Level Structure of ^{22}Mg: Implications for the ^{21}Na$(p, \gamma)^{22}$Mg Astrophysical Reaction Rate and for the ^{22}Mg Mass

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The level structure of ^{22}Mg has been studied with high-sensitivity γ-ray spectroscopy techniques. A complete level scheme is derived incorporating all subthreshold states and all levels in the energy region relevant for novae burning. The excitation energy of the most important astrophysical resonance is measured with improved accuracy and found to differ from previous values. Combining the present result with a recent resonance energy measurement of this state leads to a derived ^{22}Mg mass excess of $-400.5(13)$ keV.

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The nucleus ^{22}Mg has provoked sizable interest in recent years [1–8]. A precise and comprehensive knowledge of the states in the region of the proton threshold is essential for determining the ^{21}Na$(p, \gamma)^{22}$Mg reaction rate in oxygen-neon (ONe) nova outbursts [1,3]. This is particularly important since the 1275 keV γ ray associated with the beta decay to ^{22}Na was suggested as an astronomical observable in novae [9], and its signature has been sought by the COMPTEL satellite mission [10]. The high isotopic abundance of ^{22}Ne in presolar grains [11] is indicative of the earlier presence of ^{22}Na material that may have been associated with individual nova outbursts. As a $T_z = -1$ nucleus with a superallowed $0^+ \rightarrow 0^+$ beta decay, a precise knowledge of the mass of ^{22}Mg is required to improve the precision of tests of the conserved vector current (CVC) hypothesis in the standard model [2,12].

The single largest contributor to the ^{21}Na$(p, \gamma)^{22}$Mg reaction rate under novae burning conditions is thought to be from resonant capture on a 2^+ excited state at 5714.4(15) keV. The level was first identified in 1972 by Rolfs *et al.* [13] from its γ decay, and subsequently confirmed in 1975 by Grawe *et al.*, with an energy 5713(2) keV [14] giving a weighted value of 5713.9(12) keV [15]. The associated resonance strength was recently measured with the DRAGON spectrometer at the ISAC facility [1]. However, a significant discrepancy emerged between the precisely measured resonance energy of 205.7(5) keV and the value of 212 keV anticipated from the tabulated values of the ^{22}Mg and ^{21}Na masses [1]. It was suggested by Hardy *et al.* that this may be due to the need for a reevaluation of the ^{22}Mg mass [2]. Despite recent studies of the ^{24}Mg$(p, t)^{22}$Mg reaction [5,6], the identity of near threshold states remains largely undetermined. Besides the intrinsic importance of such information for tests of the nuclear shell model [6,8], a complete knowledge of the location of all possible states is essential for resonance strength measurements of the ^{21}Na$(p, \gamma)^{22}$Mg reaction rate [3]. The present Letter seeks to fully determine the level structure of ^{22}Mg and to indirectly determine its mass with high precision using modern γ spectroscopic techniques.

The basic experimental method has already been outlined in [16]. Here, a 15 pnA beam of 52 MeV ^{12}C ions was used to bombard a 150 μg/cm^2 ^{12}C target for about 66 h to produce ^{22}Mg nuclei via the $2n$ fusion evaporation channel.

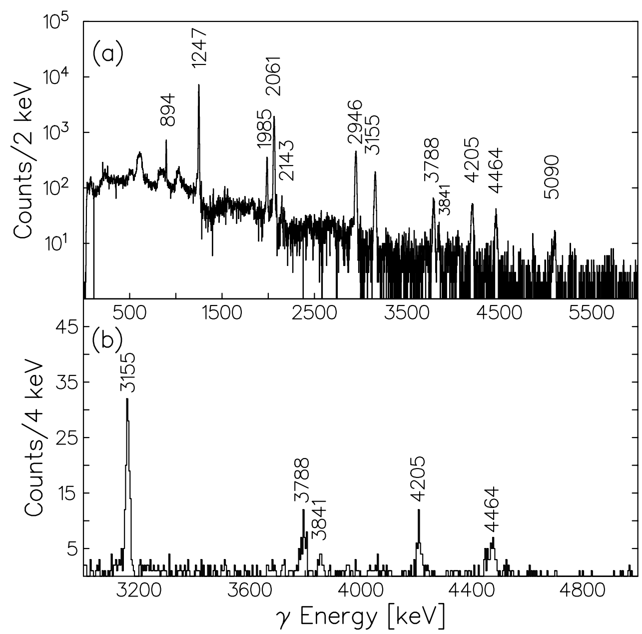

FIG. 1. (a) Gamma-ray spectrum measured in coincidence with ^{22}Mg residues. (b) High-energy γ rays detected in coincidence with the $2_1^+ \rightarrow 0_1^+$, 1247 keV transition in ^{22}Mg.

