Study of excited states of $^{35}$Ar through $\beta$-decay of $^{35}$K for nucleosynthesis in novae and X-ray bursts

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Abstract. Excited states in $^{35}$Ar have been studied via $\beta$-decay of $^{35}$K to improve spectroscopic information relevant for the $^{34,36m}$Cl($p,\gamma$)$^{35}$Ar reaction at novae and X-ray burst temperatures. An extensive set of new data has been collected, including several new proton groups, improved half-life, and direct observation of $\beta$-decay from the lowest $T = 3/2$ state in $^{35}$Ar. In this contribution selected preliminary results from the experiment are presented.

1. Introduction

The thermonuclear runaway in close binary systems such as novae and X-ray bursts proceeds through proton-rich nuclei, and many of the radiative proton capture reactions ($p,\gamma$) involving sd-shell nuclei close to the dripline are dominated by resonant capture. The key parameters in understanding the astrophysical reaction rates are the energies, decay widths and spins of these resonances. One of the reactions for which improved data are needed and which determines the synthesis of nuclei beyond sulfur and chlorine is the radiative proton capture $^{34,36m}$Cl($p,\gamma$)$^{35}$Ar.

At the moment the properties of the excited states of $^{35}$Ar above the proton separation threshold are rather poorly known and the astrophysical reaction rate is based on statistical Hauser-Feshbach calculations [1, 2, 3].

The short half-life of the $^{34}$Cl ground state, 1.53 s, and of the isomer, 32 min [4], prevent fabricating targets for direct reaction measurements. In addition intense and clean enough radioactive beams of $^{34}$Cl are not presently available. However, the excited states of $^{35}$Ar can be studied through indirect methods, such as $\beta$-decay. The excited states above the proton separation threshold, $S_p^{(35)}$Ar = 5896.29(75) keV [5], can be populated selectively through the $\beta$-decay of the $3/2^+, T = 3/2$ ground state of $^{35}$K. These states can de-excite either through $\gamma$ or proton emission, yielding a probe on the properties of these states. So far there has been only one spectroscopic $\beta$-decay study $^{35}$K [6, 7], in which the astrophysically interesting region was not covered.

In a recent experiment we have studied the excited states of $^{35}$Ar selectively through the $\beta$-decay of the ground state of $^{35}$K in hopes for providing more detailed data for the astrophysically interesting states in $^{35}$Ar. In this contribution we report preliminary results of our experiment, including several new proton groups, the first direct observation of the Isobaric Analogue State (IAS) of $^{35}$K ground state in $^{35}$Ar in $\beta$-decay, and the improved half-life of $^{35}$K.
2. Experimental method
We have studied $\beta$-decay of $^{35}\text{K}$ at the Cyclotron Institute of Texas A&M University. In this experiment the $^{35}\text{K}$ beam was produced in inverse-kinematics reaction $^1\text{H}(^{36}\text{Ar},^{35}\text{K})2\text{n}$ by bombarding a LN$_2$-cooled hydrogen gas target at 2 atm pressure with a 36-MeV/u $^{36}\text{Ar}$ beam. The reaction products recoiling from the target were separated with the Momentum Achromat Recoil Separator (MARS) [8], resulting a beam of $^{35}\text{K}$ with typical intensity of 500 pps and purity of about 70% as shown in in Fig. 1.

![Particle Identification](image)

**Figure 1.** A particle identification of the reaction products at the focal plane of the MARS. The momentum defining slits of MARS were at ±0.5 cm, yielding $\Delta p/p = 0.6\%$. The purity of the resulting $^{35}\text{K}$ beam was about 70%.

Ions of interest were implanted into a Si detector stack consisting of a 140µm Single-Sided Silicon Strip Detector, a 45µm Double-Sided Silicon Strip Detector (DSSSD), and a 1 mm thick Si-pad detector. The Si detectors were surrounded by two 70% high-purity germanium detectors (HPGe) in close geometry for efficient $\gamma$-ray detection. The beam implantation depth was controlled by using a rotatable 254 µm thick Al degrader, allowing tuning of the beam into the middle of the DSSSD. The setup is described in more detail in Ref. [9]. During the measurement cycle, the $^{35}\text{K}$ beam was pulsed with implantation period of 400 ms and decay period of 400 ms, and the data was collected only during the decay part, yielding a 50% duty cycle. The setup was calibrated with standard calibration sources and with $^{32}\text{Cl}$ and $^{36}\text{K}$ beams produced with the same primary beam and target as in case of $^{35}\text{K}$.

3. Results
In the measured $\gamma$-data, as shown in Fig. 2, we have the first direct observation of the decay of the 5572 keV Isobaric Analogue State of $^{35}\text{K}$ ground state in $^{35}\text{Ar}$. In the previous $\beta$-decay study reported in Refs. [6, 7], the location of the state was deduced from the observed singles $\gamma$-ray spectrum by adding two $\gamma$-rays that could be identified to originate only from $^{35}\text{K}$ decay. We have observed not only the previously known transitions, but have the detection in coincidence, and in addition measured the full energy $\gamma$-decay from the IAS, thus confirming the earlier assignment.

The astrophysically interesting states are located beyond the proton separation threshold of $^{35}\text{Ar}$. In our $\gamma$-ray data, some of the known states [4] above the proton threshold are observed. With selectivity of the $\beta$-decay process, one can constrain the spin-parity assignment of these
Figure 2. Observed γ-ray spectrum from the β-decay of $^{35}$K. The direct γ emission from the IAS of the $^{35}$K g.s. in $^{35}$Ar is highlighted with an arrow.

levels, as well as improve the resonance energies through the good resolution of the HPGe detectors.

We have observed also several new β-delayed particle decays as demonstrated in Fig. 3. The general features of the spectrum agree with the previous study of Ref. [7] down to the lowest energy decay observed in the previous study at around 1.3 MeV. Most of these new particle groups were likely below the detection threshold of the previous study. However, several of the new particle groups seem to be in coincidence with 461 keV or 665 keV γ-rays from $^{34}$Cl, indicating that these decays occur from levels that are well above the Gamow window of the $^{34g,m}$Cl(p,γ)$^{35}$Ar reaction.

Figure 3. The measured total decay energy spectrum of the charged particles from the β-decay of $^{35}$K. The only identifiable impurity present in the spectrum is the known proton group from the β-decay of $^{33}$Ar [10].
The high statistics of the study allows decay time analysis of the individual particle and $\gamma$ decays, yielding a half-life of 175(2) ms, which is in agreement with the known half-life of $^{35}\text{K}$ 178(8) ms [4]. The half-lives of all the new decays are in agreement with the known half-life, supporting the assignment of origin from the decay of $^{35}\text{K}$ rather than any known impurity in the beam. Detailed analysis of the data is an ongoing process.

4. Conclusions and outlook

In conclusion, we have done a high statistics measurement of $\beta$-decay of $^{35}\text{K}$, yielding an extensive new dataset of $\gamma$ and particle decays from the excited states of $^{35}\text{Ar}$. In addition to the known decay data, we have observed several new particle groups as well as several $\gamma$-rays that were not observed in the previous studies, and improved the half-life value of $^{35}\text{K}$. The detailed analysis and astrophysical interpretation of the data is under way. In the future, in-beam studies of the states in $^{35}\text{Ar}$ are planned, as well as probing the $^{35}\text{K}$ $\beta$-decay with a novel detector system based on Micromegas technology [11], allowing detection of particle decays free of $\beta$-background down to about 100 keV.

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