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Stellar and primordial nucleosynthesis of ^{7}Be: measurement of ^{3}He$(\alpha,\gamma)^7$Be

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(Dated: November 24, 2008)

The ^{3}He$(\alpha,\gamma)^7$Be reaction presently represents the largest nuclear uncertainty in the prediction of the flux of solar neutrinos and has important implications on the Big Bang nucleosynthesis, i.e. the production of primordial ^{7}Li. Recently several precise measurements have been reported, whereby the different determinations of the reaction cross section at the astrophysical relevant energies exhibit significant discrepancies. We present here the results of an experiment using the recoil separator ERNA (European Recoil separator for Nuclear Astrophysics) to detect for the first time directly the ^{7}Be ejectiles. This approach is completely independent from previous techniques leading to substantially different systematic dependencies and, thus, independent information. In addition, off-beam activation and coincidence γ-ray measurements were performed at selected energies.

At energies above 1 MeV a large discrepancy compared to previous results is observed in the absolute value and the energy dependence of the cross section is not reproduced by direct capture models. Based on the available data and models, a more robust estimate of the cross section at the astrophysical relevant energies is proposed.

PACS numbers: 24.50.+g, 25.55.-e, 26.20.Cd, 26.35.+c, 26.65.+t

The ^{3}He$(\alpha,\gamma)^7$Be reaction is presently the largest nuclear uncertainty in the prediction of the solar neutrino flux and was considered as a possible key to solve the solar neutrino puzzle. The successful experiments of SNO [1] and Kamland [2] proofed the existence of neutrino oscillations and gave an explanation of the observed solar neutrino deficit in earth neutrino detectors. The data opened a new era of neutrino spectroscopy, in which the solar neutrino fluxes serve as a probe for details of the standard model of particle physics. In addition, the precise knowledge of the different neutrino fluxes can be used to understand physical and chemical properties of the sun, provided that nuclear reaction cross sections are known with adequate accuracy. It appears possible to exploit neutrinos from the CNO-cycle and the pp-chain to determine the primordial solar core abundances of C and N [3], if the uncertainties in nuclear cross sections, neutrino observations and neutrino oscillation parameters will be significantly reduced. In the case of the cross section σ(E) of ^{3}He$(\alpha,\gamma)^7$Be, that determines the flux of the recently detected ^{7}Be neutrinos [4], a precision of 3% or better should be achieved [3, 5].

The ^{3}He$(\alpha,\gamma)^7$Be reaction has also important implications on the Big Bang nucleosynthesis (BBN). A detailed comparison of the abundances of the primordial elements (D, ^{3}He, ^{4}He, ^{7}Li) predicted by the cosmological models based on the results of the Wilkinson Microwave Anisotropy Probe (WMAP) [6] with astronomical observations demonstrate a good agreement for the D and ^{4}He abundances. However, the predicted abundance of ^{7}Li is a factor 2 to 3 larger than observation, see e.g. [7, 8]. According to Standard Model BBN, the ^{7}Li nuclei synthesized during the BBN were instantly destroyed due to the large cross section of ^{7}Li$(p,\alpha)\alpha$. The half-life of the electron capture of ^{7}Be produced by ^{3}He$(\alpha,\gamma)^7$Be is long enough that ^{7}Be survived until the proton density and energy is low enough to freeze out the ^{7}Li abundance. Therefore an accurate evaluation of σ(E) is the necessary basis for possible solutions of the ^{7}Li problem.

During the last decades many efforts have been devoted to the determination of σ(E) at the relevant energies for Big Bang nucleosynthesis and stellar core hydrogen burning. All experiments exploited either the detection of the prompt γ-rays [9–13] or the off-beam determination of the ^{7}Be atoms collected in the target [14–18], while in a few cases both techniques were used [19–21]. These experiments covered the energy range of BBN (E $\approx$ 180 to 400 keV [1]), while the Gamow energy ($E_0 = 22$ keV)

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[1] Energies are in the center-of-mass system

in the Sun was not reached and models have to be used to extrapolate the data. The results show an overall fair agreement in the energy dependence of $\sigma(\mathrm{E})$, while they disagree in their absolute values. Non-radiative transitions have been suggested as a possible source of the observed discrepancy [22]. Recent measurements provided no evidence for such transitions [16, 20, 21], confirming theoretical expectations [23]. However, a global analysis of their results [24] shows that discrepancies are still present. Finally, one should note that at energies above 1 MeV there exists essentially only one data set [9]. Consequently, these data have a large influence on the determination of $\sigma(\mathrm{E}_0)$, since they provide a strong test of the adopted model and, thus, determine the energy dependence in the extrapolation. Therefore, new data are needed aiming at a precise and accurate determination of $\sigma(\mathrm{E})$ at energies up to at least E = 2 MeV.

