proton branching ratio and lifetime, as the aforementioned experiments faced significant challenges.

In particular, the $^{23}$Al$(\beta\pi)$ experiment of Ref. [38] suffered from overwhelming $\beta$ background and relied heavily on a background subtraction model. Pollacco et al. [40] showed that gas-filled detector can be used to overcome this problem, and found indications of a branching ratio for the 204–keV level significantly lower than in Ref. [38]. Presently, we report a new proton branching ratio for the 204–keV resonance, determined based on measurements of low-energy $^{23}$Al $\beta$-delayed protons with a new system: the Gaseous Detector with Germanium Tagging (GADGET) [41]. GADGET is optimized for the detection of low-energy, low-intensity $\beta$-delayed protons with complementary high-resolution high-efficiency $\gamma$-ray detection. This Letter reports the first scientific results from GADGET.

The experiment was performed at the National Super-
conducting Cyclotron Laboratory (NSCL), where a radioactive beam of $^{23}$Al was produced. A 150–MeV/u, 75–pA primary beam of $^{36}$Ar was accelerated using the Coupled Cyclotron Facility [42] and impinged upon a $^9$Be transmission target, 1363 mg/cm$^2$ in thickness. $^{23}$Al was isolated to a purity of 69 % using the A1900 magnetic fragment separator [43] incorporating a 300 mg/cm$^2$ Al wedge and the Radio Frequency Fragment Separator (RFFS) [44]. Upon exiting the RFFS, situated about 6 m upstream of GADGET, the main contaminants were $^{21}$Na, $^{23}$Mg, and $^{16}$N, in decreasing order of intensity, as identified with standard $\Delta E$-ToF method. The beam rate was about 3000 pps. To optimize the $^{23}$Al beam energy and range, a 2–mm thick rotating aluminum degrader, located directly in front of the detection system, was used.

A detailed description of GADGET can be found in [41]. Briefly, the assembly contains the Proton Detector, which is a cylindrical vessel filled with P10 gas (set to 780 Torr for this experiment) that functions both as a beam stop and a detection medium, surrounded by the Segmented Germanium Array (SeGA) [45] for coincident $\gamma$–ray detection. The beam was operated in a pulsed mode, where $^{23}$Al ions ($T_{1/2} = 470$ ms) were accumulated in the Proton Detector for 0.5 s, and then the beam was stopped for another 0.5 s to allow their charged particle decay radiations to be detected by ionization. The ionization electrons were drifted towards the readout plane by an uniform electric field of 125 V/cm and amplified by a MICROMEGAS structure [46]. An electrostatic gating grid was used to protect the MICROMEGAS from the large signals produced during the implantation periods.

The active volume is a cylinder, 40 cm long and 10 cm in diameter. The short range of the protons in the gas versus the near-transparency to the $\beta$–particles enables the detection of the weak, low–energy, protons and effectively eliminates an otherwise overwhelming $\beta$ background. The MICROMEGAS pad plane is divided into 13 pads, labeled A-M as shown in Fig. 1. This configuration allows vetoing of high–energy protons that might escape the active volume and deposit only part of their energy in the active volume. In addition, it enables analysis of either most of the full active volume (pads A-E) for higher efficiency, or to limit the active volume into sub-sections to achieve lower $\beta$ background at the cost of efficiency loss for higher energy protons. In the current experiment, pads F,G,L,M were not instrumented which resulted in 50% veto efficiency for events in the A-E active volume. However, in the case of $^{23}$Al only a small fraction of the protons are emitted above $\sim$1 MeV [47], hence the associated background is insignificant.

