Direct Measurement of the $^{21}Na(p,\gamma)^{22}Mg$ Reaction: Resonance Strengths and Gamma–Gamma Analysis

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A series of astrophysical measurements was recently completed at TRIUMF, related to the unknown total rate of the $^{21}Na(p,\gamma)^{22}Mg$ reaction. With a high intensity ^{21}Na beam from the ISAC facility, the DRAGON recoil mass spectrometer was used to directly measure seven resonances at center of mass energies from $E_{\rm c.m.} = 200$ to 1135 keV and determine their respective contributions to the $^{21}Na(p,\gamma)^{22}Mg$ reaction rate in novae and x-ray bursts, as well as their impact on ^{22}Na production in novae. This study also allowed the investigation of different excited states in ^{22}Mg; proposed decays and spin assignments are given for the 6246, 6329, and 6609 keV levels.

1. Introduction

Novae are stellar events where light and intermediate-mass elements can be synthesized through proton capture on radioactive nuclei. The observation of γ radiation from such

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radioactive nuclei may allow insight into the physical processes of novae. For example, it is believed that detection of the 1275 keV γ ray from the β^+ decay of ^{22}Na will further the understanding of oxygen–neon novae. At high temperatures and densities, ^{22}Na is thought to be produced primarily through the ^{20}Ne$(p,\gamma)^{21}$Na$(p,\gamma)^{22}$Mg(β^+) reaction sequence; however, the rate of ^{21}Na$(p,\gamma)^{22}$Mg remains as a large uncertainty, due mostly to the lack of knowledge about the states above the proton threshold in ^{22}Mg. Consequently, many experiments have been performed to better understand the structure of ^{22}Mg [1–9].

The DRAGON group at TRIUMF-ISAC performed the first direct measurement of the rate of the ^{21}Na$(p,\gamma)^{22}$Mg reaction, populating the important $E_{\mathrm{X}} = 5714$ keV resonant state in ^{22}Mg and measuring its strength [6]. The group has just completed a series of measurements of the resonance strengths at $E_{\mathrm{X}} = 5962, 6046, 6246, 6329,$ and 6609 keV and deduced their respective contributions to the ^{22}Na production rate in oxygen–neon novae and in x-ray bursts [9]. A summary of the levels is shown in figure 1. With the data gathered in this study, it is also possible to propose decays and spin assignments in ^{22}Mg based on γ–γ correlation analysis.

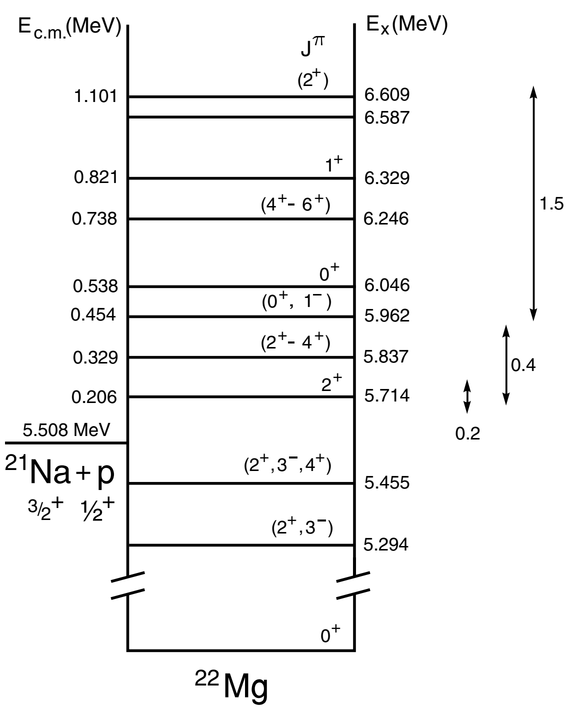

Figure 1. Level scheme of the ^{22}Mg nucleus showing the measured resonant energies $E_{\mathrm{c.m.}}$ of ^{21}Na$(p,\gamma)^{22}$Mg, the corresponding excitation energies E_{X}, and the presumed spin assignments of the states of astrophysical interest. The arrows on the right show the Gamow windows for ^{21}Na+p burning for some temperatures (in GK) typical of oxygen–neon novae or x-ray bursts. The DRAGON group has directly measured the states from $E_{\mathrm{X}} = 5714$ to 6609 keV, and determined their respective contributions to the ^{22}Na production rate in oxygen–neon novae and in x-ray bursts [9]. In the present study, the γ decay of the 6246, 6329, and 6609 keV levels were investigated to assign proposed γ transitions. Analysis is continuing for the 6046 and 5962 keV levels and it is planned to gather more data to investigate the level at 6587 keV.

2. Experiment and Results

The DRAGON (Detector of Recoils And Gammas Of Nuclear reactions) facility makes use of a windowless gas target, surrounded by a 30-element BGO γ-detector array, coupled to a recoil mass spectrometer and a final focus heavy ion detector system [10]. In this study, a radioactive ion beam of about 10^9 ^{21}Na per second was delivered by ISAC [11] onto a hydrogen target and the resulting ^{22}Mg recoils were observed in coincidence with the reaction's γ radiation. The data acquisition system was configured to allow for the observation of multiple γ rays for each individual reaction event.

In the γ–γ analysis, the energy of the highest energy detected gamma (γ_1) is plotted versus the next most energetic gamma (γ_2) to show the γ–γ correlations of the decay. From our data, we are able to assign the probable γ decays and spins for the three resonant (excited) states of 1101 (6609), 821 (6329), and 738 (6246) keV in ^{22}Mg (figure 2), with guidance from the analogue states in the better-known mirror nucleus ^{22}Ne.

