γ-ray constraints on the properties of unbound ^{32}Cl levels

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Systematic differences between measurements of excitation energies and branching ratios of unbound ^{32}Cl levels near the proton threshold have recently emerged. We investigate these ^{32}Cl properties using independent information by analyzing existing ^{32}Ar$(\beta\gamma)^{32}$Cl data and using published values from measurements of the ^{32}S(^{3}He,$t\gamma$)^{32}Cl reaction. Significant evidence emerges in support of particular values. The results increase the thermonuclear rate of the ^{31}S$(p,\gamma)^{32}$Cl reaction by up to a factor of 2 over the temperature range of 0.4 to 2 GK that is reached during type I x-ray bursts on hydrogen-accreting neutron stars.

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Introduction. Several experimental studies [1–4] of proton-unbound ^{32}Cl levels near the 1581.3(6)-keV threshold [5] have been conducted in recent years that were motivated by the desire to understand the influence of the ^{31}S$(p,\gamma)^{32}$Cl reaction on explosive hydrogen burning in astrophysical environments such as accreting compact objects in binary star systems [6]. These levels correspond to resonances in the ^{31}S$(p,\gamma)^{32}$Cl reaction that cannot yet be measured directly because a ^{31}S beam of sufficient intensity is not currently available. Consequently, most experimental studies [1–4] of the ^{31}S$(p,\gamma)^{32}$Cl reaction have used the ^{32}S(^{3}He,t)^{32}Cl reaction to populate the relevant ^{32}Cl excited states in order to determine the properties of the corresponding resonances.

In the most recent publication on the ^{32}Cl levels of interest [4], excitation energies and proton branching ratios were reported with values that differed systematically from those reported in Refs. [2,3]. In the present work, we first use published, independent γ-ray energies from Refs. [2,5,7] to resolve the differences between excitation energies. We then use data acquired in a ^{32}Ar β-decay experiment [5] in order to resolve the discrepancies between branching ratios.

^{32}Cl excitation energies. The excitation energies of unbound ^{32}Cl levels have been measured many times using the (^{3}He,t) reaction [1–4,8,9]. The two most recent measurements [4,9] produced values that differed from each other systematically in the region of astrophysical interest by about 4 keV. The earlier measurement [3,9,10] carried a combined statistical and systematic uncertainty of ≈0.5 keV. The latter measurement [4] carried statistical uncertainties of ≈2 keV and a systematic uncertainty of 4 keV. It was emphasized in Ref. [4] that uncertainties in the reaction Q values or target thicknesses could cause systematic shifts in those (^{3}He,t) measurements.[1]

The authors of Ref. [4] called for an independent measurement of the γ decays of these levels to determine the excitation energies.

In fact, γ-ray data of sufficient precision already exist for three levels that provide evidence towards a resolution of this problem. In 1997, measurements of the ^{32}S(^{3}He,$t\gamma$)^{32}Cl reaction were reported [2] in which the γ decays of two unbound levels were measured. The excitation energies were determined to be 1736(2) and 2130(2) keV. The next two ^{32}Cl excited states are likely to decay predominantly by proton emission, as shown below, so it might be very challenging to measure their energies via their γ *decays* as proposed in Ref. [4]. However, the γ-ray *feeding* of the level near 2.2 MeV can be used to constrain its excitation energy instead. Although a value for the excitation energy of this level was not reported explicitly in Ref. [5], the excitation energy can be derived by taking the difference between the precisely measured excitation energy of 5046.3(4) keV for the lowest $T = 2$ level of ^{32}Cl and the 2836(1)-keV energy of the γ ray transition deexciting it. The same γ ray has been observed in another ^{32}Ar-decay experiment [7] and measured to have an energy of 2838(1) keV. Subtracting these energies from the excitation energy [5] of the $T = 2$ level yields $E_x = 2210.3(11)$ keV [5] and $E_x = 2208.3(11)$ keV [7] for the level of interest.

These independent γ-ray values for excitation energies are compared to the values from Refs. [3,4] in Table I. The excitation energies from γ-ray data are consistent with those from both Refs. [3,4] (if the systematic uncertainty of Ref. [4] is included in the comparison) and also with the values from a 1998 data compilation [11]. However, it appears that the central values of the excitation energies of Ref. [4] are systematically low and that the systematic effect increases in magnitude with increasing excitation energy (this increase may saturate). Such an increase could result from the fact that the lowest excitation energies were strongly influenced by internal ^{32}Cl calibration points and that the calibration gradually became more dependent on external calibration points towards higher energies [4], introducing substantial systematic uncertainties

[1]The calibration method employed in Ref. [3] produced excitation energies that are effectively independent of the (^{3}He,t) reaction Q values and target thicknesses because the residual ground-state masses were treated as free parameters.