Prompt γ rays were detected using the highly efficient GAMMASPHERE array of Ge detectors in coincidence with $A = 22$, charge state 8^+ recoils detected at the focal plane of the Argonne fragment mass analyzer. ^{22}Mg, ^{22}Na, and ^{21}Ne ions were cleanly resolved using ΔE-E information from an ionization chamber situated behind the focal plane. A γ-ray energy spectrum for events in coincidence with the ^{22}Mg recoils is presented in Fig. 1(a). Figure 1(b) shows the spectrum of γ rays observed in coincidence with the known 1247 keV $2_1^+ \rightarrow 0_1^+$ transition in ^{22}Mg. The energies, intensities, and angular distribution coefficients for the ^{22}Mg γ rays observed here are given in Table I. The intensities for strong transitions were fitted as a function of angle with respect to the beam axis using the function $W(\theta) = N\{1 + a_2P_2[\cos(\theta)] + a_4P_4[\cos(\theta)]\}$. In the high-spin limit and assuming perfect alignment of an initial state, values of $(a_2, a_4) = (0.357, -0.107)$, $(-0.25, 0)$, $(0.5, 0)$ correspond to a pure $\Delta I = 2$ quadrupole, $\Delta I = \pm 1$ dipole, and $\Delta I = 0$ dipole transition, respectively. A comparison of the proposed level scheme of ^{22}Mg with the known levels in the mirror nucleus ^{22}Ne [17] is provided in Fig. 2. The basis for these assignments are discussed below.

The recent overview of the structure of ^{22}Mg by Bateman *et al.* [6] forms a useful reference point for the present study. All the levels up to the 2_3^+ state at 5035 keV are given unambiguous adopted assignments in [6] and, indeed, all the major associated γ transitions are determined here with high-energy precision. Rolfs *et al.* [13] reported a transition at 604.6(18) keV, which was assigned to the decay of an excited state at 5006(2) keV to the 2_2^+ state at 4402 keV. No such transition was observed here. This excited state has not been observed in any subsequent reaction studies. Our data support the view of Ref. [6] that this state does not exist. The conclusion here is stronger since we demonstrate below that all states expected below the threshold have now been identified. For all other reported states below the proton threshold energy of 5.5 MeV, no definite assignments were adopted in [6] largely because of ambiguities in reaction model analyses and relatively poor experimental resolution. Here, comparisons with the already known ^{22}Ne mirror level structure and γ decays (see Fig. 2) [17,18] are very valuable. An 894 keV transition is found to feed the 2_2^+ level at 4402 keV. The only state feeding the corresponding 2_2^+ level in the ^{22}Ne mirror, that is not proton unbound, is a 2^- level at 5146 keV, which predominantly decays to the 2_1^+ state. The $2^- \rightarrow 2_2^+$ analog transition is observed with similar relative intensity in the ^{22}Ne mirror in the present experiment and is the only transition observed in this energy range for ^{22}Ne. The angular distribution coefficients are consistent with a $\Delta I = 0$ dipole transition and inconsistent with a stretched dipole. Therefore, we conclude that the 2^- state in ^{22}Mg is located at 5296 keV. A 1985 keV transition is found to feed the 4_1^+ level at 3308 keV. The angular distribution coefficients support a $\Delta I = 0$ dipole assignment and are inconsistent with stretched dipole transitions. We assign this transition to the decay of the 4_2^+ level at 5293 keV, which is similarly strongly produced in ^{22}Ne and corresponds to the dominant decay transition from the analogue state in ^{22}Ne. The 2^- and 4_2^+ levels at 5296 and 5293 keV would not be resolved in charged particle reaction studies, and we conclude that the single state at 5294 keV reported in [6] is in fact a doublet with the natural parity 4_2^+ component being preferentially populated in the (p, t) reaction. The 4_1^+ state should also be fed by the 3^+ level, found at an energy of 5641 keV in the mirror, which has a 30% branch to the 4_1^+ level and a 70% branch to the 2_1^+ level [17]. A 4205 keV transition is found feeding the 2_1^+ level in ^{22}Mg. The angular distribution is consistent with a stretched dipole transition and inconsistent with a $\Delta I = 2$ decay (thereby ruling out a possible 4^+ assignment) or $\Delta I = 0$ dipole transition. We assign this transition to the decay of the

TABLE I. The energies (recoil corrected), intensities, angular distribution coefficients, and proposed assignments for the γ-ray transitions detected in coincidence with ^{22}Mg nuclei produced in the ^{12}C + ^{12}C reaction at 52 MeV.

