CONF-980774--
RECEIVED
OCT 14 1998
OSTI

New neutron capture and total cross section measurements on ^{88}Sr and their impact on s -process nucleosynthesis

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Abstract. We have made new and improved measurements of the neutron capture and total cross sections for ^{88}Sr at the Oak Ridge Electron Linear Accelerator (ORELA). Improvements over previous measurements include a wider incident neutron energy range, the use of metallic rather than carbonate samples, better background subtraction, reduced sensitivity to sample-dependent backgrounds, and better pulse-height weighting functions. Because of its small cross section, the $^{88}\text{Sr}(n,\gamma)$ reaction is an important bottleneck during the s -process nucleosynthesis. Hence, an accurate determination of this rate is needed to better constrain the neutron exposure in s -process models and to more fully exploit the recently discovered isotopic anomalies in certain meteorites. We describe our experimental procedures, compare our results to previous data, and discuss their astrophysical impact.

1 Introduction

The $^{88}\text{Sr}(n,\gamma)$ cross section is important to nuclear astrophysics for at least three reasons. (i) Because this cross section is very small (^{88}Sr has a closed neutron shell at $N = 50$), ^{88}Sr acts as a bottleneck in s -process nucleosynthesis [1]. The $A \approx 100$ region is complicated, with several different nucleosynthesis processes contributing to the abundances of nuclides in this region. Because of its bottleneck character, it is crucial to know accurately the cross section for the $^{88}\text{Sr}(n,\gamma)$ reaction so that the relative contributions of various processes to the solar system abundances can be disentangled. (ii) It has been shown that a measurement of the Rb/Sr ratio in stars can be used to extract the neutron density during the s process. Current results [2] indicate that the neutron density derived from these data is consistent only with the s process occurring during the interpulse phase in low mass asymptotic giant branch (AGB) stars. Because the cross sections were not measured to low enough energies to determine the low-temperature reaction rates needed in the models, this conclusion is based mainly on extrapolations of previous neutron capture measurements. Strontium is the normalization point for these data and strontium is mostly ^{88}Sr . Therefore, new measurements of the $^{88}\text{Sr}(n,\gamma)$ cross section are needed at lower neutron energies to provide a more robust test of stellar models. (iii) Non-solar ratios for isotopes of strontium and other elements have been observed in SiC grains in certain meteorites. Such observations provide the s -process abundance ratios for isotopes of several elements, thereby greatly expanding the number of "effectively s only" calibration points for models of the s process. Calculations indicate that isotopes with small (n,γ) cross sections provide the most sensitive test of s -process models when comparing to the meteorite data. Hence, more precise reaction rates are needed for

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nuclides such as ^{88}Sr to more fully exploit the opportunity offered by meteorite data for improved understanding of the s process.

There have been three previously reported measurements of the $^{88}\text{Sr}(n, \gamma)$ cross section from which the reaction rate has been determined [1, 3, 4]. None of these previous measurements can be used reliably to determine the reaction rate across the range of temperatures needed for stellar model calculations—the first because it was made with a pseudo-Maxwellian source and hence determines the reaction rate at the single temperature $kT = 25$ keV, the latter two because they did not extend low enough in energy. The measurements of Refs. [3, 4] also are too imprecise to allow the fullest use of new observational data to improve s -process models. Because the samples used were SrCO_3 , these measurements suffered from a relatively poor signal-to-noise ratio. Relatively large systematic errors may also plague these data because subsequent work [5] has shown that (i) background resulting from prompt neutron sensitivity was probably underestimated, (ii) the pulse-height weighting functions used may not have been adequate, and (iii) errors in the data reduction have been corrected in only an approximate manner. Finally, a resonance at 2.780 keV has been reported [6], but apparently ignored in evaluations of the reaction rate. Although the reported parameters for this resonance have large uncertainties, its inclusion leads to a 77% increase in the reaction rate at 5 keV over the rate calculated from all the other resonances reported in Ref. [4]. Hence, it is vitally important to make new measurements in this energy range.

2 Measurement technique, analysis, and results

We have made new and improved measurements of the neutron capture and total cross sections for ^{88}Sr over the energy range from 20 eV to 350 keV at the Oak Ridge Electron Linear Accelerator (ORELA). Improvements over previous measurements include a wider incident neutron energy range, the use of metallic rather than carbonate samples, separate background measurements and better background subtraction, the use of an apparatus with much smaller sensitivity to sample-dependent backgrounds, better pulse-height weighting functions, and a separate transmission measurement to determine the total cross section. The transmission data were invaluable in extracting resonance areas from the capture data (which were subsequently used to calculate the reaction rate).

The multi-level, multi-channel, $\mathcal{R}$ -matrix code SAMMY [7] was used to fit both our transmission and capture data and extract parameters for 101 resonances in the energy range from 12 keV to 350 keV. The astrophysical reaction rate calculated in the standard manner from these resonance parameters is shown in Fig. 1.

