

## Proposed measurements of $^{36}\text{Cl}$ cross sections for in-situ production in the early Solar System

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### Introduction

Short-lived radionuclides (SLRs) (e.g.,  $^{10}\text{Be}$ ,  $^{26}\text{Al}$ ,  $^{36}\text{Cl}$ ,  $^{41}\text{Ca}$ , etc.) have half-lives of 0.1 - 20 Ma and hence completely decayed since their production in, or injection into, the Early Solar System (ESS). Evidence of SLRs, in the form of enrichments of their daughter isotopes, has been found in Calcium-Aluminum-rich Inclusions (CAIs). The origin of the SLRs is still a matter of debate. Two possible sources were suggested: (1) in-situ production by irradiation of nebular gas and dust by energetic particles (p,  $\alpha$ ,  $^3\text{He}$ ) from the young Sun, (2) production in a Supernova (SN) or an AGB star and injection into the Solar Nebula [1].

Comparison of the inferred initial abundances of SLRs in the ESS with results of nucleosynthetic models suggests that different SLRs have different sources. However, uncertainties in the initial SS abundances of the SLRs, as well as in the nuclear physics and astrophysical input parameters of the models, makes identifying the sources of the SLRs a difficult task. For some SLRs, a major source of uncertainty is the lack of experimental data on the production reactions' cross sections at the relevant energy ranges.

### $^{36}\text{Cl}$ production cross sections

Lin et al. [2] and Hsu et al. [3] measured  $^{36}\text{S}$  overabundance in CAIs and interpreted it as evidence for extinct  $^{36}\text{Cl}$  ( $t_{1/2} = 0.3$  Ma). The results of these two studies indicated a high initial Solar System ratios of  $^{36}\text{Cl}/^{35}\text{Cl} \geq 1.6 \times 10^{-4}$  and  $^{36}\text{Cl}/^{35}\text{Cl} \sim 10^{-2}$  respectively. Current SN and AGB star models cannot produce such a high ratio [1, 4], hence suggesting that  $^{36}\text{Cl}$  was produced in the ESS by proto-Sun irradiation [1].

However, there are no experimental data on the production reactions' cross sections at the relevant low energy range for light ion bombardment. Instead, models of in-situ production use Hauser-Feshbach codes to estimate the cross sections [5, 6, 7]. Figure 1 shows the results of such calculations from Gounelle et al. [7]. Experimentally measured cross sections will improve the accuracy of the model's results for the production of  $^{36}\text{Cl}$  and could help as well fine tune the Hauser-Feshbach codes.

### Experimental

We are planning to measure the cross sections of the  $^{33}\text{S}(\alpha,p)^{36}\text{Cl}$  and  $^{36}\text{S}(p,n)^{36}\text{Cl}$  reactions at the relevant

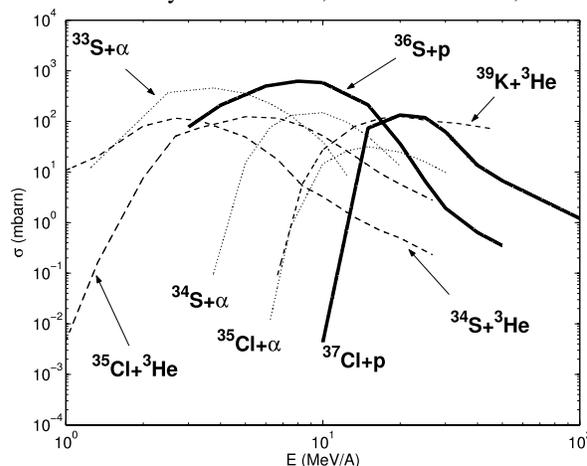


Figure 1: The calculated Hauser-Feshbach cross sections for  $^{36}\text{Cl}$  from [7].

