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^{28}Si$(p,t)^{26}$Si data reconsidered for the astrophysical ^{25}Al$(p,\gamma)^{26}$Si rate

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The ^{25}Al$(p,\gamma)^{26}$Si reaction bypasses production of potentially observable ^{26}Al in novae and strongly influences the nova contribution to galactic ^{26}Al. The nuclear structure of ^{26}Si directly impacts estimates of the astrophysical ^{25}Al$(p,\gamma)^{26}$Si reaction rate, and reactions such as ^{28}Si$(p,t)^{26}$Si have been used to understand this structure. Since the original publication of ^{28}Si$(p,t)^{26}$Si data [D. W. Bardayan *et al.*, Phys. Rev. C **65**, 032801(R) (2002)], a number of subsequent publications have greatly clarified the level scheme of ^{26}Si, and this article reports on a reconsideration of these original data in light of the new results.

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I. INTRODUCTION

The definitive observations of ^{26}Al in our galaxy provided some of the first confirmations that nucleosynthesis is ongoing. The lifetime of ^{26}Al ($t_{1/2} = 7.2 \times 10^5$ y) while long is still much shorter than the estimated age of the universe. A number of astrophysical environments may contribute to the galactic ^{26}Al abundance including asymptotic giant branch stars; massive and very massive stars, both their Wolf-Rayet winds and their final core-collapse supernovae (CCSN); and novae[1]. In higher-temperature production sites such as novae, the generation of potentially observable ^{26}Al may be bypassed by the reaction sequence ^{24}Mg$(p,\gamma)^{25}$Al$(p,\gamma)^{26}$Si [2]. The ^{26}Si nuclei subsequently decay to the first excited state of ^{26}Al, which decays ($t_{1/2} = 6.35$ s) to the ground state of ^{26}Mg, and no observable γ rays are produced. The extent to which this bypass sequence occurs depends sensitively on the ^{25}Al$(p,\gamma)^{26}$Si reaction rate [3], which continues to be uncertain as a result of the uncertain level structure of ^{26}Si and the unavailability of sufficient-intensity ^{25}Al beams that could be used to directly measure the rate.

Of relevance to the rate are nuclear levels near the proton threshold at $S_p = 5513.8(5)$ keV in ^{26}Si [4]. Especially important is identifying 2^+ or 3^+ levels near the threshold that could provide s-wave resonances for the ^{25}Al$(p,\gamma)^{26}$Si reaction. Shell-model calculations and comparisons with the ^{26}Mg mirror nucleus indicate that levels of interest may include two 4^+ states, a 1^+ state, a 3^+ state, and a 0^+ state in the rough excitation energy range $E_x = 5400$–6200 keV [2,5,6]. A number of experimental studies were conducted to search for and identify relevant levels including measurements of the ^{28}Si$(p,t)^{26}$Si [7,8], ^{29}Si$(^3$He$,^6$He$)^{26}$Si [9], and ^{24}Mg$(^3$He$,n)^{26}$Si reactions [10,11]. Later studies utilizing γ-ray measurements [12–14] found that the energy calibration of these studies were suspect since they relied upon much earlier measurements [15] that were incorrect by up to ~5 keV. Such corrections could be important because the 3^+ resonance thought to dominate the astrophysical ^{25}Al$(p,\gamma)^{26}$Si reaction rate at nova temperature has primarily been identified through these transfer-reaction measurements [16] as well as proton-transfer measurements on ^{25}Al beams [17,18], and the rate depends exponentially on the resonance energy.