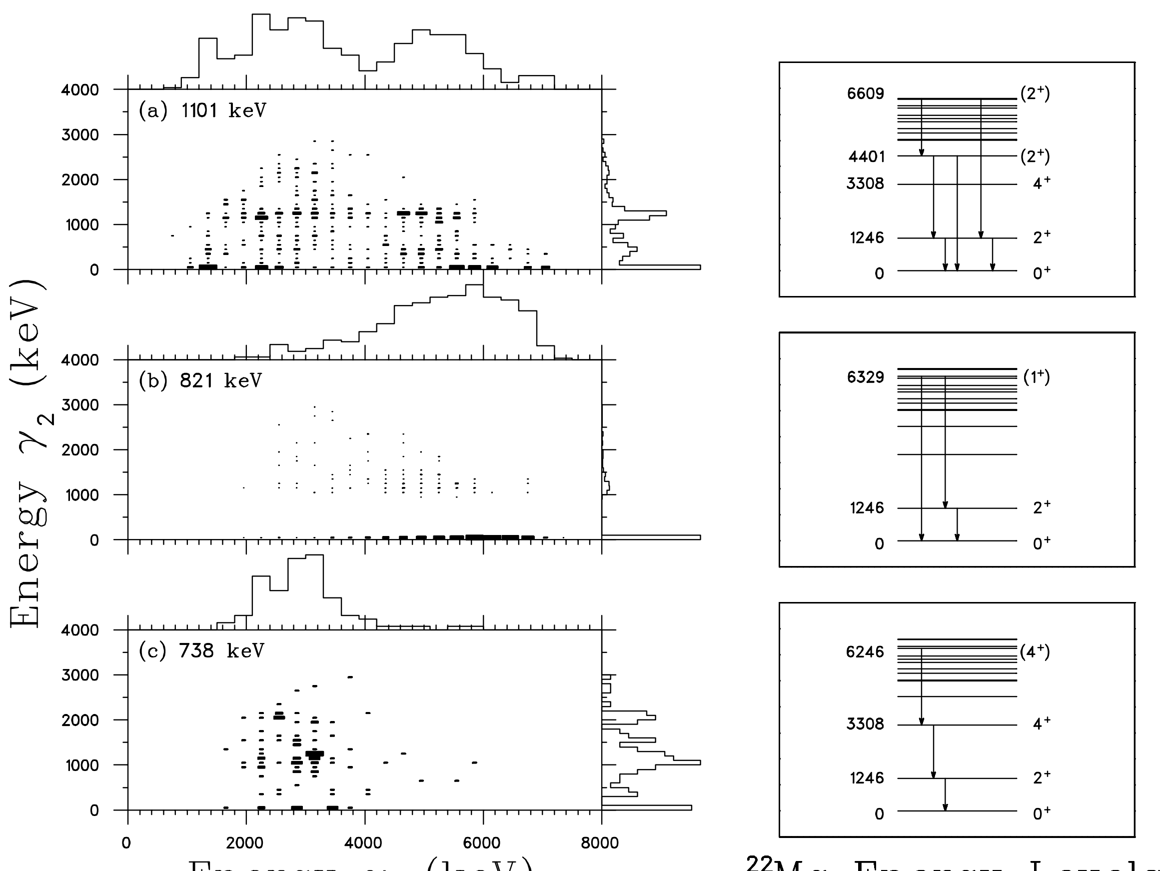

Figure 2. The left hand side shows the detected γ–γ correlations for the (a) 1101, (b) 821, and (c) 738 keV resonance states and their projections. The right hand side shows the corresponding levels in ^{22}Mg and proposed γ transitions. The resolution of the spectra $\sim$ 200 keV. The ^{22}Mg levels are taken from Firestone, Ref. [12].

The data plots (left side) show the γ–γ correlations for a given ^{22}Mg level (right side). As an example, consider the 738 keV resonance. It is proposed that the decays are 6246

$\rightarrow$ 3308 yielding a 2938 keV γ ray, then 3308 $\rightarrow$ 1246 giving 2062 keV, and 1246 $\rightarrow$ 0 giving 1246 keV. In the figure then, there should be a cluster about $\gamma_1 = 2938$ keV and $\gamma_2 = 2062$ or 1246 keV. Alternatively, if $\gamma_1 = 2938$ keV is not observed, then there should be a cluster about $\gamma_1 = 2062$ and $\gamma_2 = 1246$ keV. Based on this technique,the decays between levels is given in the right-hand side of figure 2. The spin assignments are presented in table 1, along with the analogue states in the ^{22}Ne mirror nucleus.

Table 1
Proposed spin assignments of levels in ^{22}Mg are listed along with their analogue states in the mirror nucleus ^{22}Ne.

$E_{\text{c.m.}}$ (keV)[a]	^{22}Mg Level (keV)	J^π	^{22}Ne Level (keV)[b]	J^π
1101.1 ± 2.5	6609	2^+	6817	2^+
821.3 ± 0.9	6329	1^+	6853	1^+
738.4 ± 1.0	6246	4^+	6345	4^+

[a] Taken from D'Auria *et al.*, Ref. [9].
[b] Taken from Firestone, Ref. [12].

3. Summary

From the direct measurement of the ^{21}Na$(p,\gamma)^{22}$Mg reaction, the DRAGON group has proposed decays and spin assignments for the 6246, 6329, and 6609 keV levels in ^{22}Mg through γ–γ analysis. It is planned to further analyze the decays of other lower-lying states and set branching ratios. In addition, new data is being taken to allow comment on the 6857 keV state.

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