3 Comparison to previous results and discussion

There is no indication of the resonance reported in Ref. [6] at 2.780 keV in our capture or transmission data on ^{88}Sr ; hence, if it exists it is much too small to have any significant impact on the astrophysical reaction rate. The most likely explanation seems to be that this resonance is actually in another strontium isotope. In Ref. [9], there is a resonance reported in $^{87}\text{Sr}+n$ at very nearly the same energy (2.756 keV). In addition, short measurements we have made with a natural strontium sample also show a resonance at this energy.

Figure 1: Rate for the $^{88}\text{Sr}(n, \gamma)$ reaction determined from the present work compared to previous results.

The evaluated rate of Ref. [8] has been used most frequently in recent *s*-process nucleosynthesis calculations. The authors of Ref. [8] used the resonance parameters given in Ref. [9] rather than those in the primary sources to calculate the reaction rate. There are two problems with using this procedure. First, in Ref. [9], the radiation width of the first *s*-wave resonance at 13.852-keV resonance was scaled upwards by 35% to fit the thermal cross section. Because the level density is fairly low, and because this resonance is rather broad, this change causes a significant increase in the reaction rate across a range of temperatures compared to the rate calculated using the correct radiation width for this resonance. Second, by using the parameters in Ref. [9], the subsequently published [10] correction factor (1.0737) to the original data was ignored, resulting in a smaller reaction rate. These two effects tend to cancel each other to some extent. Finally, the uncertainty for this reaction rate given in Ref. [8] is too small to be based on the data of Ref. [9]. The uncertainty in Ref. [8] is equal to the uncertainty of the more precise, single-temperature measurement of Ref. [1] although they do not cite this reference.

The reaction rate calculated from our resonance parameters is compared to results of Refs. [1, 8] in Fig. 1. For clarity, the uncertainty (about 3%) in our rate is not shown. As can be seen, our rate is significantly different from that of Ref. [8], and there is a small, but significant difference between our rate and that of the most precise previous measurement of Ref. [1]. For Ref. [1], we show the result of their actual measurement at $kT = 25$ keV in addition to the more commonly quoted value resulting from their extrapolation to $kT = 30$ keV. We do so because a $1/v$ shape was used in Ref. [1] for this extrapolation, which is clearly incorrect as shown in Fig. 1. The difference between our rate and that of Ref. [1] at $kT = 25$ keV is $\langle \sigma \rangle = 0.52 \pm 0.27$ mb. Because our measurement determines the rate resulting from resonances whereas the rate determined from the activation measurement of

Ref. [1] includes contributions from both resonant and non-resonant sources, it is possible that a non-resonant component of the cross section is responsible for the difference between the two rates. A $1/v$ contribution from the difference between the measured thermal cross section (the value given in Ref. [9] is incorrect by a factor of 10) and the thermal cross section due to known s -wave resonances is too small to explain this difference. On the other hand, because of the known spins, parities, and spectroscopic factors, direct capture of p -wave neutrons appears to be a likely cause of the difference in the two determinations of the reaction rate at $kT = 25$ keV. Therefore, we calculated the direct capture cross section using the code TEDCA [11]. A folding procedure was used to determine the optical potentials for the bound state and the entrance channel. A normalization factor, $\lambda = 0.948$, was determined from the elastic neutron scattering data. The calculations included capture to the ground state and first four excited states. The resultant direct capture cross section has an energy dependence approximately proportional to $\sqrt{E_n}$ with a value of 0.33 mb at 25 keV. The result of adding the reaction rate due to the calculated direct capture cross section to that due to the resonances as determined in our ORELA measurements is shown in Fig. 1. There is now excellent agreement between our total rate and that of Ref. [1] at $kT = 25$ keV. Hence, for the first time, with our new measurements and direct capture calculation there is now a precise and accurate $^{88}\text{Sr}(n, \gamma)$ reaction rate across the entire range of temperatures needed for s -process calculations. At $kT = 8$ keV, our new rate is 8% lower than the rate in Ref. [8].

One indication of the importance of the $^{88}\text{Sr}(n, \gamma)$ reaction rate is evident in the new results presented at this conference for strontium isotope ratios measured in single meteoric grains [12]. The s -process calculation of the $^{88}\text{Sr}/^{86}\text{Sr}$ ratio made with the latest stellar model is about 10% below the data. The reaction rate of Ref. [8] was used in these calculations. The magnitude and direction of the difference between our new rate and that of Ref. [8] are such that it is expected that new s -process calculations using our rate will be in much better agreement with the meteorite data.

This research is supported by the U.S. Department of Energy under Contract No. DE-AC05-96OR22464 with Lockheed Martin Energy Research Corporation.

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