The Structure of ^{23}Al and the Consequences on the ^{22}Mg (p, γ) ^{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 $1/2^+$, $3/2^+$ and $5/2^+$. Currently the NNDC data base gives $3/2^+$ for the ^{23}Al ground state. The mirror nucleus ^{23}Ne has $J^\pi = 5/2^+$ 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 $2s_{1/2}$ orbital, not $1d_{5/2}$ (level inversion), i.e. J^π = is $1/2^+$ for ^{23}Al. Using $1/2^+$ instead of $5/2^+$, we calculate the astrophysical S-factor and stellar reaction rate for ^{22}Mg (p,γ)^{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 β decays into ^{22}Na and, if confirmed, could explain the non-observation of the 1.275 MeV γ-ray from ^{22}Na which is the last step of the reaction chain which is named the hot NeNa cycle: ^{20}Ne(p,γ)^{21}Na(p, γ)^{22}Mg(β,ν)^{22}Na. Our ^{23}Al β-decay measurement [6] will be used to determine the J^π 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 β-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 β-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 μm 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-μm 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 γ detector and a β detector. β and β-γ 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 γ-ray detector and a 1-mm-thick BC404 plastic scintillator used to detect β 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 β-γ coincidences except that the HPGe detector was closer than usual. In two different parts of the experiment, we first measured the γ energy range 0-4 MeV with good statistics (Fig. 1a), then we measured γ 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 β-γ measurement. We use its known gamma-rays up to E_γ=7.8 MeV for energy and efficiency calibration in the range E_γ=4-9 MeV.

The ground and first three excited states of ^{23}Mg have J^π=3/2$^+$, 5/2$^+$, 7/2$^+$ and 1/2$^+$, respectively. All of these states are easily accessible energetically to β-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 β singles and β-γ coincidence decay spectrum (Fig. 1) we can get the ^{23}Al β-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^π=5/2$^+$. We found preliminary β-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 γ-ray.

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

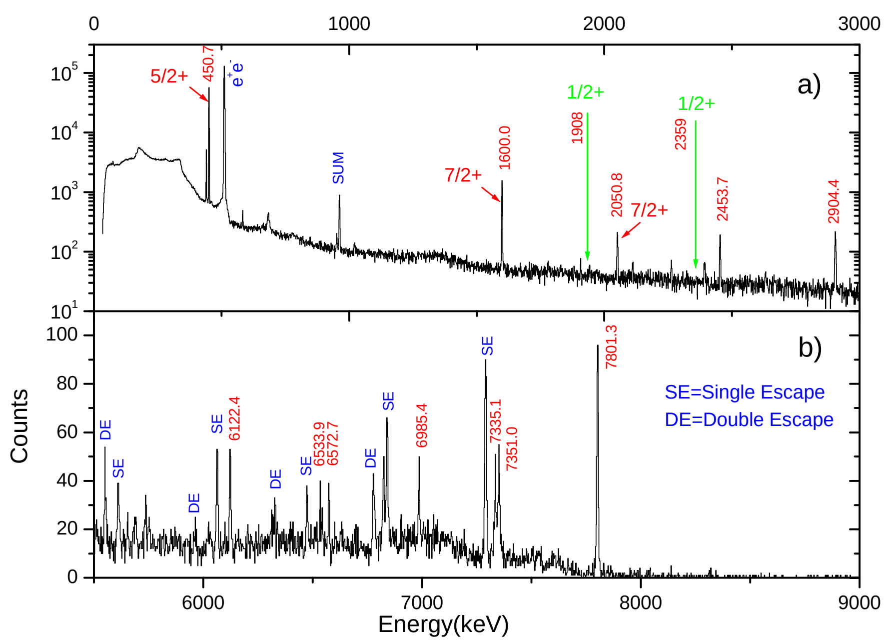

Figure 1. ^{23}Al β-γ coincidence spectrum.

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