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^{147}Sm(n,α) cross section measurements from 3 eV to 500 keV: Implications for explosive nucleosynthesis reaction rates

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We have measured the ^{147}Sm(n,α) cross section from 3 eV to 500 keV. These data were used to test nuclear statistical models which must be relied on to calculate the rates for as yet unmeasurable reactions occurring in explosive nucleosynthesis scenarios. It was found that our data are in reasonably good agreement with the reaction rate predicted by an older model but that the rates predicted by two very recent models are roughly a factor of 3 different from the data (in opposite directions). A detailed analysis indicates the strong dependence on the employed optical α potentials. These results, together with counting rate estimates for future experiments indicate that (n,α) measurements will be useful for improving reaction rate predictions across the global range of masses needed for explosive nucleosynthesis calculations.

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Recently, there has been much interest [1–5] in the astrophysical rates for reactions between α particles and intermediate-to-heavy nuclei. These reactions can often play an important role in the nucleosynthesis occurring in massive stars at high temperatures and in explosive scenarios such as supernovae. For light and intermediate nuclei, α-induced reactions are directly important. However, for heavier nuclei such reactions are suppressed by the high Coulomb barrier. Still, photodisintegration processes such as (γ,α) reactions play an essential role in the nucleosynthesis of the proton-rich intermediate to heavy elements in the so-called *p* process [6,7]. A better understanding of the nucleosynthesis occurring in these environments should lead to improved stellar models and impact related areas such as the origin of isotopic anomalies in meteorites [1]. Possible *p*-process contributions to *s*-only isotopes are also relevant for high-precision tests of *s*-process models [8].

There is scant experimental information on the rates for these reactions and the few data which have been measured are sometimes very different from theoretical predictions. Direct determinations of these rates via experiments are hampered by their very small size and by the fact that the required ‘‘target’’ isotopes are often of very low natural abundance (and hence very expensive) or radioactive. For these reasons, it is very unlikely that the rates for most of the needed reactions will be determined by direct experiments. At present, there are very few experimental α-particle reaction rate data for $A \gtrsim 70$.

Theoretical calculations are hampered by large uncertainties in the $\alpha+$nucleus optical potential in the astrophysically relevant energy range which forms a crucial part of the nuclear statistical model used to calculate these rates. Traditional methods for improving optical potentials, such as elastic scattering of α particles, have been of limited usefulness [9]. This is because the potentials must be extrapolated from measurements made at energies well above the astrophysically interesting range. The very few (α,γ) data which exist for heavy nuclei demonstrate the large uncertainties associated with this extrapolation. The potentials are not only energy dependent but also depend on the properties of the target nuclei [10,11]. Recently proposed global α-optical potentials [12–15] suffer from the lack of experimental data needed to constrain and test them.

A series of (n,α) cross-section measurements across a range of neutron energies may offer the best opportunity for enabling global improvements in the $\alpha+$nucleus optical potential for astrophysics applications. There are at least four reasons for this. First, the Q values for (n,α) reactions are such that the relative energy between the α particle and the residual nucleus are in the astrophysically interesting range, so no extrapolation is necessary. Second, although the cross sections are expected to be relatively small, by scaling the sample size to that employed in a previous measurement [18] using predicted cross sections [19], we calculate that as many as 30 nuclides across a wide range of masses should be accessible to measurements. Third, unlike $(n_{thermal},\alpha)$ data (see, e.g., [20,21]) which can be strongly influenced by a single resonance, it becomes possible to probe the energy-dependence of the α potential by varying the neutron energy. Finally, a recent study [3] has shown that calculated (α,n) rates, via the α-transmission coefficients, are sensitive to the α potential used in the model. By detailed balance arguments, (n,α) reactions should display the same sensitivity. To demonstrate that in fact this is the case, in Fig. 1 we show

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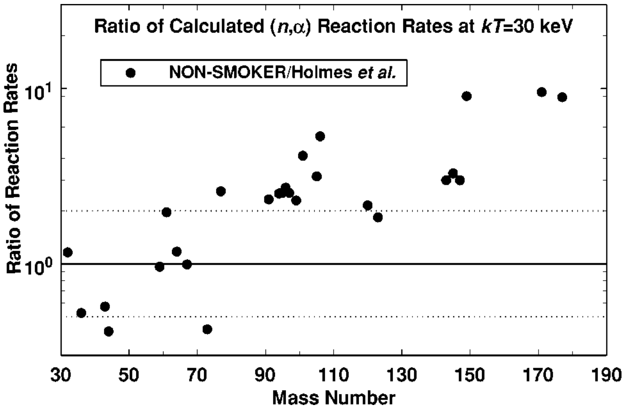

