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New measurement of the ^{3}He(α,γ)^{7}Be cross section at medium energies

M. Carmona-Gallardo,[1] B. S. Nara Singh,[2,*] M. J. G. Borge,[1] J. A. Briz,[1] M. Cubero,[1] B. R. Fulton,[2] H. Fynbo,[3] N. Gordillo,[4]
M. Hass,[5] G. Haquin,[6] A. Maira,[4] E. Nácher,[1] Y. Nir-El,[6] V. Kumar,[5] J. McGrath,[2] A. Muñoz-Martín,[4] A. Perea,[1] V. Pesudo,[1]
G. Ribeiro,[1] J. Sánchez del Rio,[1] O. Tengblad,[1] R. Yaniv,[6] and Z. Yungreis[6]
[1] *Instituto de Estructura de la Materia CSIC, Madrid, Spain*
[2] *Department of Physics, University of York, York, United Kingdom*
[3] *Department of Physics and Astronomy, Aarhus University, Aarhus, Denmark*
[4] *Centro de Microanálisis de Materiales de Madrid, UAM, Madrid, Spain*
[5] *Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel*
[6] *Soreq Research Centre, Yavne, Israel*
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We report on a new cross-section measurement for the ^{3}He(α, γ)^{7}Be reaction at three medium energies of $E_{\rm c.m.}$ between 1 and 3 MeV. The interest stems from the significant role played by the reaction in calculating an accurate solar neutrino flux and the primordial ^{7}Li abundance. The energy dependence of the astrophysical S_{34} factor observed in the present work, especially above 1 MeV, highlights the need to constrain theories in order to obtain a precise extrapolated value for $S_{34}(0)$. In this context, a comparison with the recent theoretical work in a fully microscopic fermionic molecular dynamics approach and a few other representative calculations emphasize the need for further experimental as well as theoretical work to resolve the existing conflicts.

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The cross section of the ^{3}He(α, γ)^{7}Be direct capture reaction was first studied by Holmgren *et al.* [1], being followed by *a posteriori* measurements of solar fusion reactions of ever-increasing sophistication and accuracy. These measurements are driven by the need to obtain more precise information that is crucial for a critical evaluation of solar models, solar neutrino fluxes, and big-bang nucleosynthesis (BBN) [2–4]. Specifically, the ^{3}He(α, γ)^{7}Be reaction plays a key role in calculating the high-energy solar neutrino flux that probes the temperature as well as the metallicity of the solar interior [3] and in explaining the primordial ^{7}Li abundances [4]. In recent years, the so-called ^{7}Li problem has attracted a considerable amount of attention as the disagreement between the observations and the predictions of the primordial ^{7}Li abundances became worse resulting in a persistent discrepancy of a factor of 3. This open problem poses severe challenges to the cosmological models that have been used for predicting the primordial abundances of nuclei [4–7]. In Ref. [5], a change of $\sim$16% was calculated in the central value of ^{7}Li abundance at BBN energies by utilizing the results from an evaluation of the available data on the astrophysical S_{34} factor. This work highlights the need for an accurate knowledge of this reaction rate for reliable predictions of the ^{7}Li abundance and therefore for any progress towards a solution.

There have been a number of efforts on both the experimental and the theoretical fronts that followed Ref. [1], in particular at low energies [8–13]. A "best" result of $S_{34}(0) = 0.56(3)$ keV b was reported in Ref. [3] from an evaluation of the modern data that became available after 1998 (Ref. [14]) for the energies below 1 MeV. This improved value can be compared with the previous recommendation [14] of 0.53 (5) keV b. Such efforts also suggested that the precision could be improved if the theoretical spread in the extrapolated values is minimized. In addition, recent work of the ERNA (European recoil mass separator for nuclear astrophysics) Collaboration [15] is in conflict with the data from Ref. [8] and highlights the importance of precise measurements at medium energies, without which the theoretical extrapolations would be less constrained (see below).

Around the time when the ERNA data were published, none of the available theoretical calculations could fit the available data over a large energy range between 100 keV and 2.5 MeV [16]. This situation has changed after the recent theoretical work based on a fully microscopic calculation using a realistic effective interaction [17]. Except for the data from Ref. [8], this new calculation is somewhat consistent with all the existing measurements including those from Ref. [15] up to 2.5 MeV. The previously available theoretical models seem not only to differ from this new work but also to disagree among themselves. In particular, inconsistencies are observed in the predicted energy dependence of the S_{34} factor in the range of $E_{\rm c.m.} = 2$ to 3 MeV [15,18]. Clearly, focused experimental and theoretical efforts are essential in order to obtain precise knowledge in this energy region.