J^π	Level energy (keV)	γ energy energy (keV)	γ intensity (keV)	γ branching	a_2/a_4	Assignment
2_1^+	1247.18(3)	1246.98(3)	100.0(8)		0.17(3)/ − 0.07(3)	$2_1^+ \rightarrow 0_1^+$
4_1^+	3308.21(6)	2061.09(5)	54.7(7)		0.34(4)/ − 0.15(5)	$4_1^+ \rightarrow 2_1^+$
2_2^+	4402.0(3)	3154.7(3)	10.0(4)			$2_2^+ \rightarrow 2_1^+$
2_3^+	5035.4(5)	3788.0(5)	3.9(3)			$2_3^+ \rightarrow 2_1^+$
1_1^+	5089.3(8)	3841.0(10)	0.94(15)	0.36(5)		$(1_1^+) \rightarrow 2_1^+$
		5089.9(12)	1.70(17)	0.64(5)		$(1_1^+) \rightarrow 0_1^+$
4_2^+	5293.1(14)	1984.80(14)	8.3(3)		0.33(10)/0.13(12)	$4_2^+ \rightarrow 4_1^+$
2_1^-	5296.0(4)	893.98(9)	5.4(3)		0.15(6)/0.09(7)	$2_1^- \rightarrow 2_2^+$
3_1^+	5452.4(4)	4205.4(5)	4.2(3)	0.78(4)	−0.31(18)/ − 0.06(23)	$3_1^+ \rightarrow 2_1^+$
		2143.5(6)	1.2(2)	0.22(4)		$3_1^+ \rightarrow 4_1^+$
2_4^+	5711.0(10)	4463.5(10)	3.1(4)	0.86(4)		$2_4^+ \rightarrow 2_1^+$
			0.49(12)	0.14(4)		$2_4^+ \rightarrow 0_1^+$
6^+	6254.2(3)	2945.8(2)	22.1(5)		0.30(7)/ − 0.07(8)	$6_1^+ \rightarrow 4_1^+$

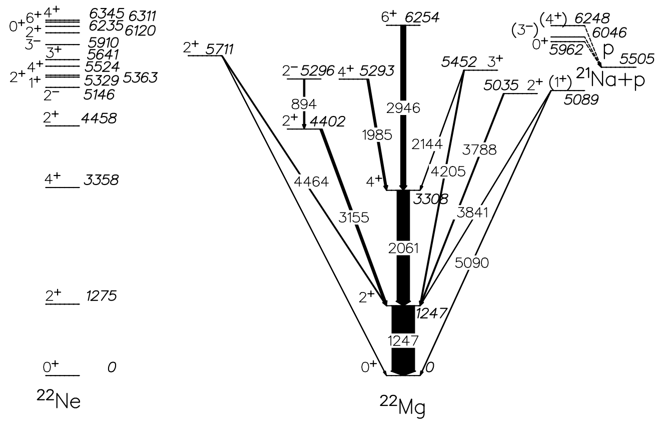

FIG. 2. The γ-decay scheme of ^{22}Mg (obtained in this work) and known levels assigned in ^{22}Ne. Only the portion of the ^{22}Ne level scheme overlapping with the ^{22}Mg level scheme is given.