Fig. 2 shows the proton energy spectrum for pad A (red) and for event-level summing of the five central pads (A–E, blue). The $\beta$ background is substantially suppressed relative to previous experiments [38, 48], allowing the extraction of the 204–keV peak intensity from both spectra. The single pad spectrum shows further reduced $\beta$ background due to the smaller active volume, at the cost of a fast-declining efficiency as function of proton energy. For interpretation of the proton spectrum a simplified decay scheme is presented in Fig. 3. There are no beam contaminants that emit $\beta$–delayed charged particles, with the exception of the $^{16}$N that has small $\alpha$–particle branching ratio ($1.2 \times 10^{-5}$). In addition, those emissions are mostly in an energy range 1.5 MeV to 3 MeV [49–51], which is significantly above the region of
The intensities of the low-energy $^{23}$Al $\beta$-delayed proton peaks from past [38, 48, 52, 53] ([52] as compiled by [38]) and present work, relative to the 866–keV peak intensity. Note that the 583–keV peak is contributed to by two separate decays (see text and Fig. 3 for details).

| Reference          | $E_{c.m.}$ (keV) | $204$ | $275$ | $583$ |
|--------------------|-----------------|------|------|------|
| Tighe [48]         | 2.2(5)          | 0.9(3) | 0.7(1) |
| Peräjärvi [52]     | 0.10(8)         | 0.13(9) | 0.73(49) |
| Saastamoinen [38]  | 0.34(6)         | 0.45(9) | 0.69(3) |
| Sun [53]           | 0.34(12)        | 0.43(15) | 0.61(12) |
| Present Work       | 0.066(6)        | 0.288(10) | 0.685(22) |

Since the intensities of both the 583–keV and 866–keV proton peaks were extracted precisely and accurately in past [38, 48, 52, 53] ([52] as compiled by [38]) and present experiments, the agreement between the branching ratios of the 583–keV peak is an additional verification of the efficiency calculation. Despite the excellent $\beta$ background suppression in the present experiment, extracting the intensity of the 204–keV peak still required modeling of the background in the combined spectrum with an exponential function, which was chosen based on the GEANT4 simulation. We then used the central pad spectrum, where the 204–keV peak is much cleaner, to verify the intensity ratios of the 204–keV to the 275–keV peaks. We obtained a ratio of $I_{204}^{bp}/I_{275}^{bp} = 0.210(15)$ for the central pad, in agreement with $I_{204}^{bp}/I_{275}^{bp} = 0.228(18)$ for the combined spectrum.

We measured the ratio of intensities of the 204–keV and 866–keV protons in $^{23}$Al($\beta$p)$^{22}$Na decay to be $I_{204}^{bp}/I_{866}^{bp} = 0.066(6)$. To put this value into context, it is instructive to review the previous literature on the
TABLE II. Strength of the 204–keV (c.m.) $^{23}$Na(p,$\gamma$)$^{23}$Mg resonance. The strength for indirect values is calculated assuming various combinations of the branching ratios and lifetimes of the 7.79–MeV state, and 7/2 spin assignment. Upper limits are calculated within a 90% C.L.

| method        | reference             | $\omega\gamma$ (meV) |
|---------------|-----------------------|-----------------------|
| direct        | Stegmüller/Seuthe [27, 28] | $1.8(7)$             |
| direct        | Sallasla [36, 37]     | $5.4^{+1.6}_{-0.9}$  |
| indirect      | Peräjäri [52]        | $10(8)\times10^{-3}$, $0.4(3)$ | $10(3)$ fs [34] | $\tau < 12$ fs [56] |
| indirect      | Saastamoinen [38]    | $3.7(9)\times10^{-2}$, $1.4^{+0.5}_{-0.4}$ | $> 0.71$ |
| indirect      | Present Work         | $6.8(9)\times10^{-3}$, $0.26(8)$ | $> 0.17$ |

The lowest-energy proton peak from $^{23}$Al($\beta$3$p$)$^{22}$Na decay (Table I). As suggested by [38], it seems likely that the “peak” in Tighe et al. [48] is really misinterpreted low-energy background or noise combined with a threshold and, therefore, we believe it is reasonable to disregard the measurement of Ref. [48]. The 204–keV peak intensity in Sun et al. [53] is consistent with Ref. [38], but based on very limited statistics. The present value is consistent with the value reported by Peräjäri et al. [52], which has large error bars, but the present value is a factor of 5 lower than the value in Ref. [38]. The unique systematic effect in Ref. [38] was related to the use of a Si implantation detector, for which a very large subtraction of background from $\beta$ particles was required to extract the proton spectrum at the lowest energies. The present work was carried out with a gas-filled detector specially designed to mitigate $\beta$-particle background in the region of interest, strongly reducing uncertainties associated with background subtraction. The gas-Si telescope used in Ref. [52] was also relatively insensitive to $\beta$-particle backgrounds. Therefore, we consider the present value and the one from Ref. [52] to be the most reliable. The present value provides a much smaller uncertainty that can be attributed in part to several orders-of-magnitude higher statistics.