In an attempt to confirm or dispute the newly obtained energy dependence of the S_{34} factor found in the recent experimental [15] and theoretical [17] works, we carried out measurements in the energy range of $E_{\rm c.m.} = 1$ to 3 MeV. The available data for the S_{34} factor were obtained by employing three different methods, namely, the direct counting of ^{7}Be nuclei, the online detection of the prompt γ rays resulting from the reaction, and the offline measurement of γ activity following the decay of the ^{7}Be nuclei. Here, we report results obtained using the last method in a low-background environment, which was chosen for its simplicity and minimal number of possible systematic errors [9]. The observed γ

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[*] snarasingh@gmail.com

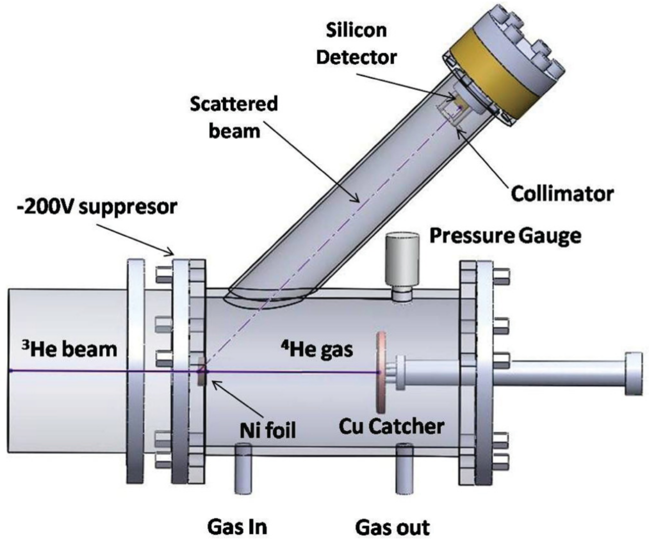

FIG. 1. (Color online) Schematic diagram of the setup used in the experiment. See text for more details.

radiation arises from the deexcitation of the 477.6 keV level in ^{7}Li, populated by the electron capture of ^{7}Be with a half-life of 53.35 (50) days [19] and a branching ratio of 10.44 (4)% [19,20].

The experiment was carried out at Centro de MicroAnálisis de Materiales (CMAM) in Madrid [21]. The center houses a 5 MV Cockcroft-Walton accelerator that delivered ^{3}He ions of different energies with precisions better than 5 keV to the target chamber shown in Fig. 1. Most of the components of our experimental setup are the same as those used in the work presented in Ref. [9]. The ^{3}He beam impinged onto the ^{4}He gas target after passing through a nickel (Ni) foil window that isolated the beamline from the target gas inside the chamber. In order to avoid localized heating, the beam was defocused over the Ni foil to cover an area of $\sim 3 \times 3$ mm^2 and the electrical currents were always lower than 300 nA.

The total number of beam particles (N_p) was determined by continuously measuring the beam current as described below and was cross-checked by detecting the scattered beam from the Ni foil of 1.03 (2) μm thickness that was determined using a triple α source and standard energy loss technique. The chamber, Ni foil, and the Cu catcher were in contact with each other, but were electrically isolated from the beamline. An electron suppressor biased to -200 V was placed upstream close to the Ni foil in order to stop electrons escaping from it due to the beam passage. Thus, the chamber acted as a Faraday cup and the current was integrated using a charge integrator, which generated a pulse for each 10^{-10} C. The scattered beam particles from the Ni foil were monitored using a silicon surface barrier detector with a collimator of 0.270 (3) mm radius at an angle of 44.9 (4)°. The latter two values were determined by utilizing a reference collimator [having a well-determined large radius of 2.000 (25) mm] together with an α source and scattering of ^{4}He beam from a ^{12}C foil at different energies, respectively. The beam intensity was estimated utilizing the scattered particle spectra, precise Ni foil thickness, and the calculations for the elastic scattering cross sections [22]. The number of beam particles obtained by using the Si spectra agrees within $\sim$2% with that obtained from the charge integration.

