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New neutron capture and transmission measurements for ^{134,136}Ba at ORELA and their impact on *s*-process nucleosynthesis calculations

P. E. Koehler[a], R. R. Spencer[a], R. R. Winters[b], K. H. Guber[a], J. A. Harvey[a], N. W. Hill[a], and M. S. Smith[a]

[a]Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6354
[b]Department of Physics and Astronomy, Denison University, Granville, Ohio 43023

We have made high-resolution neutron capture and transmission measurements on isotopically enriched samples of ^{134}Ba and ^{136}Ba at the Oak Ridge Electron Linear Accelerator (ORELA) in the energy range from 20 eV to 500 keV. Previous measurements had a lower energy limit of 3 - 5 keV, which is too high to determine accurately the Maxwellian-averaged capture cross section at the low temperatures (kT $\approx$ 6 - 12 keV) favored by the most recent stellar models of the s-process. Our results for the astrophysical reaction rates are in good agreement with the most recent previous measurement at the classical *s*-process temperature, kT = 30 keV, but show significant differences at lower temperatures. We discuss the astrophysical implications of these differences.

1. INTRODUCTION

Recent stellar models [1,2] have for the first time come reasonably close to reproducing the observed *s*-process isotopic abundances. However, exceptions to the general good agreement between the calculations and the data were observed for the *s*-only isotopes ^{134}Ba and ^{136}Ba. Because their abundances are thought to arise almost exclusively from the *s*-process, the *s*-only isotopes are the most important calibration points for the models; hence, the difference between the observed and calculated abundances for ^{134}Ba and ^{136}Ba may be a sign of a problem with the model. However, previous measurements did not extend to low enough energies to reliably determine the reaction rates at these lower temperatures (kT$\approx$6-12 keV), so it is possible that this disagreement is due to the input cross section rather than the model. A second problem with previous determinations of the reaction rates for these isotopes is the lack of high quality neutron transmission data. The neutron widths determined from these data can be indispensable in the calculation of the often substantial corrections for resonance self shielding and multiple scattering that have to be applied to the (n,γ) data. A final motivation for the present work was to compare capture cross sections which we measured using the pulse height weighting technique to recent measurements made with a 4π BaF_2 detector [3]. Problems with previous measurements made using the pulse height weighting technique have called into question the accuracy of the technique. A comparison of our data to those measured with the 4π BaF_2 detector should serve as a further test of the accuracy of our weighting functions. A detailed account of the present work has been submitted for publication

DISCLAIMER

elsewhere [4].

2. EXPERIMENTAL PROCEDURES

The ORELA was operated at a pulse rate of 530 Hz, a pulse width of 7 ns, and a power of approximately 4 to 7 kW. The samples were approximately 3.7 g (^{134}Ba) and 9.4 g (^{136}Ba) of isotopically enriched, compressed barium carbonate powder. The transmission measurements were made on ORELA flight path 1 with a source-to-detector distance of 79.759 m using a ^{6}Li-loaded glass scintillator. The capture measurements were made on ORELA flight path 7 at a source-to-sample distance of 40.12 m using a pair of C_6D_6 detectors. The capture apparatus has been improved in several significant ways compared to the setup [5] used in many of the previous ORELA measurements. These improvements include replacing the C_6F_6 detectors with C_6D_6, greatly reducing the amount of mass near the detectors and sample, and improvements in the calculation and application of the pulse-height weighting functions for the detectors[6]. The overall normalization was made using the 4.9 eV resonance in the ^{197}Au(n,γ) cross section.

3. COMPARISON TO PREVIOUS RESULTS

The multilevel R-matrix code SAMMY [7] was used to fit the capture and transmission data. For ^{134}Ba, we fitted 86 resonances between approximately 100 eV and 11 keV. For ^{136}Ba, we fitted 92 resonances between 447 eV and 35 keV.

A comparison of the capture kernels from the analysis of our data to previous work [8,9] indicates that the pulse-height weighting functions we have used are correct and that the neutron widths were most often underestimated in the previous analyses. However, the neutron widths for the broadest resonances, which have the largest corrections, were systematically overestimated in previous work [8]. The net effect is that the previous reaction rates were underestimated by a small amount. For example, we calculated that the reaction rate of reference [9] at 10 keV is almost 3% too low because of this effect. Although fairly small, this difference is a sizeable fraction of the total uncertainty at 10 keV of 4.2% given in reference [9].

The astrophysical reactivities, $N_A\langle\sigma v\rangle$, calculated from our data are compared to previous work in figure 1. The reactivities were calculated using our fits to the data below 11 keV in ^{134}Ba and 35 keV in ^{136}Ba and our cross section data above these energies. From the uncertainty in the ^{197}Au(n,γ) and ^{6}Li(n,α)^{3}H cross sections, the statistical precision of the calibration measurements, and the repeatability of the calibration runs, we calculate that the normalization uncertainty is 3%. The statistical uncertainties in the reactivities are negligible compared to the overall normalization uncertainty. At the classical *s*-process temperature, kT = 30 keV, there is good agreement between our data and the two previous measurements for ^{136}Ba [3,8], whereas for ^{134}Ba, our data are in good agreement with the most recent measurement [3], confirming that the previous reaction rate of reference [8] is 20% too large.