3_1^+ level at an excitation energy of 5452 keV to the 2_1^+ level. A slightly weaker transition is observed at 2144 keV, which when added with the 3308 keV 4_1^+ level gives an excitation energy in precise agreement with the proposed 3_1^+ level at 5452 keV. This is consistent with the two branches observed for the decay of the 3^+ mirror state in ^{22}Ne. We therefore assign the 2144 keV line to a weaker decay branch of the 3_1^+ state to the 4_1^+ state in ^{22}Mg. The only remaining subthreshold state, the 1^+ level, is ruled out as there would be no branch to the 4_1^+ state. The 5454.3(16) keV state discussed in [6] can now unambiguously be identified with the 3^+ level observed here. Bateman *et al.* [6] suggested a natural parity assignment based on its observation in the ^{24}Mg$(p, t)^{22}$Mg reaction. However, although it is present in the spectrum in [6], it is noticeably suppressed in strength compared to the population of the natural parity states as assigned in the present study. This suppression is also observed in [6] for the unnatural parity 2^- state (assigned here) and for an unassigned state at 5089.7(17) keV in ^{22}Mg. Here we observe a transition at an energy of 5089 keV that is not in coincidence with other γ rays, consistent with the direct decay of the 5089 keV level to the ground state. Additionally, a slightly weaker transition is observed at 3841 keV. When combined with the energy of the 2_1^+ level, this gives an excitation energy in precise agreement with the 5089 keV level. We therefore identify these transitions with the decay of the remaining subthreshold analog 1^+ level at 5329 keV in ^{22}Ne, which has a 67% ground state branch and a 33% branch to the 2_1^+ level. The present data provide a complete picture of the level structure of ^{22}Mg below the proton threshold. It is notable that while the positive parity states below the threshold drop by 200–300 keV, in comparison to the states in ^{22}Ne, the only negative parity state at 5146 keV increases in energy by $\approx$ 150 keV. This relative upshift of negative parity levels in the $T_z = -1$ partner was also observed in our study of ^{20}Na and is characteristic of proton hole excitations [16].

Considering now the levels above the proton threshold, we clearly observe a 2946 keV transition to the 4_1^+ level giving an excitation energy of 6254.2(3) keV. The measured angular distribution is consistent with a stretched quadrupole transition and a 6^+ assignment is proposed. Rolfs *et al.* [13] observed a similar transition and quoted an excitation energy of 6298(50) keV with a minimum assigned spin of $6\hbar$, consistent with the present data. Bateman *et al.* [6] reported a doublet structure at 6248.2(45) keV from the (p, t) reaction study. Earlier $(^3\text{He}, n)$ reaction studies [19,20] suggested a tentative 4^+ assignment for a single state around this energy, and shell model calculations as well as mirror systematics [6] would suggest nearly degenerate 4^+ and 6^+ levels. The 4_3^+ state would be expected to decay predominantly by $l_p = 2$ proton emission and would then not be observed in the present study, whereas light ion particle transfer studies would be less likely to feed the high-spin 6^+ state. We therefore conclude that the 4^+ state most likely lies a few keV below the 6^+ state identified here. Davids *et al.* [4] have recently demonstrated that the levels at 5962 and 6046 keV predominantly proton decay and, consequently, would not be observed in the present study. They assigned a 0^+ structure to the 5962 keV level, similar to Ref. [17] and in contrast to Ref. [5], which assigned these quantum numbers to the 6046 keV level. We note that the recent (p, γ) resonance strength value reported for the 6046 keV level [3] would imply a partial half-life $\approx$ 5 fs, much lower than the value of 235(83) fs for the 0^+ analog mirror electromagnetic decay in ^{22}Ne [17]. The resonance strength measured for the 5962 level [3] would imply a partial half-life $\approx$ 70 fs for a 0^+ state. Therefore, this would further support a 0^+ assignment to the 5962 keV level, and, indeed, the distorted-wave Born approximation fits to the data presented in [5] also appear consistent with this assignment. A tentative 1^- assignment was given to the 6046 keV level [4]. However, we would conclude that a 3^- assignment is now much more plausible. This is the only mirror level yet to be identified in this energy region. The 1^- mirror level is found at 6691 keV in ^{22}Ne and would imply an anomalously large energy shift. Recently, a state has been identified at 6591 keV in ^{22}Mg by resonant scattering of ^{21}Na on protons and paired with the 1^- state in ^{22}Ne [21]. Assuming the same mirror energy shift for the 3^- state as for the 2^- state gives an energy of 6059 keV, very close to the observed 6046 keV level. Assuming a 3^- assignment for the 6046 keV level, and taking the recent (p, γ) resonance strength measurement of [3], gives a partial half-life of about 35 fs in excellent agreement with the mirror transition value of 32(9) fs [17]. Conversely, a 1^- assignment would yield a half-life of about 15 fs compared with the mirror value of 240(130) fs [17] in ^{22}Ne. As a natural parity state, the 3^- level would be strongly populated in the (p, t) reaction [6], as is indeed observed, and would decay predominantly by $l_p = 1$ proton emission consistent with the measurements reported in [4]. Therefore, we assign the 6046 keV level to the 3^- state. This completes the identification of all ^{22}Mg states expected in the excitation energy range shown in Fig. 2. All the known states from the mirror nucleus ^{22}Ne below the excitation energy of 6345 keV are now identified with a level in ^{22}Mg, and all states predicted by the shell model calculation [6] have now been observed. This is an important conclusion for the measurement of the ^{21}Na$(p, \gamma)^{22}$Mg reaction rate, since it clearly indicates all the astrophysical strength has been exhausted by the resonance studies reported in [3] and no further resonances need to be considered in the nova burning regime. Further to this conclusion, we find no evidence for γ decay from the 5837 keV state reported in [13], and as in earlier reaction studies (e.g., [4]), we propose this state is not present in ^{22}Mg.

