^{33}S(α,p)^{36}Cl CROSS SECTION MEASUREMENT FOR PRODUCTION IN THE EARLY SOLAR SYSTEM

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Introduction: Understanding the origins of short-lived ($t_{1/2} < 5$ million years) and now extinct radionuclides is important in studying the early Solar System (ESS). Their short half-lives relative to the 4.568 Ga age of the Solar System makes short-lived radionuclides (SLRs) good chronometers for dating planetary processes in the ESS. Evidence of their existence has been determined from measured isotopic enrichments in their daughter nuclides in meteorites. However the origins of SLRs has continued to be a matter of debate. Creation in a supernova or asymptotic giant branch (AGB) star and injection into the ESS [1] and irradiation of nebular gas and dust by solar energetic particles (SEPs) from the proto-Sun vary the abundances and distributions of SLRs [2].

Recent meteorite measurements have shown large ^{36}S excess, which has been attributed as the in-situ decay of ^{36}Cl [3, 4]. Supernova and AGB models have been unable to reproduce these high inferred ^{36}Cl/^{35}Cl ratios [5]. This leads us to believe that ^{36}Cl was produced in the ESS by SEP irradiation. Unlike ^{26}Al, ^{36}Cl has showed a large variation in ESS abundances [6]. It is believed this variation is due to a heterogeneous distribution of ^{36}Cl throughout the ESS, supporting a local irradiation scenario. It appears that ^{36}Cl is uncoupled from the creation of ^{10}Be, another SLR believed to be the product of the irradiation scenario. ^{36}Cl thus must be created in a unique time and location in the ESS.

The ^{24}Mg(^{3}He,p)^{26}Al reaction cross section has been measured recently to resolve previous discrepancies in the relevant energy range [7, 8]. These experimental results have proven the importance of experimental data of critical reactions for these irradiation models. The irradiation models ratio lack experimental cross section data for the reactions used for the production of ^{36}Cl. The lack of cross section data accounts for a significant fraction of the overall uncertainty of the calculated yields [9]. ^{33}S(α,p)^{36}Cl is one of the most important reactions for ^{36}Cl production. We have measured the average cross section for ^{33}S(α,p)^{36}Cl reaction over the energy range 1.84 - 2.04 MeV/A [10]. The results of the first measurement will be presented as well as preliminary results of a more complete coverage of the energy range.

Measurement: The ^{33}S(α,p)^{36}Cl was performed via accelerator mass spectrometry (AMS) at the Nuclear Science Lab at Notre Dame. The activation was performed in inverse kinematics with a 90 MeV ^{33}S beam incident upon a gas cell filled with 5 Torr of helium. The gas cell was electrically isolated from the beamline, and the beam current was integrated throughout the 77-hour activation. The ^{33}S beam and produced ^{36}Cl atoms were implanted in a high purity aluminum foil.

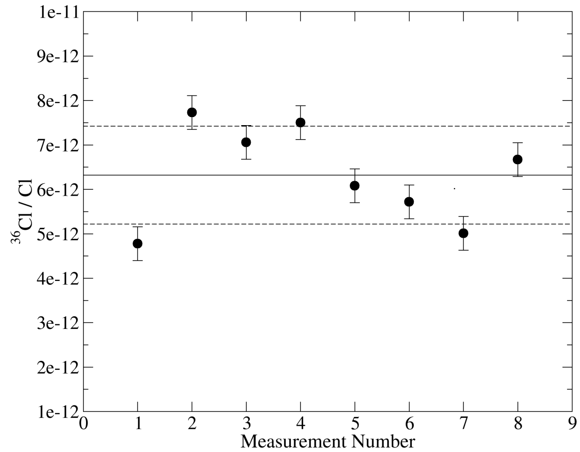

Figure 1: Measured ^{36}Cl/Cl concentration. The solid line is the average of the 8 measurements. The dashed lines are 1σ standard deviation of the mean.

The ^{36}Cl was chemically extracted from the aluminum foil at PRIME lab at Purdue University. The foils were dissolved in a solution of HNO_3, HF, and 50 g of chlorine carrier (1.101 mg/g). $AgNO_3$ was added to the aliquot forming a AgCl supernatant. The vials were centrifuged and the excess solution was decanted away. Finally, the samples were baked at 70°C to remove any excess moisture.