Although there is good agreement with previous work at the classical *s*-process temperature, at the lower temperatures favored by recent stellar models our reaction rates for ^{134}Ba and ^{136}Ba are lower and higher, respectively, than in previous work [3]. The difference appears to be due to the effect of resonances below the energy range of reference [3]

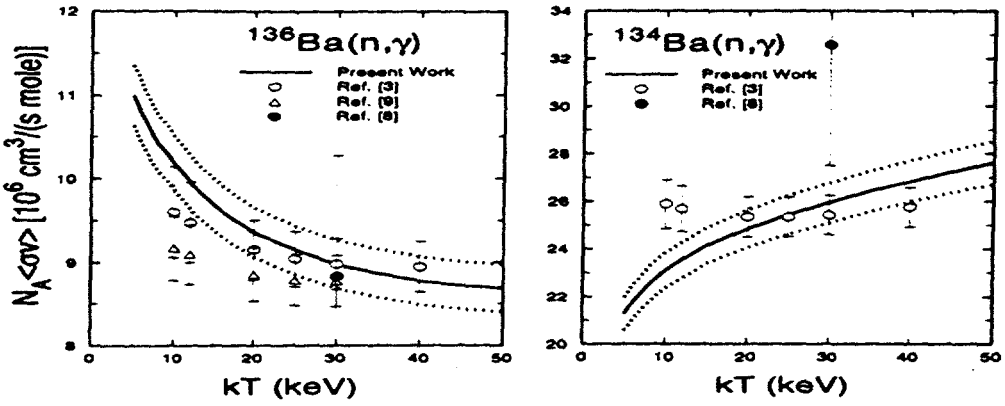

Figure 1. Astrophysical reactivities for ^{134,136}Ba(n,γ) from our measurements compared to previous work. The uncertainties in our rates are indicated by the dotted curves.

where the contribution to the reaction rate due to resonances below 5 keV was estimated using calculations. In contrast, we directly measured the strengths of these resonances. If the rates of reference [3] are corrected for this effect (by -7.0% for ^{134}Ba and +7.8% for ^{136}Ba), then they agree with our rates to within the quoted uncertainties.

4. ASTROPHYSICAL IMPLICATIONS

Because there is good agreement between our reaction rate and those of reference [3] at kT = 30 keV, there is no change in the results from classical *s*-process calculations, and the calculated *s*-only barium abundances remain too large compared to the measured abundances. However, the relatively strong decrease in the ^{134}Ba/^{136}Ba ratio of reaction rates indicated by our data has the effect of decreasing the effective *s*-process temperature from a classical analysis of the branching at ^{134}Cs compared to an analysis based on the reaction rates of references [3,9]. Using our reaction rates, and allowing for a factor of three uncertainty in the ^{134}Cs β-decay rate, we calculate a mean *s*-process temperature in the range, $kT_s = 10 - 20$ keV. This is inconsistent with the value $kT_s = 29 \pm 5$ keV deduced from the analysis of the branchings at ^{151}Sm, ^{154}Eu, and ^{175}Lu [1]. This inconsistency in the temperature deduced from the classical analysis of different branching points may indicate the need for more sophisticated stellar models.

Because our reaction rate for ^{136}Ba at low temperatures is higher than the previously accepted rate [3,9], it is expected that the relative overproduction of this isotopes seen in previous calculations based on a stellar model will be reduced. We used the reaction network code NETZ [10] to calculate the *s*-process nucleosynthesis in a scenario approxi-

mating the recent stellar model of reference [2]. Using the reaction rates of reference [9], the production of ^{134}Ba and ^{136}Ba are too high by 33% and 22%, respectively, normalized to the average overproduction of the *s*-only calibration points ^{124}Te and ^{150}Sm. Using our new reaction rates, the relative overproduction of ^{136}Ba is decreased to 19% whereas the overproduction of ^{134}Ba is increased to 38%. Hence, the relative overproduction of the *s*-only barium isotopes remains a problem for this model.

Unfortunately, the current version of NETZ cannot be used to calculate the nucleosynthesis in the newer model of reference [1]. However, given the difference between our rates and those of reference [3] extrapolated to 8 keV, we expect that our new rates would reduce the overproduction of ^{136}Ba and increase the overproduction of ^{134}Ba in this model. However, there have been very few cross section measurements down to the low energies necessary to obtain accurate reaction rates at the low temperature of this model. Our measurements as well as similar data on ^{138}Ba [11] have shown that extrapolations from measurements at higher energies are not reliable; hence, new measurements are needed on many isotopes to fully evaluate this new model.

It might be possible to remedy the relative overproduction of ^{134}Ba by increasing the (n,γ) cross section and decreasing the β-decay rate of the radioactive branching point ^{134}Cs within the respective estimated uncertainties. However, the fact that the unbranched isotope ^{136}Ba is substantially overproduced in the model calculations indicates that there may be more fundamental problems in the new stellar models or with the solar barium abundance[3].

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