FIG. 1. Ratio of (n,α) reaction rates at $kT=30$ keV calculated with two different statistical models, versus mass number. Shown are ratios of rates calculated with the NON-SMOKER code [14] to those calculated by Holmes *et al.* [19] for the 30 nuclides that should be accessible to measurements.

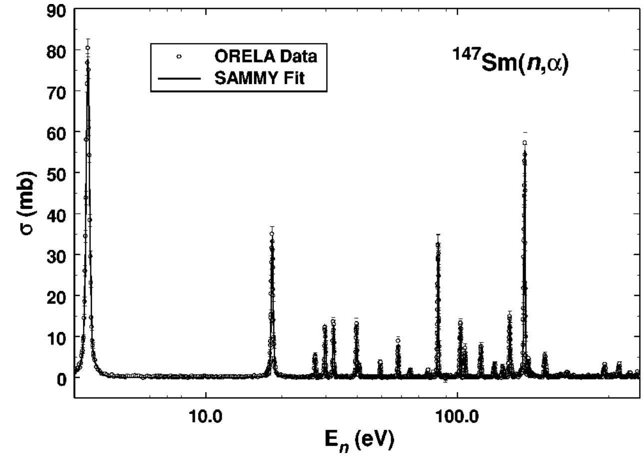

FIG. 2. ^{147}Sm(n,α) cross-section data (points) and SAMMY fits (solid curve) from the present work in the resolved resonance region from 3 to 530 eV. The error bars represent the one-standard-deviation statistical uncertainties.

the ratio of two statistical model calculations of (n,α) reaction rates as a function of mass for the 30 nuclides that should be accessible to measurements. This ratio shows the same trend observed in Ref. [3] from which it can be concluded that the measurement of (n,α) reaction rates will allow sensitive tests of the α potentials used in the models.

The ^{147}Sm data presented herein are the first (n,α) cross-section measurements in this mass range over the broad range of energies of interest to nuclear astrophysics. It is intended that they represent the first in a series of measurements aimed at a global improvement in the calculation of rates for α-induced reactions of interest to explosive nucleosynthesis models.

The experiment was performed at the Oak Ridge Electron Linear Accelerator (ORELA) white neutron source. The ORELA was operated at a repetition rate of 525 Hz, a power of 6–8 kW, and a pulse width of 8 ns. Neutron energies were measured via time of flight. Because the cross section was so small ($\approx 25\,\mu$b at 30 keV) and the sample has to be thin enough to allow the outgoing α particles to escape without too much straggling, it was necessary to use a sample with relatively large area, to place the detector directly in the beam to obtain the largest possible solid angle, and to use the shortest available flight path to obtain the maximum flux. Placing such a large detector directly in the beam at a short distance from the neutron production target can result in large backgrounds at the higher neutron energies from effects due to the "γ flash" that occurs at the beginning of each burst of neutrons. In fact, γ flash effects have limited previous measurements [22,23] of this type to neutron energies less than a few keV. In the present Rapid Communication these problems were overcome by employing a compensated ionization chamber (CIC) [18] for the detector. Although a CIC can have poorer pulse-height resolution than, for example, a gridded ionization chamber, it reduces γ-flash effects by several orders of magnitude, allowing measurements to be made to much higher neutron energies (500 keV in the present case).

The source-to-sample distance was 8.835 m and the neutron beam was collimated to 10 cm in diameter at the sample position. Two samples were placed back-to-back in the center of our parallel-plate CIC with the planes of the samples perpendicular to the neutron beam. Hence, the cross section was measured over nearly the entire 4π solid angle. The samples were in the form of $\mathrm{Sm_2O_3}$ enriched to 95.3% in ^{147}Sm and were 5.0 mg/cm^2 thick by 11 cm in diameter. The ^{6}Li$(n,\alpha)^3$H reaction was used to measure the energy dependence of the flux and to normalize the raw counts to absolute cross section. A ^{6}Li sample in a separate parallel-plate CIC was used as a flux monitor. The most recent ENDF evaluation [24] for the ^{6}Li$(n,\alpha)^3$H reaction was used in calculating the absolute cross sections. The data were corrected for the small background due to the spontaneous α decay of ^{147}Sm and for the effects of α straggling in the samples. This latter correction (14%) was calculated using the computer code SRIM [25]. The overall normalization uncertainty of approximately 6% is dominated by the uncertainty ($\pm 4\%$) in this correction and by uncertainties ($\pm 3\%$) in the sample sizes.