We present the results of a new approach, where $\sigma(\mathrm{E})$ of $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ was determined by the direct detection of the ^{7}Be recoils using the recoil separator ERNA at the Dynamitron Tandem Laboratorium of the Ruhr-Universität Bochum, Germany. Concurrently, the capture γ-rays were detected in coincidence with the recoils at selected energies, thus allowing a direct comparison of σ with the cross section for γ-ray emission, σ_γ. The details of the experimental setup and procedures are reported in [25] and references therein. Briefly, a ^{4}He ion beam emerging from the tandem was focused by a quadrupole doublet, filtered by a 52° analyzing magnet, and guided into the 75° beam line of ERNA by a switching magnet. A quadrupole doublet after the switching magnet was used to focus the beam onto a ^{3}He recirculating windowless gas target. One Wien filter before the analyzing magnet and another before the gas target provided the necessary ion beam purification from recoil-like contaminants. The number of projectiles impinging on the target was determined from the elastic scattering yield observed in two collimated silicon detectors located on both sides of the target chamber at 75° with respect to the beam axis. A γ-ray detection setup (3 NaI detectors) was installed at the gas target. After the gas target, the separator consisted sequentially of the following elements: a quadrupole triplet, a Wien filter, a quadrupole singlet, a 60° dipole magnet, a quadrupole doublet, a Wien filter, and a detector for the recoils. Different end detectors were used depending on the recoil ion energy. Finally, several steerers, Faraday cups, and slit systems were installed along the beam line for diagnostic purposes. In the energy range of the experiment, the recoil yield for each significant charge state q was measured in separate runs. Thus, $\sigma(\mathrm{E_{eff}})$ at the effective interaction energy $\mathrm{E_{eff}}$ is given by the relation:

$$\sigma(\mathrm{E_{eff}}) = \sum_{\mathrm{q}} \frac{\mathrm{N}_{^7\mathrm{Be,q}}}{\mathrm{N}_{^4\mathrm{He,q}} \cdot \mathrm{T(q)}} \cdot \frac{1}{\mathrm{N}_{^3\mathrm{He}}\epsilon_{^7\mathrm{Be}}} \quad (1)$$

where $\mathrm{N}_{^4\mathrm{He,q}}$, $\mathrm{N}_{^7\mathrm{Be,q}}$, and T(q) are the number of projectiles impinging on the target, the number of recoils collected in the end detector and the transmission of the recoils from the target to the final detector for a selected charge state q, respectively. The transmission $\mathrm{T(q)} \equiv \mathrm{T}$ turned out to be sufficient for the full acceptance of the recoils independent of their charge state [25]. Finally, $\mathrm{N}_{^3\mathrm{He}}$ represents the target number density and $\epsilon_{^7\mathrm{Be}}$ is the detection efficiency of the final detector. The determination of σ is affected by a systematic uncertainty of 5%, due to the uncertainties on the determination of T (1.0% at E ≥1 MeV, 2.0% at E <1 MeV), $\mathrm{N}_{^3\mathrm{He}}$ (4%), $\epsilon_{^7\mathrm{Be}}$ (0.6% at E ≥1 MeV, 1.7% at E <1 MeV), and $\mathrm{N}_{^4\mathrm{He}}$ (1%). For the ratio of σ_γ to σ, the following expression holds:

$$\frac{\sigma_\gamma(\mathrm{E_{eff}})}{\sigma(\mathrm{E_{eff}})} = \frac{\sum_{\mathrm{q}} \mathrm{N}_{\gamma,\mathrm{q}}/\mathrm{N}_{^4\mathrm{He,q}}}{\sum_{\mathrm{q}} \mathrm{N}_{^7\mathrm{Be,q}}/\mathrm{N}_{^4\mathrm{He,q}}} \cdot \frac{\mathrm{N}_{^3\mathrm{He}}}{\int \mathrm{N}_{^3\mathrm{He}}(\mathrm{z})\epsilon_\gamma(\mathrm{z})\mathrm{dz}} \quad (2)$$