In addition to better determining the resonance energies, understanding the calibration of these previous data sets is important for the interpretation of the nuclear structure of ^{26}Si about which there are a number of open questions [1]. For instance, our current understanding [4] is that the above-mentioned 3^+ resonance arises from a ^{26}Si level at 5928 keV, which lies near a 0^+ level at 5890 keV. It is not clear, however, why this 3^+ level was relatively strongly populated in the ^{28}Si$(p,t)^{26}$Si study [8] while the 0^+ level was not observed at all. One would naively expect that natural spin/parity levels to be most strongly populated in ^{28}Si$(p,t)^{26}$Si. Could this interpretation have been impacted by the uncertain energy calibration? Another open question revolves around the existence of this 0^+ level. So far its existence has only been reported in studies of ^{24}Mg$(^3$He$,n\gamma)^{26}$Si [13,14,19,20], but it should have also been observable in the ^{24}Mg$(^3$He$,n)^{26}$Si study by Parpottas *et al.* [10]. If this level at 5890 keV exists and is in fact a 0^+ level, then there appears to be too many 0^+ levels in this energy region when compared to the shell model [4,6,14] since Parpottas *et al.* had already identified a 0^+ level at 5946 keV. Again clarifying the level structure of ^{26}Si including the calibration of the earlier ^{28}Si$(p,t)^{26}$Si data could shed some light onto these open questions.

In this article, the data from Ref. [7] are reanalyzed in light of the higher-precision excitation energies for lower-lying levels that are currently available from γ-ray measurements [12,14]. With the greater understanding of the ^{26}Si level structure, weaker peaks in the ^{28}Si$(p,t)^{26}$Si spectra can also be considered with greater certainty. Finally, the implications for the ^{25}Al$(p,\gamma)^{26}$Si astrophysical rate are discussed.

II. ANALYSIS

The triton energy spectra from the ^{28}Si$(p,t)^{26}$Si reaction [7] measured as a function of angle were reanalyzed

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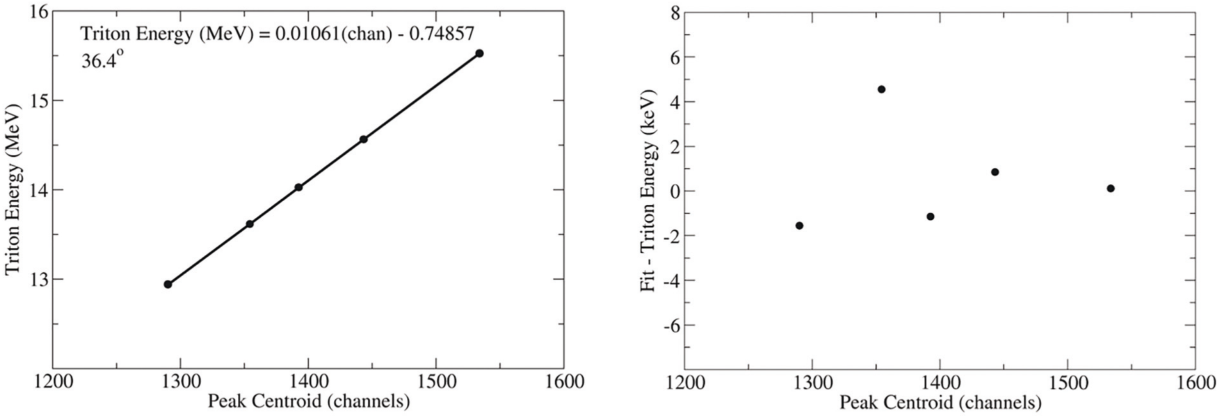

FIG. 1. (Left) The expected triton energies arising from population of the five calibration levels vs. the peak centroids extracted at 36.4°. The line shows the linear fit to the data, which was extrapolated to lower triton energies to extract the excitation energies of higher-lying ^{26}Si levels. The average deviation of the fit from the expected triton energies was 2 keV. (Right) The residuals of the fit.