$E \leq 20$  MeV/A range for irradiation from the young Sun [7]. These two reactions were chosen because as shown in Fig. 1, they are calculated to have the highest cross sections. The measurements will be done by accelerator mass spectrometry (AMS). AMS is a technique used to count rare atoms, usually radioactive isotopes, and has the widest dynamic range. Depending on the rare atom, it could measure a ratio of (rare atom)/(normalizing atom) as low as  $\sim 10^{-17}$  [8]. AMS has been used successfully in the past to measure a number of cross sections. These include the weak  $s$ -process important reaction  $^{62}\text{Ni}(n,\gamma)^{63}\text{Ni}$  [9], the  $\alpha$ -rich freezeout important reaction  $^{40}\text{Ca}(\alpha,\gamma)^{44}\text{Ti}$  [10], the SLR  $^{26}\text{Al}$  production reaction  $^{24}\text{Mg}(^3\text{He},p)^{26}\text{Al}$  [11], and even  $^{36}\text{Cl}$  production by higher energy proton spallation on Ti [12].

The cross section measurement consists of three steps: (1) a target is activated and the reaction products are implanted in a catcher; (2) the catcher with the reaction products is treated chemically to extract  $^{36}\text{Cl}$  and reduce  $^{36}\text{S}$ , the main isobar; (3)  $^{36}\text{Cl}$  in the chemically treated sample is counted by AMS. Separation of  $^{36}\text{Cl}$  from the remaining  $^{36}\text{S}$  (and other interfering species) will be achieved by using gas-filled magnetic spectrograph (GFM) [13], as shown schematically in Fig. 2.

A simulation of the expected separation of  $^{36}\text{Cl}$  and  $^{36}\text{S}$  is shown in Fig. 3. The calculation was done at an

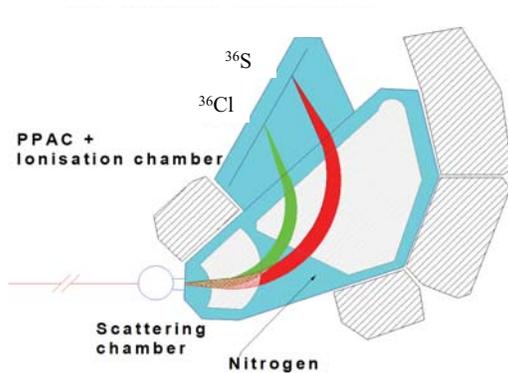


Figure 2: Schematic separation of  $^{36}\text{Cl}$  and  $^{36}\text{S}$  in the GFM.

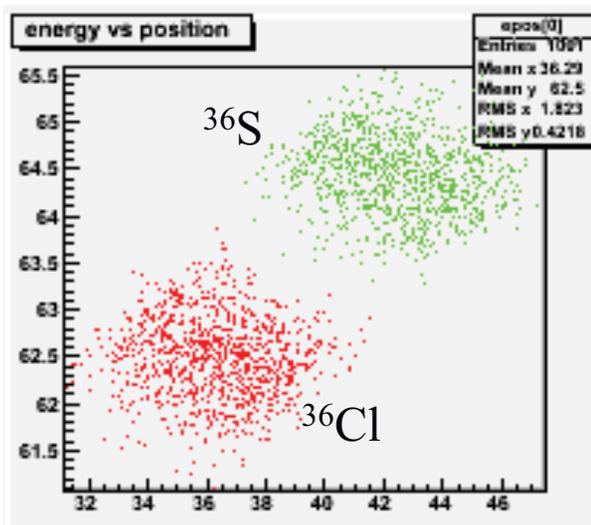


Figure 3: A simulation of the expected separation of  $^{36}\text{Cl}$  and  $^{36}\text{S}$  in energy vs. position. The calculation was done at  $E=90$  MeV,  $B=0.48$  T,  $N_2=3$  Torr in the GFM.

energy of 90 MeV, a magnetic field of 0.48 T and an  $N_2$  pressure in the GFM of 3 Torr. The measurements will be performed in the Nuclear Science Lab at University of Notre Dame.

## References

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