The Structure of $^{23}$Al and the Consequences on the $^{22}$Mg (p, $\gamma$) $^{23}$Al Stellar Reaction Rate

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There is interest in the structure of $^{23}$Al due to its nuclear astrophysics significance [1,2]. The ground state spin and parity for $^{23}$Al is uncertain, with assignments that include $\frac{1}{2}^+$, $\frac{3}{2}^+$ and $\frac{5}{2}^+$. Currently the NNDC data base gives $\frac{3}{2}^+$ for the $^{23}$Al ground state. The mirror nucleus $^{23}$Ne has $J^\pi = \frac{5}{2}^+$ for its ground state. Recently it was claimed [3-5] that proton rich $^{23}$Al is a halo nucleus. That can be explained only if the last proton in the 2s$\frac{1}{2}$ orbital, not 1d$\frac{5}{2}$ (level inversion), i.e. $J^\pi = \frac{1}{2}^+$ for $^{23}$Al. Using $\frac{1}{2}^+$ instead of $\frac{5}{2}^+$, we calculate the astrophysical S-factor and stellar reaction rate for $^{22}$Mg (p, $\gamma$)$^{23}$Al and find an increase of 30-50 times over the current estimate for the temperature range $T_9$=0.1-0.3. This results in a significant depletion of $^{22}$Mg before it $\beta$ decays into $^{22}$Na and, if confirmed, could explain the non-observation of the 1.275 MeV $\gamma$-ray from $^{22}$Na which is the last step of the reaction chain which is named the hot NeNa cycle: $^{20}$Ne(p, $\gamma$)$^{21}$Na(p, $\gamma$)$^{22}$Mg($\beta$,v)$^{22}$Na. Our $^{23}$Al $\beta$-decay measurement [6] will be used to determine the $J^\pi$ of the ground state of $^{23}$Al.

In 2005, we had three experiments to produce and study $^{23}$Al, beginning with production tests at two different $^{24}$Mg beam energies, 45 and 48 MeV/u, respectively. At both energies $^{23}$Al was produced and separated, but the latter was found more productive. Therefore, we produced $^{23}$Al and studied its $\beta$-decay using a 48 MeV/nucleon $^{24}$Mg beam from the K500 cyclotron via the $^{24}$Mg(p, 2n)$^{23}$Al reaction on a hydrogen gas cryogenic target cell cooled by LN$_2$. The reaction products and projectiles entered the MARS recoil separator where the $^{24}$Mg beam was filtered out and the fully stripped reaction products were spatially separated from one another, leaving a relatively pure $^{23}$Al beam of about 4000 pps at the extraction slits in the MARS focal plane. Its $\beta$-decay was further studied using the fast tape transport system. This was the first time pure and intense $^{23}$Al samples were produced and separated. This $^{23}$Al beam came out of the vacuum system by passing through a 50 $\mu$m thick Kapton window, a 0.3 mm thick BC-104 scintillator, a dummy tape and a stack of aluminum degraders (30.5 mils). A 75-$\mu$m thick aluminized Mylar tape on the fast tape-transport system was used to collect $^{23}$Al. Because the ranges of impurities in the beam are different from that of $^{23}$Al, a pure $^{23}$Al sample was collected on the tape. In our measurement, we collected $^{23}$Al on the tape for 1 second. Then we shifted the RF phase to stop the $^{24}$Mg beam. Following this we moved the $^{23}$Al sample in 177 ms with the tape transport system to a counting station which consists of a HPGe $\gamma$ detector and a $\beta$ detector. $\beta$ and $\beta$-$\gamma$ coincidence data were recorded for a predetermined counting period of 3.2 seconds. This cycle was precisely clock controlled and was repeated continuously. The sample was positioned between the HPGe $\gamma$-ray detector and a 1-mm-thick BC404 plastic scintillator used to detect $\beta$ particles. The BC404 was located 3 mm from the sample, while the HPGe was about 4.9 cm away. Time-tagged coincidence data were stored event by event in the computer. This experimental setup [7] is a typical one for measuring $\beta$-$\gamma$ coincidences except that the HPGe detector was closer than usual. In two different parts of the experiment, we first measured the $\gamma$ energy range 0-4 MeV with good statistics (Fig. 1a), then we measured $\gamma$ energy range 0-9 MeV for about 20 hours (Fig. 1b). We also separated pure samples of $^{24}$Al, by tuning MARS for this product, and...
did a similar $\beta$-$\gamma$ measurement. We use its known gamma-rays up to $E_\gamma=7.8$ MeV for energy and efficiency calibration in the range $E_\gamma=4-9$ MeV.

The ground and first three excited states of $^{23}$Mg have $J^\pi=3/2^+,$ $5/2^+,$ $7/2^+$ and $1/2^+$, respectively. All of these states are easily accessible energetically to $\beta$-decay from $^{23}$Al. Depending on which states are actually populated by allowed GT transitions – as determined by log$ft$ values – the spin and parity of the parent ground state can be unambiguously determined. From the measured $\beta$ singles and $\beta$-$\gamma$ coincidence decay spectrum (Fig. 1) we can get the $^{23}$Al $\beta$-decay scheme and the branching ratios. We find that it populates directly the $3/2^+$, $5/2^+$ and $7/2^+$ states, but not the $1/2^+$ state. Combined with GT transition rules, we clearly determine that $^{23}$Al ground state spin and parity is $J^\pi=5/2^+$. We found preliminary $\beta$-branching ratios and log$ft$ values for 14 states in total. It so appears that the larger capture rate implied by the lower spin value of $^{23}$Al will not explain the missing cosmic 1275 keV cosmic $\gamma$-ray.

The future research plan is the following. An additional experiment at TAMU is going to add a BGO shield to the present HPGe $\gamma$-ray detector to reduce background in the $\beta$-$\gamma$ decay spectrum of $^{23}$Al and increase the ability to detect high energy $\gamma$ rays. We also need better statistics for the $\gamma$ energy range 4-9 MeV. So we can get more precise $^{23}$Al $\beta$-$\gamma$ decay energy level scheme, $\beta$ & $\gamma$-branching ratio and a precise $^{23}$Al half life.

![Figure 1. $^{23}$Al $\beta$-$\gamma$ coincidence spectrum.](image)