Using the present value for the ratio $I_{204}^{23}/I_{866}^{23}$, we determine the absolute intensity of the 204–keV peak by adopting the absolute intensity of the 866–keV peak from Ref. [38], $I_{866}^{23} = 0.41(1)$% [38]. The adopted value for the intensity of the 866–keV proton peak is relatively insensitive to systematic effects because of its higher energy and intensity, and it is also consistent with the absolute intensity of Ref. [53], albeit with large uncertainty. The result is $I_{204}^{23} = 0.0260(24)$%. Ref. [40] indicated a branching ratio on the order of 0.02%, consistent with our current value. The ratio of this value to its sum with the well-known $\beta\gamma$ intensity through the same 7.79–MeV state of $^{23}$Mg, $I_{7.79}^{23} = 3.95(37)$% [38, 57, 58] yields a proton branching ratio of $\Gamma_p/\Gamma = 6.8(9) \times 10^{-5}$.

In order to calculate the resonance strength using our new value for the proton branching ratio, we must adopt a spin and lifetime for the resonance. Multiple arguments have been made for a (7/2)$^+$ spin and parity assignment, which we adopt [38, 54, 59]. The only finite literature value for the lifetime is 10(3) fs from an in-beam gamma-ray spectroscopy measurement [34]. Using these values would lead to a resonance strength of $\omega\gamma = 0.26(8)$ meV, which is 7 and 22 times lower than the directly measured values from Refs. [27, 28] and [36, 37], respectively (see Table II). Taking this number at face value would dramatically reduce the significance of the 204–keV resonance at peak nova temperatures and reduce the $^{22}$Na(p,$\gamma$)$^{23}$Mg destruction rate. However, we do not advocate using this new value for several reasons. First, it is difficult to imagine how the direct measurements could be inaccurate by such large factors in the direction of being too high. Second, the finite lifetime value has never been confirmed by an independent finite measurement. Third, the increased $^{22}$Na production would lead to serious tension between nova nucleosynthesis models and observational limits [20, 21]. Finally, assuming spin and parity assignment of (7/2)$^+$, shell-model calculations predict a much shorter lifetime of $\sim 0.6-1.7$ fs (see Ref. [60] for calculation details), yielding a resonance strength of $\omega\gamma = 1.5-4.2$ meV, which is on the same order as the direct measurements. We therefore conclude that the lifetime of the 7.79–MeV excited state of $^{23}$Mg must be re-measured prior to use with the branching ratio to obtain a resonance strength. Presently, we recommend adopting a more conservative lower limit on the resonance strength, from a recent lifetime measurement by Kirsebom et al. [56] which provides a 95% C.L. upper limit of 12 fs on the lifetime of the 7.79–MeV state. Table II summarizes the resulting resonance strengths using various values for the branching ratios with both lifetimes, and the direct measurement values.

In summary, we have measured the low-energy $^{23}$Al $\beta$-delayed proton intensities with the best accuracy so far, using a new detection system, GADGET [41]. The result leads to a new proton branching ratio for the key 204–keV resonance, which is a factor of 5 lower than the most precise and most recent literature value [38]. If the present value is used together with the lifetime from Ref. [34] then the resonance strength is 7 and 22 times lower than the two direct measurements Ref. [27, 28] and [36, 37], respectively, compounding the existing discrepancies.
and introducing serious problems with the interpretation of the nuclear and astrophysical data. However, we assert that re-examination of the lifetime value for the $^{23}$Mg 7.79–MeV state is essential for reliable extraction of the key 204–keV resonance strength.

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