in light of improved knowledge of the ^{26}Si level structure. The previous calibration energies [1795.9(2), 2783.5(4), 3332.5(3), 3756(2), 4445(3), 4805(2)] keV from Ref. [15] were replaced with [1797.3(1), 2786.4(2), 3336.4(2), 3757.1 (3), 4445.5(12)] keV from [14]. Especially problematic in the previous calibration was the assumption of a single level at 4805 keV, which has now been shown to be a triplet at 4796.7(4), 4811.9(4), and 4832.1(4) keV [14]. Because of this, this triplet was excluded from the current calibration data. An example of the new calibration is plotted in Fig. 1. The results from this procedure are compared in Table I with the results from the γ-ray measurements [14] at lower excitation energies and with the (^{3}He, n) [10] and (p, t) measurements [21] at higher excitation energies. The excitation energy for the important 3^+ level is now extracted at 5922(2) keV from the ^{28}Si(p, t)^{26}Si data, which is in much better agreement with the weighted average of previous measurements, 5927.6(10) [4]. While there was observed to be a weak shoulder on the high-triton energy side of the 3^+ state, the extracted centroid did not change within uncertainties by including an additional peak in the fit. The source of this weak peak is discussed further in the subsequent paragraph. The recalibration of the ^{28}Si(p, t)^{26}Si data apparently will not resolve the question as to why the 3^+ level was strongly populated in that measurement. With the current better understanding of the ^{26}Si level structure, the ^{28}Si(p, t)^{26}Si data can also be examined for evidence for the 5890-keV 0^+ level, which so far has only been observed in ^{24}Mg(^{3}He, $n\gamma$)^{26}Si [13,14,19,20] measurements. The relevant energy range from Fig. 1 of Ref. [7] is expanded in Fig. 2. There is indeed evidence for an additional peak on the higher triton-energy side (lower excitation energy) of the 5922-keV peak. The peak seems to rapidly disappear at larger angles which is consistent with what would be expected for an $\ell = 0$ transfer that exhibits a minimum around 22°. At larger angles the resolution degrades significantly as a result of the larger angular bins of the detector strips preventing any further observations at these angles. The energy extracted for this peak places the level at 5870(14) keV, which is somewhat lower than the accepted value of 5890.1(6) keV, but the uncertainty is rather large as a result of the single measurement. In comparison, the other levels reported in this work were observed at several angles and the results averaged. While it is difficult to be conclusive, it does seem that the 5890-keV level was populated in the ^{28}Si(p, t)^{26}Si measurement, but further measurements are needed at lower angles and with better resolution to extract a definitive angular distribution.

TABLE I. The ^{26}Si excitation energies from several recent publications compared to the recalibrated levels from this work.

Ref. [14] ^{24}Mg(^{3}He, $n\gamma$)	Ref. [10] ^{24}Mg(^{3}He, n)	Ref. [21] ^{28}Si(p, t)	this work ^{28}Si(p, t)
5147.4(8)	5145(4)	–	5149(2)
5288.5(7)	5291(4)	–	5295(3)
5517.0(5)	5515(4)	–	5519(5)
5890.1(6)	–	–	5870(14)
–	5912(4)	–	5922(2)
–	5946(4)	–	–
–	6312(4)	6296(2)	6305(4)
–	6388(4)	6380(3)	6386(4)
–	6788(4)	6785(5)	6792(4)
–	–	–	7024(9)
–	7152(4)	7151(5)	7166(5)
–	7425(4)	7415(2)	7432(6)

III. THE ^{25}Al(p, γ)^{26}Si REACTION RATE

Since the results from this work are consistent with previous evaluations, adoption of the results and conclusions for the ^{25}Al(p, γ)^{26}Si rate from Ref. [1] are recommended. A major question, however, is whether the contribution from a 4^+ 5950-keV level should be included. Shell model calculations [2,5] predict only four 4^+ levels below $E_x = 6.5$ MeV, and these seem to be already accounted for by the well-known 4446-, 4797-, 5289-, and 5517-keV levels [14]. This also agrees with what is known in the mirror, ^{26}Mg, with levels known at 4318, 4900, 5474, and 5716 keV. With no missing