The γ decay of the important 2_4^+ astrophysical resonance is confirmed here with the observation of a weak, 14(4)%, branch feeding the ground state directly and a much stronger, 86(4)%, branch feeding the 2_1^+ level [Fig. 1(b)], in excellent agreement with the first reported observation by Rolfs *et al.* [13], where the corresponding branches were 13(3)% and 87(3)%, respectively. This is important to confirm as the resonance strength measurement of Ref. [1] was predicated on knowing the γ-decay paths from this level. However, the measured energy of the $2_4^+ \rightarrow 2_1^+$ transition leads to an excitation energy of 5711.0(10) keV, which disagrees with the much earlier weighted average [15]. The measured 4205 keV energy of the 3^+ to 2_1^+ transition is also lower compared to the value of 4214(4) keV reported in Ref. [13]. In the present experiment, ^{152}Eu and ^{56}Co sources were used to calibrate the γ-ray detectors. Above 0.8 MeV, deviations from linearity were below 0.1 keV up to the maximum energy of 3.251 MeV in ^{56}Co, and no indication for nonlinearity was found from the summing lines up to about 4.3 MeV. In addition, the energy of 4636.4(1.5) keV was measured for the known 4634.8(1.8) keV transition in ^{22}Ne, validating the energy calibration up to the energy of the $2_4^+ \rightarrow 2_1^+$ transition. The $2_4^+ \rightarrow 0_1^+$ transition was not used to obtain the energy of the 2_4^+ state due to lack of reference γ lines at such high energies. No evidence was found for any gain mismatch between individual γ detectors. The Doppler correction was carefully verified by considering rings of Ge detectors at a fixed angle with respect to the beam axis. Since GAMMASPHERE is symmetric with respect to the beam axis, γ-ray energies transformed into the center of mass system do not depend on the choice of recoil velocity. The above tests eliminate possible sources of systematic errors. Taking the resonance energy measured in [1], and using the ^{21}Na mass value from Audi *et al.* [22], combined with the new excitation energy value gives a mass excess of $-400.5(13)$ keV, in agreement with the revised value of $-402(3)$ keV suggested in [2] and with recent high precision values of $-399.92(27)$ keV [23] and $-399.64(63)$ keV [24] measured at CERN and Argonne, respectively. If the most precise values of the masses of ^{21}Na and ^{22}Mg [23] are used in combination with the DRAGON resonance energy measurement [1], an excitation energy of 5709.9(6) keV is derived now in excellent agreement with the directly measured value here of 5711.0(10) keV. Using the prescription from [12] and decay data from [2] with the present derived value of the ^{22}Mg mass leads to an $\mathcal{F}t$ value for the superallowed Fermi transition of 3082.3(9.5) s [25] (the mass of ^{22}Na from [22] was used in the calculations), which compares well with the expected CVC hypothesis value of 3072.3(8) s.

In conclusion, modern in-beam γ spectroscopic techniques have enabled us to make a full structure determination of ^{22}Mg, both below the proton threshold and in the region relevant for astrophysical burning. We conclude that no further measurements of the ^{21}Na$(p, \gamma)^{22}$Mg reaction are needed to determine resonant reaction rates under nova conditions. The new precise measurement of the γ-ray energy from the most important astrophysical resonance is used to derive a ^{22}Mg mass value. This result is in good agreement with mass values recently obtained for ^{22}Mg and removes previous discrepancies (and uncertainties over systematic effects) between the ^{22}Mg mass and astrophysical resonance energy values.

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