where $\mathrm{N}_{\gamma,\mathrm{q}}$ is the number of γ-rays detected in coincidence with $\mathrm{N}_{^7\mathrm{Be,q}}$ recoils for the selected charge state q, while $\epsilon_\gamma(\mathrm{z})$ and $\mathrm{N}_{^3\mathrm{He}}(\mathrm{z})$ represent the γ-ray detection efficiency and the target number density as a function of the reaction coordinate z along the target, respectively. The effective interaction energy is given by $\mathrm{E_{eff}} = \mathrm{E_{in}} - \Delta\mathrm{E}/2$, where $\mathrm{E_{in}}$ is the energy corresponding to the beam energy, because, due to the small target thickness ($\mathrm{N}_{^3\mathrm{He}} = (2.00 \pm 0.08) \cdot 10^{17}\mathrm{atoms/cm^2}$), the total energy loss is small (i.e. $\Delta\mathrm{E} < 2$ keV) and the cross section can be assumed constant over the target thickness. The ratio σ_γ/σ is affected by a 5% systematic uncertainty, dominated by the γ-ray detection efficiency [25], and can be used to determine σ_γ once σ is known. Hence, the two determinations are not statistically independent and should not be used simultaneously in a fit to the data.

In addition, off-beam measurements were performed to obtain cross section values independent of the recoil separator. The details of that experiment will be given elsewhere [26]. Shortly, a copper catcher was installed at a distance of 31 cm from the gas target center to collect the produced ^{7}Be nuclei. The activity of the ^{7}Be nuclei was determined with the same setup as in [17] in the Low-Level Laboratory of the Laboratori Nazionali del Gran Sasso, Italy. Possible contributions of contaminant reactions to the observed ^{7}Be yield were investigated in background runs using ^{4}He instead of ^{3}He as target gas. The normalization error of the activation is 5%, due to the uncertainty in the efficiency calibration of the HPGe detector (1.8%) [17], the gas target thickness (4%), and the beam current integration (1%). In all three approaches, statistical errors are determined by the counting statistics and the current normalization (typically 1%).

The total cross section was measured in the energy range E = 700 − 3200 keV, while γ-ray coincidence measurements were performed at 6 energies between E = 1100 and 3000 keV. Sample identification matrices and gamma-ray spectra are shown in [25]. The results are plotted in the form of the astrophysical S-factor ($\mathrm{S(E)} = \mathrm{E}\cdot\sigma(\mathrm{E})\cdot\exp(31.29\cdot 4\sqrt{1.720/\mathrm{E}})$, E in keV) in Fig.1 and compared with the results of previous work in the overlapping energy range. In regard to the determination of σ_γ, the influence of different γ-ray angular distributions proposed for this reaction, i.e. as in [27] and isotropy, was studied with a GEANT4 simulation of the detection setup. Differences were found to be negligible and, therefore, an isotropic angular distribution was adopted. This distribution describes fairly well the observed relative yields in the different detectors at energies lower than E = 2500 keV, while at higher energies significant deviations were observed. Since the angular information provided by our γ-ray detector setup is insufficient to fix the parameters of the angular distributions, these data points were excluded from the analysis. It is worth noting that the resonance corresponding to the $\mathrm{J}^\pi = 7/2^-, \mathrm{E_x} = 4570\,\mathrm{keV}$ state in ^{7}Be was observed for the first time in this reaction. The experimental resonance strength is $\omega\gamma = 0.33 \pm 0.21\,\mathrm{eV}$, corresponding to $\mathrm{B(E2)} = 52 \pm 31\,e^2\mathrm{fm}^4$; a shell-model estimate including core polarization effects gives $\mathrm{B(E2)} = 12\,e^2\mathrm{fm}^4$ [28].

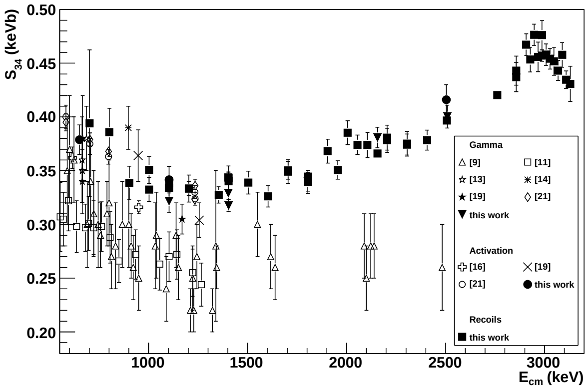

FIG. 1: Results of the cross section measurements of the present work. The data are plotted in the form of astrophysical S-factor as a function of the center-of-mass effective interaction energy. The results of previous work in the same energy range are also shown.

