Cross-Section Measurements of the $^{86}$Kr($\gamma$, $n$) Reaction to Probe the $s$-Process Branching at $^{85}$Kr

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Abstract. For the first time, cross-section measurements were carried out for the $^{86}$Kr($\gamma$, $n$) reaction in order to probe the $s$-process branching point nucleus $^{85}$Kr. The branching point nuclei in the $s$-process path are of importance in testing and constraining the nucleosynthesis models. Cross-section measurement for the photon-neutron reaction on the neighbouring stable isotope is carried out to deduce the aforesaid neutron capture cross-section, as has been adopted in the present case of $^{85}$Kr branching point. The cross-section results from the $^{86}$Kr($\gamma$, $n$) reaction were compared with the statistical model calculations using TALYS code.

1. Introduction

The $s$-process branching point nuclei, with the branching ratio depending on the stellar conditions (temperature, neutron density) are excellent tests to the nucleosynthesis models [1]. The particular branching at $^{85}$Kr is significant since it is independent of temperature and depends only on the neutron density [2]. Knowledge of this parameter is crucial, in particular, for constraining models of the Asymptotic Giant Branch (AGB) stars. However, extraction of the neutron density from isotopic abundance ratios (for $^{82}$Kr and $^{86}$Kr) that has been measured in solar system materials or in presolar grains of primitive meteorites demands accurate knowledge of the $^{85}$Kr($n$, $\gamma$)$^{86}$Kr cross section. Unfortunately, the nucleus $^{85}$Kr is unstable ($T_{1/2}$ = 10.76 years) and the $^{85}$Kr($n$, $\gamma$) reaction has not been measured yet. Consequently, the neutron capture cross section of $^{85}$Kr is listed with a factor of 2 uncertainty even in the latest Kadonis V0.3 [3] evaluation of the ($n$, $\gamma$) rates. It has been shown by M. Lugaro [4], for example, that the current models of the AGB stars can easily reproduce the whole range of the $^{86}$Kr/$^{82}$Kr ratios observed in the SiC presolar grains simply by varying the $^{85}$Kr($n$, $\gamma$) cross section by a factor of 2.

Owing to the short $\beta$-decay half-life of the branching point nucleus, it is not possible to carry out neutron capture experiments, apart from the general inconvenience of working with radioactive targets. Theoretical estimates based on statistical model calculations vary considerably, based on the choice of parametrizations of level density, gamma ray strength functions and neutron-nucleus optical potential. Neutron capture cross sections on branching point nuclei, nevertheless,
can be derived from probing the $(\gamma, n)$ photodisintegration cross section of the neighbouring stable nucleus. The impetus is to find a parameter set that reproduces the $(\gamma, n)$ cross sections and to apply the same set for the reverse $(n, \gamma)$ reaction to predict the capture cross section on the neighbouring branching point nucleus. Such prediction is expected to be more accurate compared to choice of parameters based on global or local systematics used to derive the parameters from the neighbouring nuclei [1].

2. Experiment and Data Analysis

The $^{86}$Kr$(\gamma, n)$ cross-section measurements were carried out at the High Intensity Gamma-Ray Source (HI\γS) facility located on the campus of Duke University. The facility has a 0.24-1.2 GeV storage ring where quasi-monoenergetic $\gamma$-beam is produced by the intracavity Compton back-scattering of the free electron laser photons from the electron bunches. At present HI\γS delivers the most intense monoenergetic $\gamma$-beams, with an average flux of $\sim 10^7$-$10^8 \gamma$/s in the energy range from 1 to 20 MeV and typical energy spread (FWHM) of 1-3%. The latter depends on the collimator diameter used for particular measurements [6]. The first measurements were carried out at beam energies $E_\gamma = 9.970 \pm 0.238$, $10.115 \pm 0.275$, $10.170 \pm 0.234$, $10.290 \pm 0.270$, $10.360 \pm 0.277$, $10.490 \pm 0.258$, and $11.005 \pm 0.250$ MeV.

