Decay of ^{23}Al and Resonances in ^{22}Na(p,γ)^{23}Mg at Astrophysically Relevant Energies

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Efforts were made for a long time to determine the reaction rate for the proton capture reaction ^{22}Na(p,γ)^{23}Mg, the most credible candidate for depleting ^{22}Na out of the NeNa cycle [1]. Data showed early on that resonant capture plays the overwhelming role. States in ^{23}Mg above the proton separation energy are resonances in this reaction and can play roles in the rate of this reaction at astrophysical energies. The problem received much attention related to the anomalous Ne isotopic ratio found in some meteorites (Ne-E anomaly) [2,3] and to the breakout of the NeNa cycle cited above. Confusion still exists about the precise position of resonances and their strength even after a few direct measurements [1,4] and many spectroscopic studies [5-10], leading to uncertainties for the reaction rate in stellar environments that may be yet of a few orders of magnitude [5,6]. The major problem arises from the large density of states at this excitation energy which could not be easily separated and identified. Some of these states are populated in the decay of ^{23}Al, including the isobaric analog state of its ground state which can be identified by its preferential population. In the present report we separate two important states, and identify the IAS.

Radioactive ^{23}Al was produced and separated using MARS and its β-decay was studied using the fast-tape transport system and beta and gamma-ray detectors. The details of the experiment and the results related to the determination of spin and parity of ^{23}Al ground state and of its lifetime are discussed in other contributions to this report [11,12]. In this experiment we determined for the first time the *ft*-value for the transition to a state at 7803 keV: *ft*=2042(120) s. This is in excellent agreement with the value expected for a pure Fermi transition from a T_z=-3/2 state: *ft*=2048(0.5) s, a fact which identifies it as the IAS of ^{23}Al ground state. This state was seen before [10] and assumed correctly to be the IAS, based on its preeminence in decay, but its *ft*-value could not be determined there, it was assumed to have log*ft*=3.4(2). The relevant part of the decay scheme of ^{23}Al is shown in Figure 1.

The states above the proton binding energy in ^{23}Mg (S_p=7580.3(14) keV) become resonances in the capture process and, therefore, their precise E_{exc}, J^π, and decay widths are needed to evaluate the resonant part of the reaction rate. Two beta-delayed proton decay studies [9,10] measured proton spectra resulting from the proton decay of ^{23}Mg excited states populated from the initial beta-decay of ^{23}Al. Proton peaks at energies from around 200 to 900 keV were seen. The relative populations are similar in the two experiments for all higher energy proton peaks, but differ sharply for the lowest state that both studies identify as the isobaric analog state. The experiment of Perajarvi *et al.* [10] is the only one that measures simultaneously proton and gamma-decay ratios. Tighe *et al.* [9], find a much stronger proton peak at E_p=223(20) keV, depopulating what they assume to be the J^π=5/2$^+$, T=3/2 IAS. Proton decay of that state could only occur through mixing of a T=1/2 component. The observed proton-decay is about 50 times larger than expected from calculations with commonly accepted isospin non-conserving interactions [13], and the authors conclude that they found "extremely strong isospin mixing", and, consequently, a very large resonance strength ωγ=45(25) meV. In the present experiment we identify the