Finally, the results of the activation at E = 630, 1103 and 2504 keV are also shown. In conclusion, all three methods agree within their statistical uncertainties and confirm that there is no evidence of non-radiative transitions ($\sigma_\gamma/\sigma = 0.97 \pm 0.05$). Table I summarises the numerical values of the results, including the experimental intensity ratios $\mathrm{R}=\sigma_{429}/\sigma_{\mathrm{gs}}$, that are plotted in Fig.2 and compared with previous results.

TABLE I: Numerical values of the measurements performed in the present work.

Recoils

E_{eff} (keV)	σ (μb)
701	1.14±0.20
802	1.46±0.08
902	1.59±0.07
1002	1.96±0.07
1002	1.86±0.06
1102	2.16±0.02^a
1102	2.19±0.04
1103	2.16±0.06
1203	2.44±0.05
1203	2.44±0.09
1353	2.79±0.07
1403	3.06±0.04^a
1403	3.03±0.08^a
1403	3.06±0.10
1504	3.27±0.10
1604	3.37±0.10
1704	3.84±0.12
1704	3.86±0.09
1804	4.01±0.04^a
1804	3.95±0.12
1904	4.49±0.14
1955	4.38±0.11
2005	4.92±0.14
2055	4.87±0.12

Recoils (continued)

E_{eff} (keV)	σ (μb)
2105	4.96±0.16
2156	4.95±0.05^a
2205	5.24±0.16
2205	5.20±0.16
2305	5.32±0.14
2306	5.33±0.16
2406	5.54±0.14
2507	5.97±0.06^a
2762	6.70±0.07
2857	7.2±0.4
2857	7.1±0.4
2908	7.7±0.3
2928	7.5±0.4
2947	7.9±0.3
2968	7.6±0.5
2987	7.59±0.09
2988	7.9±0.5
3008	7.6±0.3
3028	7.6±0.3
3048	7.6±0.4
3068	7.5±0.3
3089	7.7±0.4
3110	7.4±0.3
3130	7.3±0.6

Activation

E_{eff} (keV)	σ (μb)
650	0.95±0.11
1103	2.23±0.10
2504	6.0±0.4

Gamma

E_{eff} (keV)	σ_γ (μb)
1102	2.08±0.07
1403	2.93±0.08
1403	2.83±0.05
1804	3.95±0.10
2156	5.15±0.13
2507	6.02±0.16

Intensity ratio

E_{eff} (keV)	R
1102	0.42±0.03
1403	0.403±0.018
1403	0.413±0.012
1804	0.408±0.017
2156	0.367±0.015
2507	0.390±0.017

^{a}Measurements where coincidence γ-rays were detected.

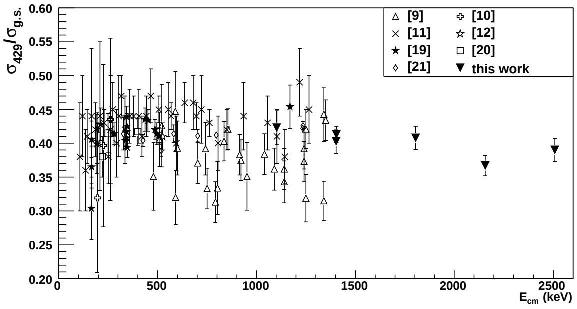

FIG. 2: Ratio of the cascade-to-ground state transition intensities measured in this work as a function of the center-of-mass energy, compared to previous measurements.