The target was 1012 mg of Kr gas enriched to 99.4% in $^{86}$Kr, contained in a stainless steel cell as shown in Fig. 1. An empty cell of identical material and dimensions was used to subtract the background contribution. The emitted neutrons from the $(\gamma, n)$ reaction was detected using a $4\pi$ assembly of $^3$He proportional counters, fabricated into a single unit, also shown in Fig. 1. The assembly consists of 18 individual counters, arranged in two concentric rings. Each counter was filled with $^3$He gas at 6 atm pressure. The space around the counters was stuffed with polyethelene that themalizes the emitted neutrons before they are captured (detected) in the $^3$He counters. The counter produces TTL outputs corresponding to the detected events, that were recorded on a scaler in a VM-USB based data acquisition system. The detector has an axial cylindrical hollow wherein the target was placed for the present measurements. The efficiency characteristics of the detector were studied previously [5] and were used in the present work. The $\gamma$-flux incident on the target was measured using a plastic scintillator that was cross-calibrated at three different $\gamma$-energies, between 10.0 and 11.0 MeV using the Au-foil activation [6].

At each beam energy, consecutive measurements were carried out using the gas cell and the empty cell and the net number of neutrons from the $^{86}$Kr$(\gamma, n)$ reaction was extracted. The photoneutron cross-section was determined from the formula,

$$\sigma(E_\gamma) = \frac{N_n}{N_\gamma N_t \epsilon_n g}$$

(1)

where $N_n$ is the net number of neutrons, $N_\gamma$ is the number of incident $\gamma$-rays, $N_t$ is the number of target atoms, $\epsilon_n$ is the neutron detection efficiency and $g$ is the fraction of the incident $\gamma$-rays with energy higher than the neutron threshold ($S_n=9.86$ MeV).
Experimental cross-sections for $^{86}$Kr($\gamma, n$) reaction plotted along with the calculated excitation functions using the TALYS code. The different parameter sets used in the calculations are explained in the text.

3. Results and Discussions

The experimental $^{86}$Kr($\gamma, n$) cross-section from the present measurement is plotted in Fig. 2, along with the statistical model calculations using the TALYS [7] code. Two sets of parameters, differing in the choice of the Nuclear Level Density (NLD) and Gamma Strength Function (GSF) models, were used to fit the experimental results. One set of parameters used the macroscopic models, generalized energy dependent Lorentzian model for GSF and back-shifted Fermi gas (BSFG) model for NLD. The other set comprised of microscopic models, Skryme-Hartree-Fock-Bogoliubov plus quasiparticle Random Phase Approximation (QRPA) for GSF and Hartree-Fock-Bogoliubov plus a combinatorial method, adopted for NLD. Apart from the calculations with the default values, the microscopic GSF was adjusted by scaling factors in TALYS-1.2, for better agreement with the measured values. It was generally observed that the microscopic models led to better agreement with the experimental data, as illustrated in Fig. 2.

This was the first measurement of the low energy tail of the Giant Dipole Resonance (GDR) of the $^{86}$Kr($\gamma, n$) reaction. The GDR for $^{86}$Kr has not been experimentally measured, till day. The GDR parameters used in the aforesaid statistical model calculations were from the systematics. This could have resulted in the observed differences between the experimental results and the model predictions. Measurements are in progress at higher energies to map the entire GDR distribution. The experimentally derived GDR can help constrain the statistical model predictions and result in a credible parameter set that can be subsequently applied to extract the neutron capture cross section on $^{85}$Kr branching point nucleus. It is noteworthy to mention that at incident photon energies just above the neutron separation energy, the GDR seldom decays into the high spin ground state ($J^\pi=9/2^+$) of $^{85}$Kr, since such a decay would require f-wave neutrons that are hindered by small penetrability. More significant role is expected by the low spin isomer ($J^\pi=1/2^-$) of $^{85}$Kr. Measurements are underway to investigate the exclusive isomeric cross section of $^{86}$Kr($\gamma, n$)$^{85m}$Kr reaction using activation technique.

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