At low pressures ($\sim$50 Torr) the ^{4}He target can be treated as an ideal gas, thus the number of ^{4}He atoms per cm^2 in the chamber is given by $N_t = (9.66 \times 10^{18}) L \frac{P}{T_0+T_c}$, where L is the target length in cm, P is the gas pressure in Torr, and T_0 and T_C are the room temperature [295 (1) K] and the correction due to the the beam heating, respectively. The distance L between the Ni foil and a Cu catcher attached to a movable arm, as shown in Fig. 1, could be fixed by moving the arm to an appropriate position. A gas circulation system was used to monitor and maintain a constant pressure of the gas inside the chamber. Fluctuations in pressure were found to be less than 0.9 Torr and an upper limit of 0.1 Torr was evaluated for the error in the time averaged pressure. A low contamination of the target gas was estimated due to the air leaks under these conditions that would lead to only sub-keV uncertainties in $E_{\text{c.m}}$ yielding negligible error contributions. The values for T_C (between 8 to 24 K) used in the present work were estimated by assuming their linear dependence on the beam power P_b (see, for example, Ref. [23]) and using T_C (at $P_b \sim 1$ W)$\sim$17 K obtained in Ref. [9].

The ^{7}Be recoils were collected on a 50 mm Cu catcher with typically $\sim$20 mm spot size, which was subsequently placed at a distance of 20 mm from the high-purity (HP) Ge detector of the low-background detection station at Soreq Research Center, Yavne, Israel, for the measurement of the γ activity. This arrangement had a precise efficiency calibration required for our case of a broad ^{7}Be spatial distribution [9,19,24].

Figure 2 shows the γ-ray spectra corresponding to the ^{7}Be catchers prepared at energies of $E_{\text{c.m.}} = 1.054$ and 2.007 MeV (i.e., the beam energies of 2507 and 4010 keV, respectively). These spectra were collected during 241.1 and 168.0 h, respectively, to obtain optimal statistical uncertainty in the γ counting. For a comparison, Fig. 2 also shows in the upper part a spectrum corresponding to an empty shield (no Cu catcher) that was collected during 168.0 h in the week preceding the

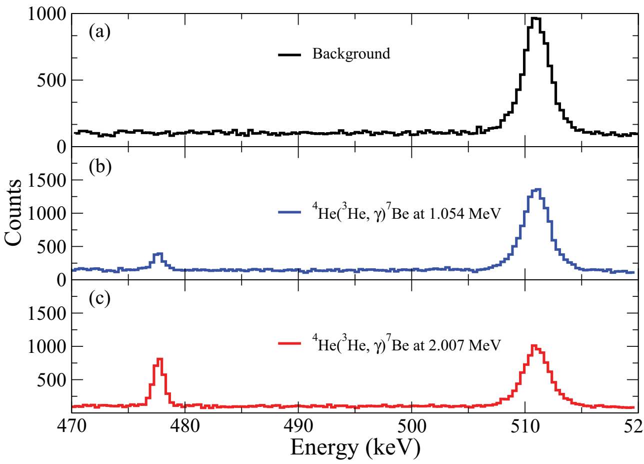

FIG. 2. (Color online) γ spectra from the ambient background (a) and from the Cu catchers prepared at $E_{\text{c.m.}} = 1.054$ (b) and 2.007 (c) MeV.

catchers campaign. This background spectrum does not show any peak around 478 keV. A similar result was obtained for a Cu catcher prepared with no target gas but with the ^{3}He beam at an energy around 4.0 MeV. Utilizing the efficiency of 4.4 ± 0.1% and the branching ratio as well as the half-life from Ref. [19], we deduce the number of ^{7}Be nuclei at the time when the implantation for the corresponding Cu catcher was stopped. The number of ^{7}Be nuclei obtained for the three different catchers prepared using beams of 2507, 4010, and 5312 keV energies are 2.26 (16) $\times 10^6$, 7.87 (28)$\times 10^6$, and 6.05 (30)$\times 10^6$, respectively. The cross sections σ were then obtained using $N_{^7\mathrm{Be}} = \sigma N_p N_t$, where $N_{^7\mathrm{Be}}$ and N_p are the numbers of ^{7}Be and beam nuclei, respectively.

The S factor in keV b for the reaction studied in this work can be given as $S(E) = E\sigma(E)\exp(2\pi\eta)$, where η is the Sommerfeld parameter given by $2\pi\eta = 164.12/E^{1/2}$, $\sigma(E)$ is the cross section in barns, and E is the center-of-mass energy in keV. The center-of-mass energy at the middle of the target is given by

$$E_{\mathrm{c.m.}} = \frac{4}{7}\left(E_b - \Delta E_b(\mathrm{Ni}) - \frac{\Delta E_b(^4\mathrm{He})}{2}\right), \qquad (1)$$

where E_b is the beam energy. ΔE_b(Ni) and ΔE_b(^{4}He) are the energies that were deposited by the incoming beam in the Ni foil and the gas target, respectively. These were accurately estimated from simulations using the TRIM package [25].