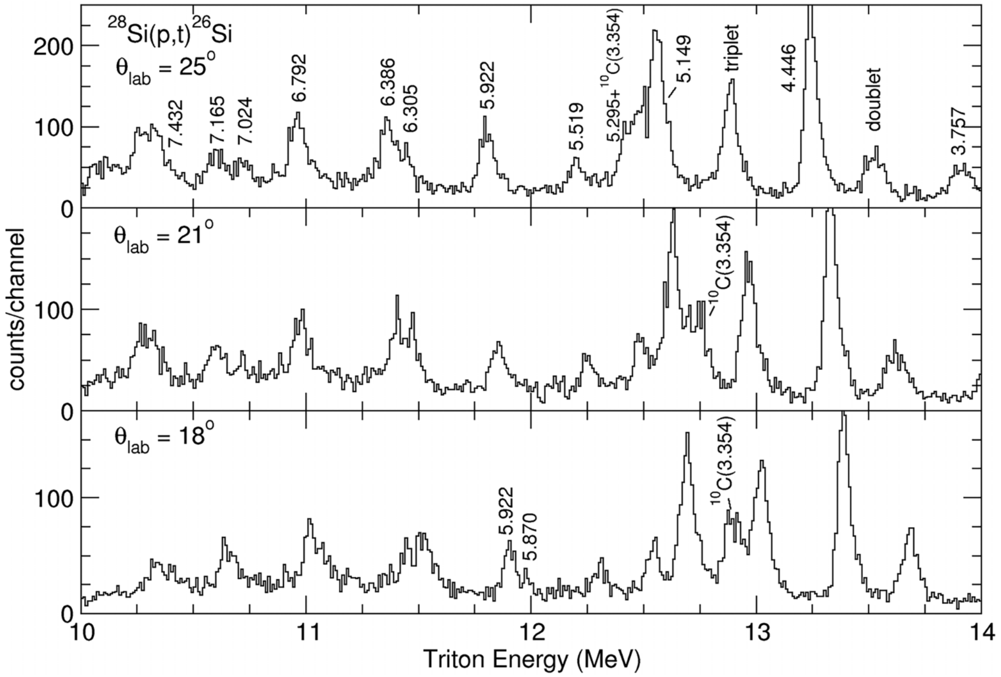

FIG. 2. The recalibrated triton energy spectrum from the ^{28}Si$(p, t)\,^{26}$Si reaction. There is corroborating evidence for a level near 5890 keV in ^{26}Si.

^{26}Si levels in this energy range, it leaves one to wonder what the nature of the 5946-keV [9,10] level is and whether it actually exists at all. Despite numerous measurements using a variety of probes, no study has been able to actually observe simultaneous population of the proposed triplet at 5890, 5926, and 5946 keV. The only measurements to actually observe the 5946-keV level were the ^{29}Si$(^3$He, ^{6}He$)\,^{26}$Si study [9] in which a single peak is seen at 5945(8) keV and the ^{24}Mg$(^3$He, n$)\,^{26}$Si study by Parpottas *et al.* [10] in which a doublet is seen at 5912(4) and 5946(4) keV. As mentioned above, Parpottas *et al.* should have also observed the 5890-keV level, which has been reported in four other ^{24}Mg$(^3$He$, n\gamma)\,^{26}$Si measurements [13,14,19,20]. It also interesting to note that the separation of levels observed by Parpottas *et al.* ($\Delta E_x = 34$ keV) is nearly the same as the current accepted separation between the $0^+/3^+$ doublet ($\Delta E_x =$ 37 keV). Because of this uncertainty related to whether another state actually exists at 5946 keV and the lack of shell model predictions for such a state, it is recommended that no 4^+ resonance contributions be considered in calculating the ^{25}Al$(p, \gamma)\,^{26}$Si reaction rate. This is similar to what is argued in Ref. [18].

IV. CONCLUSIONS

The ^{25}Al$(p, \gamma)\,^{26}$Si rate has a significant influence on predictions of the nova contribution to galactic ^{26}Al abundance. The rate is estimated from the properties of ^{26}Si levels, and the ^{28}Si$(p, t)\,^{26}$Si reaction has been a primary probe of the states above the proton threshold. In light of recent advances in understanding the ^{26}Si level structure, original ^{28}Si$(p, t)\,^{26}$Si [7] data have been reconsidered. The excitation energy of the important 3^+ level was extracted as 5922(2) keV bringing the results in much better agreement with other studies. Evidence for the 0^+ level at 5890 keV was reported from a measurement other than ^{24}Mg$(^3$He$, n\gamma)\,^{26}$Si. Further studies of ^{28}Si$(p, t)\,^{26}$Si at smaller angles with high resolution would be required to confirm such an observation and its 0^+ character. No evidence was observed for a level previously reported at 5946 keV. Studies confirming the observation of such a level in Refs. [9,10] would be interesting as no additional levels are expected in this energy range from shell model calculations [2,5].

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