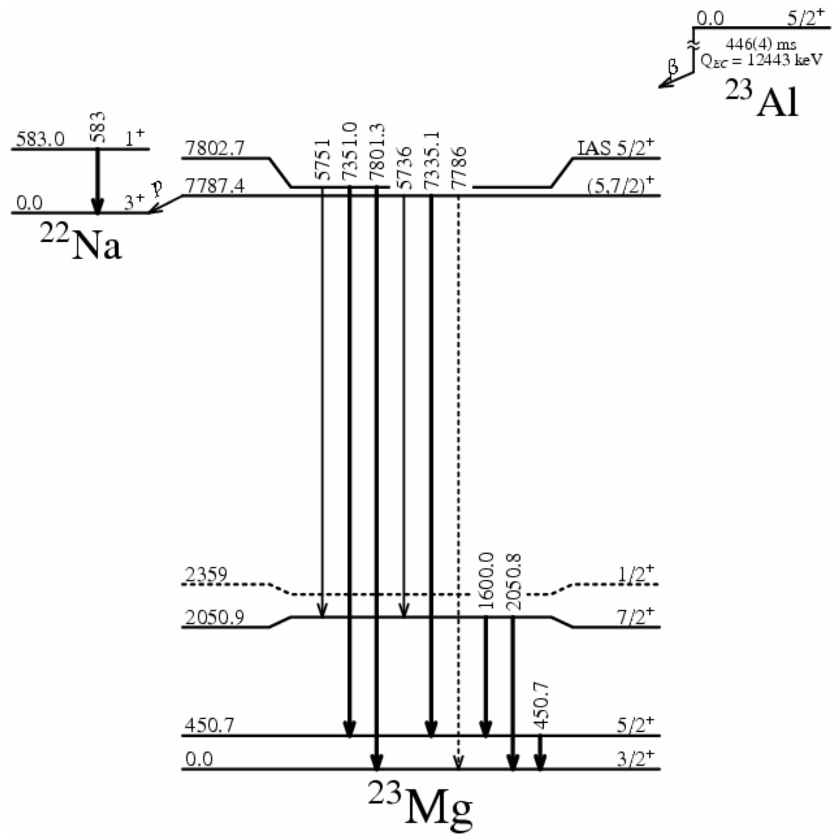

Figure 1. The decay scheme of ^{23}Al relevant for the above discussion.

IAS (log*ft*=3.33) at E_{exc}=7803(2) keV and find another state strongly populated (log*ft*=3.84) only 16 keV below at E_{exc}=7787(2) keV (see Fig. 1 of [11]). For these two states we find gamma-decay branches to the ground state/first excited state (451 keV)/second excited state (2051 keV) to be 100/45(5)/5.5(21) and 3.8(25)/100/20(5), respectively. Hints or assumptions about a doublet in this energy region exist in literature [1,10], but never before were the two states populated and separated in the same experiment. Both studies populated only the lower state and found that it decays to the first excited state at 451 keV, in agreement with what we find here as the dominant branch. We assume that the strong peak seen at low energy in the proton spectra measured with a resolution of 40 keV by Tighe *et al.* [9] is actually from the decay of the lowest state. This is a normal T=1/2 isospin state and therefore our assumption excludes the strong, anomalous, isospin mixing needed to explain their data. Its strong direct population in beta-decay determines its positive parity and restricts spin assignments to J=3/2, 5/2 and 7/2. Strong proton decay to the ^{22}Na $J^{\pi}=3^{+}$ ground state excludes 3/2. From the remaining two possibilities we could exclude 5/2 also based on two arguments: one related to the proximity to a state of same spin and parity (IAS) which would induce a strong "repulsion" even for small mixing matrix elements, and the second one based on the dissimilarity of their gamma-ray decay patterns (see branchings above). Therefore we propose $J^{\pi}=7/2^{+}$ for this state at E_{exc}=7787(2) keV, in agreement with the recent $J^{\pi}=(7/2^{+})$ assignment of Ref. [5].

Using the proton branching relative to higher energy peaks measured by [9] and the proton to gamma branchings determined in [10] for the same high energy peaks, we find for this state Γ_p/Γ_γ=0.080(17). From this and the lifetime of the state measured in a recent GAMMASPHERE experiment [5] $T_{1/2}$=10(3) fs, we determine the resonance strength $\omega\gamma$=2.6(9) meV for this state. This is in reasonable agreement with the value obtained from the direct measurement involving a difficult radioactive ^{22}Na target [1] and with the value adopted by the NACRE compilation [4]. The resonance strength for the IAS could not be determined or estimated without further assumptions.

In conclusion, we found a doublet in ^{23}Mg with small *ft*-values at 7803(2) keV and 7787(2) keV and identified the states as the isobaric analog state of ^{23}Al ground state and a J^π =7/2$^+$ state with large proton decay branch. Both are resonances contributing to the depletion reaction ^{22}Na(p,γ)^{23}Mg. For the latter resonance at E_{res}=207(3) keV we find its resonance strength to be $\omega\gamma$=2.6(9) meV, making it the dominant contribution in the reaction rate at the temperatures of explosive H burning in ONe novae. To further improve our knowledge about this reaction rate a re-measurement of the beta-delayed proton and gamma decay of these ^{23}Mg states is desirable.

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