The energies of the beam from the accelerator were determined by using the ^{27}Al$(p,\gamma)^{28}$Si resonance at $E_p =$ 991.2 keV and an upper limit of 5 keV uncertainty was estimated based on the observed systematics in experiments carried out at CMAM using several different beams [21]. It is worth noting that for the medium energies used in our experiment the uncertainties associated with the energy loss and E_b are lower than those obtained at the lower reaction energies used in Ref. [9]. Correspondingly, the deduced S_{34} factors have lower error contributions from the uncertainty in $E_{\mathrm{c.m.}}$.

Table I shows the details of the three measurements carried out at beam energies of 2507, 4010, and 5312 keV corresponding to $E_{\mathrm{c.m.}} =$ 1.054, 2.007, and 2.804 MeV, respectively. The uncertainties in our measurements mainly stem from the γ counting (up to 7.3%), the energy (up to 0.2%), N_p from charge integration (∼2.0%), and N_t (∼0.8%). The latter is composed of estimated errors from variations in pressure (up to 0.2%), temperature (up to 0.8%) and length (∼0.2%) of the target. The errors in N_p (∼5%) estimated from beam monitoring have contributions from the angle (∼3.5%) and the solid angle (∼2.5%) of the silicon detector as well as the Ni foil thickness (∼2%). We estimate an upper limit of ∼2% error contribution from the N_p obtained using the charge integration method by a cross-check with the results obtained using scattered particle spectra.

TABLE I. Details of measurements that were carried out at different values of $E_{\mathrm{c.m.}}$ with similar target gas pressure P and length L. σ^{IC} and σ^{RS} are the cross sections obtained using the number of beam particles (N_p) deduced using the integrated charge on the chamber and the silicon spectra, respectively. S_{34} is the astrophysical S factor based on σ^{IC}. The errors from the γ counting statistics and the systematic uncertainties are given separately.

$E_{\mathrm{c.m.}}$ (keV)	P (Torr)	L (cm)	σ^{IC} (μb)	σ^{RS} (μb)	S_{34} (keV b)
1054	60.16	11.64	2.05(14)(7)	2.14(15)(11)	0.34(2)(1)
2007	60.18	13.11	4.70(12)(13)	4.59(12)(24)	0.37(1)(1)
2804	56.68	13.29	6.82(29)(18)	6.68(29)(35)	0.42(2)(1)

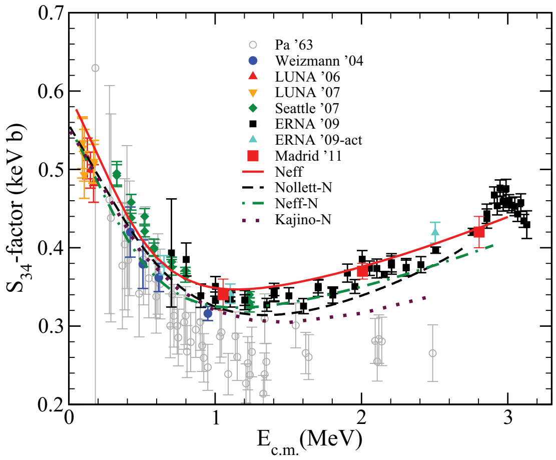

FIG. 3. (Color online) S_{34} factor from the present work (Madrid '11) is shown along with the existing modern data. The latter are taken from Ref. [9] (Weizmann '04), [10,11] (LUNA '06, LUNA '07), [12] (Seattle '07), and [15] (ERNA '09/'09-act). A resonance structure can be noted in the data around $E_{\mathrm{c.m.}} =$ 3 MeV, which was first observed in Ref. [15]. This corresponds to a $7/2^-$ state residing at an excitation energy of 4570 keV in ^{7}Be. Old measurements (Pa '63) from Parker *et al.* [8] at medium energies do not agree with Madrid '11 and ERNA '09/'09-act. New calculations from Ref. [17] are also shown without (Neff) and with (Neff-N) normalization together with the normalized representative calculations from Ref. [26] (Nollett-N) and [27](Kajino-N). Striking differences in the shapes of theoretical curves and discrepancies with the data can be seen.