The AMS measurement was performed with the Magnet for Astrophysical Nucleosynthesis studies Through Isobar Separation (MANTIS) AMS system at Notre Dame [11, 12]. In 8 measurements, the measured concentration was found to be ^{36}Cl/Cl = $6.32 \pm 1.1 \times 10^{-12}$ (Fig. 1). We derive an experimental average cross section of 192 ± 33 mb, by averaging the cross section over the energy loss in the target.

The energy loss in the target was calculated using the SRIM code [13]. The energy of the ^{33}S ions after the nickel entrance foil to the gas cell is 64.3 MeV, while the energy loss through the helium gas is 0.8 MeV. The uncertainty in the energy loss through the entrance foil is greater than through the helium target. For this reason a conservative value of 5% uncertainty is assigned to the mean energy of the ions through the gas cell giving a total energy range of 6.4 MeV. The averaged cross section is then measured over the energy range ΔE = 1.84 - 2.04 MeV/A.

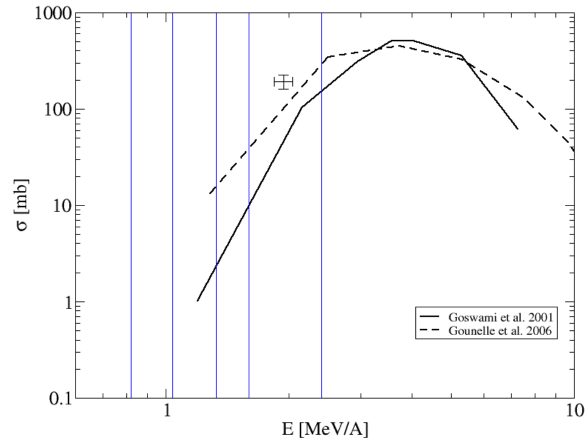

Figure 2: Experimental result compared with calculated values using Hauser-Feshbach codes. The solid and dashed lines are from [14] and [15] respectively. The vertical blue lines are the energies of the recent activations that have not been measured by AMS yet.

Results: The first experimental cross section is shown in Fig. 2 compared to the cross sections calculated using Hauser-Feshbach codes. Integrating the cross section curves over ΔE = 1.84 - 2.04 MeV/A, we get 34 mb and 102 mb from [14] and [15] respectively. Our result of 192 mb is significantly higher than the previous calculated values. The particle fluence required to produce an abundance of ^{36}Cl/^{35}Cl $\sim 2 \times 10^{-5}$ overproduces other SLRs, e.g., ^{10}Be, ^{26}Al, ^{53}Mn [5]. This higher cross section value would require a lower SEP fluence and reduce this overproduction of other SLRs. This first result begs the need of a more comprehensive study of the ^{33}S(α,p)^{36}Cl reaction cross section. With a better understanding of the ^{36}Cl producing reactions, the irradiation models will have to be investigated with the experimental cross section data.

Since the initial measurement, five more activations have been performed. One of these activations at higher energy and the other four at lower energies. These energies are shown as the vertical blue lines in Fig. 2. Preliminary results for the cross sections will be discussed in the poster presentation.

References: [1] G. J. Wasserburg, et al. (2006) *Nuclear Physics A* 777:5. [2] F. H. Shu, et al. (1997) *Science* 277:1475. [3] Y. Lin, et al. (2005) *Proceedings of the National Academy of Sciences* 102(5):1306. [4] W. Hsu, et al. (2006) *The Astrophysical Journal* 640(1):525. [5] B. Jacobsen, et al. (2011) *The Astrophysical Journal Letters* 731(2):L28. [6] D. Nakashima, et al. (2008) *Geochimica et Cosmochimica Acta* 72(24):6141 . [7] C. Fitoussi, et al. (2008) *Phys Rev C* 78:044613. [8] G. F. Herzog, et al. (2011) *Meteoritics and Planetary Science* 42:1427. [9] I. Leya, et al. (2003) *The Astrophysical Journal* 594(1):605. [10] M. Bowers, et al. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* (0): ISSN 0168-583X. [11] D. Robertson, et al. (2007) *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 259(1):669. [12] D. Robertson, et al. (2008) *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 266(15):3481 . [13] J. F. Ziegler, et al. (2011) The stopping range of ions in matter. [14] J. N. Goswami, et al. (2001) *The Astrophysical Journal* 549(2):1151. [15] M. Gounelle, et al. (2006) *The Astrophysical Journal* 640(2):1163.