The data were fitted using the *R*-matrix code SAMMY [26] to extract the α widths for resonances in the resolved region (below 530 eV). The data and fits in this energy range are shown in Fig. 2. α widths from previous measurements [22,23] are in reasonable agreement with our results. The data for the unresolved region are shown in Fig. 3 together with cross sections calculated by three statistical model codes [14,17,19] frequently used for astrophysical applications. The theoretical cross sections are renormalized by the constant factors given in the figure. As can be seen, the older calculation of Ref. [19] is much closer to the data than the more recent calculations of Refs. [14,17] which are roughly a factor of 3 different from the data in opposite directions. The reasons for these differences will be discussed in the following. The comparison to our new data provides important clues to problems with the α potentials in the models.

Because the results of the statistical model calculations are a convolution from several independently predicted nuclear properties it can be difficult to disentangle the differ-

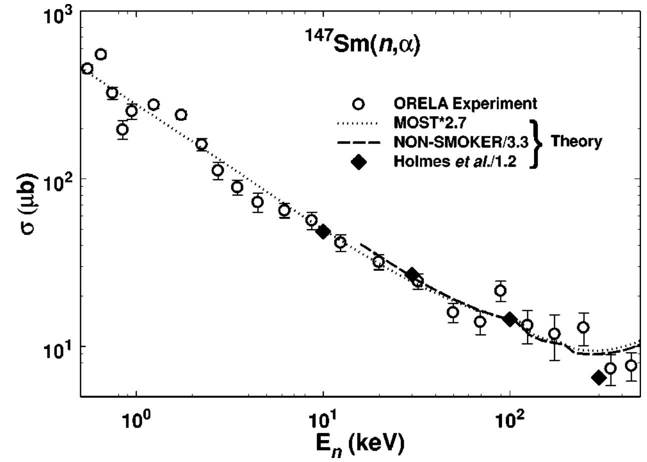

FIG. 3. Cross sections for the ^{147}Sm(n,α) reaction in the unresolved region. Shown are the measurements of the present work (circles with error bars depicting one-standard-deviation statistical uncertainties) and calculations by Holmes *et al.* [19] (diamonds), as well as calculations using the newer statistical model codes NON-SMOKER [14] (long-dashed curve), and MOST [17] (dotted curve). Note that the theoretical calculations of Refs. [14,17,19] have been normalized by the factors given in the legend.

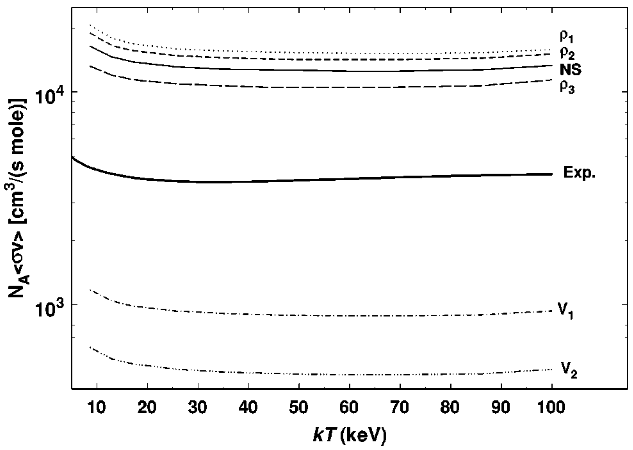

FIG. 4. Astrophysical rates for the ^{147}Sm(n,α) reaction obtained by varying the $\alpha+$nucleus potential (V) as well as the nuclear level density description (ρ) in the calculations. Shown are the present experimental values (''Exp.'') as well as the NON-SMOKER calculations [14] using the standard parameters (''NS'') as well as two different potentials and three different level density descriptions. Calculations using the equivalent square well potential (''V_1,'' as in [19]) and using the potential from Ref. [15] (''V_2'') are shown as well as calculations using the experimental level density parameters [33] (''ρ_1''), and the theoretical level density prescriptions given in Ref. [19] (''ρ_2''), and in Ref. [34] (''ρ_3'').