Figure 3 gives a compilation of data from Ref. [8] (Pa '63) and [9] (Weizmann '04) and the measurements that followed it together with our new data (Madrid '11). Prior to our work, only two sets of data from Ref. [8] (Pa '63) and [15] (ERNA '09) included measurements above 1 MeV, which differ in the energy dependence of the S_{34} factor. The latter work also provides two measurements above 1 MeV (ERNA '09-act) that were carried out using the activity method in the proximity of our data points (Madrid '11). It can be seen that our new work, using a completely different setup and experimental conditions, presents an accurate measurement around 2 MeV that is in a clear agreement with ERNA '09/'09-act [15]. We calculated $\chi^2 = 0.5$, using three S_{34} data points from the present work and Ref. [15] around the three different energies given in Table I. This could be used to gauge the agreement between our results and the ERNA work. A similar analysis of our data exhibits a conflict with the work from Ref. [8] and results in $\chi^2 = 21.5$. It should be noted that an extrapolation of data from Ref. [8] was used to deduce the point around 2.8 MeV and an interpolation was sufficient for all the other data points.

A few theoretical calculations from Ref. [17,26,27] are also shown in Fig. 3, which fairly represent the current standpoint with the predictions. Recent work in a fully microscopic approach, "Neff", uses a realistic effective interaction and reproduces the nucleon-nucleon scattering data [17]. Therefore, any adjustment of theoretical parameters including the absolute scale of the $S_{34}(E)$ curve is not required and this approach yields $S_{34}(0) = 0.593$ keV b. For the purpose of a visual comparison of their shapes, the absolute scales of the theoretical $S_{34}(E)$ curves "Neff-N" [17], "Nollett-N" [26], and "Kajino-N" [27] are normalized so as to give $S_{34}(0) = 0.553$ keV b, which was taken from Ref. [15]. As can be seen, these representative approaches exhibit significant differences in the energy dependence of the S_{34} factor, especially above 1 MeV. Further investigations will be required to gain an understanding of the underlying basic physics and the assumptions of the theoretical models and to address the inconsistencies.

The measurements from Ref. [9] and the current work around 1 MeV are of particularly significant importance. Both works use the same activation and counting setup. An agreement between these points strongly supports the reliability of the new set of measurements around 2 and 3 MeV. Clearly, none of the representative approaches including that of Neff explain them in a completely consistent manner. An analysis of the present data combined with those from Ref. [9] (i.e., seven data points) and the calculated values from the Neff curve gives $\chi^2 \sim 18$ (of which ∼14 comes from the data point at 950 keV).

We would like to stress that the present situation is far from being settled for both the experimental data and the theoretical calculations. For example, different sets of data around 1 MeV shown in Fig. 3 *agree* with each other within the experimental uncertainties. On the other hand, the precise data at 950 keV from Weizmann '04 [9] *do not agree* with the Neff calculations [17] and deviate by $\sim 4\sigma$. Furthermore, the Neff calculations should be treated with caution because they can only explain the energy dependence, but not the absolute scale observed for the $S(E)$ data for the $^3\mathrm{H}(\alpha,\gamma)^7\mathrm{Li}$ reaction. This is in contrast with the results from Ref. [26], where an agreement is seen for this reaction while conflicts between data and calculations related to the absolute scale of the $S_{34}(E)$ curve exist. We also note that the experimental work on this reaction was carried out almost two decades ago [28] and more accurate measurements in the future may change the current interpretation.

In summary, we have obtained new data on the S_{34} factor in the medium energy range using the activation method. Prior to the work presented in Refs. [15,17], the dependence at high energy of the S_{34} factor was not carefully considered. Our data in the $E_{\mathrm{c.m.}} = 1$ to 3 MeV range obtained by using a well-established setup agree well with that from the recent work of ERNA [15] and disagree with the old data from Ref. [8]. Consequently, a factor of 3 discrepancy remains between the observed and the calculated ^{7}Li abundances. A reduction in the error contribution from S_{34} to solar neutrino flux calculations can also be expected in the future. In addition, a consistent picture for the data above 1 MeV has emerged due to the agreement between the present and ERNA data, which is a significant step forward, and based on this we *strongly recommend* future work in the medium energy range. This is in contrast with the experimental efforts concentrating on measurements at low energies approaching solar or BBN energies. In order to reduce the systematic uncertainties in S_{34}, it would be most desirable to obtain a data set that consistently covers the full energy range under consideration, using complementary techniques. Such efforts would not only provide a precise reaction rate relevant to the BBN but also result in a model-independent shape of the $S_{34}(E)$ curve, yielding an accurate data-based extrapolation to solar energies. In addition, angular distributions of the prompt γ rays from the fusion reaction are needed, especially at the higher energy range, in order to obtain the contribution of s- and d-wave components to the reaction cross section and to better constrain the theoretical models [13]. This should help reducing the theoretical spread in the extrapolated $S_{34}(0)$ values.

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