TABLE I. Excitation energies (keV) for unbound ^{32}Cl levels from selected measurements.

J^π	(^{3}He,$t\gamma$) [2]	$\beta\gamma$ [5]	(^{3}He,t) [3]	$\beta\gamma$ [7]	(^{3}He,t) [4][a]
3^+	1736(2)		1736.7(6)		1734.2(14)
3^+	2130(2)		2131.1(4)		2127.5(19)
1^+		2210.3(11)	2209.5(5)	2208.3(11)	2203.1(28)
2^+			2283.5(5)		2278.6(25)

[a]Statistical uncertainty only shown. Systematic uncertainty was 4 keV for all levels shown.

from the dependence on the assumed target properties [3,9,10] (primarily) and reaction Q values [9] (secondarily).

^{32}*Cl proton branching ratios*. Two measurements of the decay properties of unbound ^{32}Cl levels near the proton threshold using the (^{3}He,t) reaction have been reported to date [2,4]. In both measurements, excited states of ^{32}Cl were tagged by detecting the tritons. In the first measurement [2], γ rays were detected in coincidence with the tritons using Ge detectors at 90° and 135° to determine the γ-ray branching ratios Γ_γ/Γ of levels in the range $1730 \lesssim E_x \lesssim 2300$ keV. In the second measurement [4], protons were detected in coincidence with the tritons in an array of silicon strip detectors subtending angles between 131° and 166° to determine proton branching ratios Γ_p/Γ in the range $2120 \lesssim E_x \lesssim 3900$ keV. Both of these measurements effectively determined the proton branching ratios because γ decay and proton decay are the only open channels (i.e., $\Gamma_p/\Gamma + \Gamma_\gamma/\Gamma = 1$) so the resulting values can be compared directly. As shown in Table II, the two measurements are inconsistent at the energies where they overlap.

We use information from the β decay of ^{32}Ar [5] to help resolve the systematic discrepancy between branching ratios. As mentioned above, ^{32}Ar decay populates the level at $E_x = 2209.5$ keV both directly [$I = 0.15(3)\%$] and via γ-decay from the $T = 2$ state [$I = 0.24(3)\%$] [5]. The feeding and decay of the 2209.5-keV state in ^{32}Ar β decay are peculiar. Usually, low-spin states with higher excitation energy than those decaying by proton emission also decay by particle emission. Here, however, the $T = 2$, $J^\pi = 0^+$ state that lies about 2837 keV above this state has a significant γ-ray branching ratio of $\Gamma_\gamma/\Gamma = 0.085$ because the proton decay is isospin forbidden. Of this γ-ray branching, 12.5% is to the unbound 2209.5-keV state, producing the unusual circumstance of a β-γ-proton sequence, which has only been proposed to occur in a few other systems in this mass region [12]. The absolute intensity of the proton emission from the $E_x = 2209.5$-keV state in ^{32}Ar β decay has been observed to be $I = 0.385(8)\%$, but this state has never been observed to decay by γ-ray emission.

TABLE II. Proton branching ratios Γ_p/Γ for proton-unbound ^{32}Cl levels near threshold.

J^π	E_x (^{32}Cl) (keV) [14]	Γ_p/Γ (^{3}He,t) [2]	Γ_p/Γ[a] $\beta\gamma$	Γ_p/Γ (^{3}He,t) [4]
3^+	2131.1	0.48 ± 0.28		0.07 ± 0.04
1^+	2209.5	>0.92	>0.80	0.54 ± 0.07
2^+	2283.5	>0.95		0.66 ± 0.13

[a]90% C.L. lower limit deduced in the present work from data in Ref. [5].

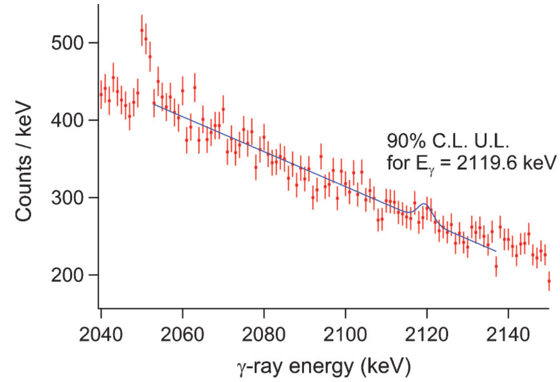

FIG. 1. (Color online) ^{32}Ar β-delayed γ-ray spectrum from Fig. 12 of Ref. [5], showing a linear background plus the 90% C.L. upper limit on the intensity of a γ ray with $E_\gamma = 2119.6$ keV. Generalizing this search over the energy range of $2110 < E_\gamma < 2123$ keV, we find the weakest limit at $E_\gamma = 2120.3$ keV, as discussed in the text.