ent contributions. In the present case, the two most important ingredients are the particle transmission coefficients and the level densities of the excited states. Recently [3], the model of Ref. [19] and the predecessor (SMOKER code) [28] of both the NON-SMOKER [14,16] and MOST [17] codes were compared in the context of their application to type II supernova nucleosynthesis for $A<100$. The authors of Ref. [3] observed a systematic trend in the ratio of the predicted (α,p) and (α,n) rates with mass number at a given temperature. This trend was traced to differences in the α-particle potentials used in the two models which leads to a systematic difference in the α-particle transmission functions for $A>60$. The older model [19] employed optical square well potentials (with empirical corrections) and made use of the black nucleus approximation whereas the newer model [28] employed a phenomenological Woods-Saxon potential based on extensive data [29]. The more recent models of Refs. [14,17] differ in the prediction of several nuclear properties, among them the $\alpha+$nucleus potentials and the level density prescriptions [30,31]. The aim of these improvements was to use more recent developments and to provide a firmer physical basis for the model by reducing the reliance on empirical ''fine tuning'' in the hope that the resultant model globally will be more reliable far off stability where no experimental data are available.

We studied theoretically the dependence of the calculated reaction rates on the optical α potential as well as the nuclear level density. Figure 4 compares experimental reaction rates calculated from our data using standard techniques [27] to the rates calculated with the NON-SMOKER code using three different optical $\alpha+$nucleus potentials in the calculation of the α transmission coefficients. One calculation was made using the standard NON-SMOKER settings with the potential of Ref. [29]. A second calculation was made with the equivalent square well potential as used in Ref. [19] and the third calculation employed the potential [15] used in the code MOST. As can be seen, differences of about a factor of 30 can be accounted for in the variation of the optical potential alone. The covered range includes the experimental reaction rate which can thus be described by an altered α potential. However, from the present data the $\alpha+$nucleus optical potential cannot be extracted without considering the uncertainties in the nuclear level density being used in the calculations. Also shown in Fig. 4 is the standard NON-SMOKER result in comparison to the results when using three other nuclear level densities within the same code. The range covered with the three different theoretical level density prescriptions is a factor of about 1.4, by far smaller than the one given by the variation of the α potential. However, we want to emphasize that this is not a systematic study of the sensitivity but merely presented to illuminate the source of the differences in the results from various statistical model calculations. To remove the uncertainty introduced by the level density predictions one can use experimental level density information where possible. The Reference Input Parameter Library (RIPL) [32] gives level density parameters derived from experiment for Fermi-gas models which can be directly utilized in statistical model calculations. The RIPL gives parameters for the relevant nuclei ^{148}Sm and ^{144}Nd [33]. Among these, the level density in the compound nucleus ^{148}Sm has the larger impact. The result obtained when using these experimentally determined Fermi-gas parameters is also shown in Fig. 4 where it can be seen that the uncertainty in the calculations due to the nuclear level density description is approximately a factor of 1.5. Although it is possible to obtain an α potential by fitting the current experimental data, such a potential probably would be of limited usefulness. For example, it has recently been shown [5] that a potential constructed to give good agreement with the experimental data for the ^{144}Sm(α,γ) reaction can be off by as much as a factor of 100 compared to the data for the ^{70}Ge(α,γ) reaction. More experimental data are needed across as wide a range of masses and energies as possible to constrain the several parameters thought to be needed to define a global α potential.

The proper treatment of the statistical model of nuclear reactions involving α particles poses a very important problem in nuclear astrophysics today. It is especially crucial for a better understanding of the nucleosynthesis occurring in stellar explosions such as supernovae and the origin of the p nuclides. We have demonstrated the feasibility of a new approach for reducing the main uncertainty in the calculation of rates for reactions involving α particles. It is evident that further experimental data of the type presented herein are needed to more fully explore this problem if the statistical model and the explosive nucleosynthesis calculations which in large part rely on them are to be improved.

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