In the comparison with previous works, there is a significant discrepancy of both the absolute scale and the energy dependence of the S-factor from previous results [9] in the energy range E > 1000 keV. It is worth noting that the intensity ratio in [9], as shown in Fig. 2, deviates significantly from all other determinations, including the present data. The origin of this discrepancy is difficult to identify, but might influence the determination of the cross section. At E ≤1000 keV, there is an excellent agreement with the determination of [19] and the recent determinations of [20]. In regard to [16], the agreement is only within 2σ. Even larger is the discrepancy with [11]: one should note, however, that those data needed a renormalization [13], and, thus, they do not provide independent information on the absolute scale. The comparison with the remaining data sets is more complex, since it must be done through model calculations. In Fig. 3 the results of different calculations are reported, compared to the results of the present work and [16–18, 20, 21] at E ≤2000 keV. This selection considers the more recent experiments, where higher accuracy and precision of the data is claimed. In all cases where the same experiment produced correlated data at a given energy, only the more precise value was considered. Direct capture model does not provide a good description

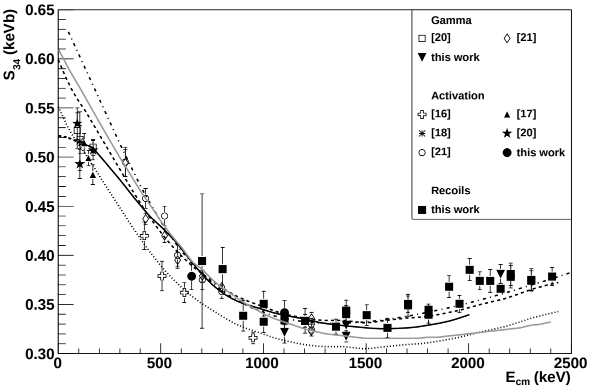

FIG. 3: Comparison of the results of the data of the present experiment and recent work with different model calculations [29–32] normalized to different data sets at E ≤2000 keV, see text for details. (All data: solid black [29], solid grey [30]. Data of the present work and [20]: dashed [31], dash-dotted [32]. Data of [16–18, 21]: dotted [31]).

of the observed energy dependence of the S-factor above 1 MeV, where it is supposed to be still accurate, e.g. see [30]. A better result is obtained using microscopic models, e.g. [29, 31–33]. The fit to the different data sets was obtained by rescaling the results of the calculations by a constant factor k at E ≤2000 keV. This procedure is somewhat questionable for microscopic models, but the possible inaccuracy resulting from the scaling stays small when $k \approx 1$. The calculations of [31] and [32] provide a poor fit, when all data are considered (Q = 173.8 for [31],Q = 366.8 for [32], $\nu = 46$, where Q is the least square function and ν is the number of degrees of freedom). This is due to the fact that [16] and [17, 18, 21] are essentially not compatible, within the models of [31] and [32], with our data and the data of [20]. A fit performed on the two subsets of data separately gives $S_{34} = 0.62 \pm 0.03\,\text{keV} \cdot \text{b}$ for [20] and present work ($k = 1.18$, Q = 54.0 for [31], $k = 0.93$, Q = 34.1 for [32], $\nu = 36$), and $S_{34} = 0.55 \pm 0.02\,\text{keV} \cdot \text{b}$ for [16–18, 21] ($k = 1.08$, Q = 9.5 for [31], $k = 1.08$, Q = 17.8 for [32], $\nu = 11$). The quoted uncertainties include both the statistical error, that was evaluated following the Monte Carlo procedure described in [34], and the uncertainty due to the two models. The model of [29] gives a somewhat better description of all data. Here an estimate $S_{34} = 0.52 \pm 0.02\,\text{keV} \cdot \text{b}$ is obtained ($k = 1.03$, Q = 158, $\nu = 46$). The same result is obtained using [33] ($k = 0.86$, Q = 126, $\nu = 46$).

In conclusion, until new experimental or theoretical information will be available to assess which is the correct determination, a conservative estimate of $S_{34} = 0.57 \pm 0.07\,\text{keV} \cdot \text{b}$ is suggested. This estimate represents an improvement with respect to the recommendation of [35], but it is still far from the precision required by solar models. As regards BBN, a value $^7\text{Li/H} = (5.4 \pm 0.6) \cdot 10^{-10}$ is found using the BBN code of [36] with the WMAP determination for the baryon fraction, $\Omega_b h^2 = 0.02273 \pm 0.00062$. The quoted uncertainty on ^{7}Li/H takes into account all relevant nuclear processes involved in ^{7}Li and ^{7}Be production/destruction, including the effect of the different models mentioned above. This theoretical determination is larger than the obsevational value by a factor 3 or more, see e.g. [8], thus worsening the primordial ^{7}Li problem.

The authors thank the LUNA collaboration and LNGS for their support of the activation measurements.

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