We have analyzed the ^{32}Ar β-delayed γ-ray spectrum displayed in Fig. 12 of Ref. [5] to search for the γ decay of the 2209.5-keV level. Based on both the decay properties of the well-known mirror level at $E_x = 2230$ keV in ^{32}P and shell model calculations [13], we expect the γ decay of the 2209.5-keV level in ^{32}Cl to be dominated by a 2119.6-keV transition to the first excited state at $E_x = 89.9$ keV. We estimate this γ ray to carry 92% of the total γ-ray branching using the properties of the mirror level. We have searched for γ rays with energies across the range $2110 < E_\gamma < 2123$ keV and we find no evidence for this transition (Fig. 1). Using the upper limit on the intensity of the 2119.6-keV γ ray, normalizing it to the intensity of the 2837-keV transition [$I = 0.24(3)\%$] that directly feeds the 2209.5-keV level, and employing the ratio of detection efficiencies for these two different γ-ray energies yields a 90% confidence level (C.L.) upper limit on the intensity of the 2119.6-keV γ ray of $I < 0.084\%$. Dividing this value by the proton-decay intensity, and accounting for 8% of the γ-ray intensity in other potential branches, this translates into $\Gamma_p/\Gamma_\gamma > 4.2$ (90% C.L.), or a limit on the proton branching ratio of $\Gamma_p/\Gamma > 0.81$ (90% C.L.). Over the broader energy range of $2110 < E_\gamma < 2123$ keV, we find the weakest limit to be $\Gamma_p/\Gamma > 0.80$ (90% C.L.) at $E_\gamma = 2120.3$ keV.

Our limits depend on the γ-decay branches of the 1^+, 2.21-MeV level, which were estimated by assuming mirror symmetry with ^{32}P. Isospin symmetry demands that corresponding electromagnetic transition strengths in mirror nuclei ought to be similar and it has been shown empirically [6] that for the general case of pure or mixed $M1/E2$ transitions this assumption is good to within a factor of 1.7. The shell model [13] suggests that the 2.12-MeV transition (and each of the strongest competing transitions) from this level is nearly pure $M1$ and it should, therefore, be dominated by the isovector component. As a result, we expect the assumption of mirror symmetry for this case to be even better than the empirical factor of 1.7. Upon varying the transition strengths within the expected limits of isospin symmetry, we find that it is difficult to impose enough mirror asymmetry to make our limit on the proton branching ratio consistent with the value in Ref. [4].

Our limit on the proton branching ratio favors the value of Ref. [2] as shown in Table II, suggesting that the values from Ref. [4] might be too low for all three of the unbound levels investigated at excitation energies below 2300 keV. A possible explanation for the low proton branching ratios deduced in Ref. [4] could be the difficulties associated with producing and verifying a sharp, consistent detection threshold for an array of several silicon detectors with 16 strips apiece. Whether or not there was a problem of this kind with the thresholds in Ref. [4], it seems prudent to interpret the proton branching ratios reported therein as lower limits for the time being, given the evidence presented here. We caution that the proton branching ratios reported in Ref. [4] have already been adopted in the most recent $A = 32$ data evaluation [14].

Conclusions. In order to clarify systematic differences between (^{3}He,t)-reaction measurements of ^{32}Cl excitation energies and proton branching ratios, we have appealed to independent ^{32}S(^{3}He,$t\gamma$) and ^{32}Ar($\beta\gamma$) data. Our results support the excitation energies reported in Ref. [3] and the branching ratios reported in Ref. [2].

Accurate excitation energies will facilitate direct measurements of the ^{31}S$(p,\gamma)^{32}$Cl reaction when sufficiently intense low-energy beams of ^{31}S become available. The higher proton branching ratios favored restore the picture from Ref. [6] where proton emission was estimated to dominate γ decay for both the 2.21- and 2.28-MeV levels. Assuming a value of Γ_p/Γ near unity [6] for the 2.21-MeV level increases the thermonuclear ^{31}S$(p,\gamma)^{32}$Cl reaction rates deduced in Ref. [4] by up to a factor of 2 over the temperature range $0.4 < T < 2$ GK that is important for type I x-ray bursts on hydrogen-accreting neutron stars.

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