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Precision study of ground state capture in the ^{14}N$(p,\gamma)^{15}$O reaction

M. Marta,[1] A. Formicola,[2] Gy. Gyürky,[3] D. Bemmerer,[1] C. Broggini,[4] A. Caciolli,[4,5] P. Corvisiero,[6] H. Costantini,[6] Z. Elekes,[3]
Zs. Fülöp,[3] G. Gervino,[7] A. Guglielmetti,[8] C. Gustavino,[2] G. Imbriani,[9] M. Junker,[2] R. Kunz,[10] A. Lemut,[6] B. Limata,[9]
C. Mazzocchi,[8] R. Menegazzo,[4] P. Prati,[6] V. Roca,[9] C. Rolfs,[10] M. Romano,[9] C. Rossi Alvarez,[4] E. Somorjai,[3] O. Straniero,[11]
F. Strieder,[10] F. Terrasi,[12] H. P. Trautvetter,[10] and A. Vomiero[13]
(LUNA Collaboration)
[1]*Forschungszentrum Dresden-Rossendorf, Dresden, Germany*
[2]*Istituto Nazionale di Fisica Nucleare (INFN), Laboratori Nazionali del Gran Sasso, Assergi, Italy*
[3]*Institute of Nuclear Research (ATOMKI), Debrecen, Hungary*
[4]*INFN Sezione di Padova, Padova, Italy*
[5]*Dipartimento di Fisica, Università di Padova, Padova, Italy*
[6]*Università di Genova and INFN Sezione di Genova, Genova, Italy*
[7]*Dipartimento di Fisica Sperimentale, Università di Torino, and INFN Sezione di Torino, Torino, Italy*
[8]*Istituto di Fisica Generale Applicata, Università di Milano, and INFN Sezione di Milano, Milano, Italy*
[9]*Dipartimento di Scienze Fisiche, Università di Napoli Federico II, and INFN Sezione di Napoli, Napoli, Italy*
[10]*Institut für Experimentalphysik III, Ruhr-Universität Bochum, Bochum, Germany*
[11]*Osservatorio Astronomico di Collurania, Teramo, and INFN Sezione di Napoli, Napoli, Italy*
[12]*Seconda Università di Napoli, Caserta, and INFN Sezione di Napoli, Napoli, Italy*
[13]*INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy*

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The rate of the hydrogen-burning carbon-nitrogen-oxygen (CNO) cycle is controlled by the slowest process, ^{14}N(p,γ)^{15}O, which proceeds by capture to the ground and several excited states in ^{15}O. Previous extrapolations for the ground state contribution disagreed by a factor 2, corresponding to 15% uncertainty in the total astrophysical S factor. At the Laboratory for Underground Nuclear Astrophysics (LUNA) 400 kV accelerator placed deep underground in the Gran Sasso facility in Italy, a new experiment on ground state capture has been carried out at 317.8, 334.4, and 353.3 keV center-of-mass energy. Systematic corrections have been reduced considerably with respect to previous studies by using a Clover detector and by adopting a relative analysis. The previous discrepancy has been resolved, and ground state capture no longer dominates the uncertainty of the total S factor.

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Recent data on the abundance of the elements carbon, nitrogen, and oxygen (CNO) in the solar atmosphere [1] lead to a contradiction between solar model predictions and measurements for several helioseismological quantities [2]. In the present precision era, this puzzle represents the foremost problem of the standard solar model [2] since the resolution of the solar neutrino puzzle [3]. To address this point, it has been suggested to determine the CNO abundances in the solar center from neutrino data [4]. Neutrinos emitted in solar CNO cycle burning are expected to lead to about 1000 events/year both in the Borexino detector [5] and in the proposed SNO + detector [6]. A correct interpretation of this expected data, based on the known solar core temperature and known neutrino properties [4], requires the rate of the CNO cycle to be known with systematical uncertainty matching these statistics.

The rate of the CNO cycle is controlled [7] by the ^{14}N$(p,\gamma)^{15}$O reaction. Its cross section $\sigma(E)$, parameterized[1] as the astrophysical S factor

$$S(E) = \sigma E \exp[212.4/\sqrt{E}], \tag{1}$$

has been extensively studied in the past (Ref. [8] and references therein). Recently, it has been shown that capture to the ground state in ^{15}O (Fig. 1), previously [8] believed to account for half of the$S$ factor[2] extrapolated to zero energy $S_{\text{tot}}(0)$, is strongly suppressed [9–15]. This finding is independently supported by a reduction in the γ width of the subthreshold state at 6792 keV in ^{15}O seen in Doppler shift attenuation [9] and Coulomb excitation [12] works, and by fits [10,11,13–15] in the R-matrix framework (Table I). The resulting 50% reduction in the total cross section has subsequently been directly observed at an energy as low as $E \approx 70$ keV [16].

For the Gamow peak of the Sun ($E \approx 27$ keV), however, extrapolations remain indispensable. For the dominant contribution to $S_{\text{tot}}(0)$, i.e., capture to the state at 6792 keV, recent experimental data and R-matrix fits are consistent [14,15]. For capture to the ground state, recent experimental data ($E \approx 120$–480 keV) from LUNA [13,15] and TUNL [14] are consistent with each other, and they both rule out a previous R-matrix fit [11]. However, the extrapolated $S_{\text{GS}}(0)$ values [13,14] disagree significantly (Table I). This

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[1] E_p denotes the beam energy in the laboratory system, and E the effective energy in the center of mass system in keV.

[2] $S_i(0)$ denotes the S factor, extrapolated to zero energy, for capture to the state at i keV in ^{15}O. $S_{\text{GS}}(0)$ and $S_{\text{tot}}(0)$ refer to ground state capture and to the total S factor, respectively.

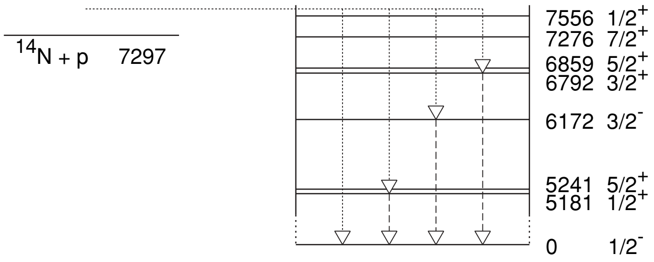

FIG. 1. Energy levels of ^{15}O, in keV [15,21].

discrepancy has 15% impact on $S_{\rm tot}(0)$, limiting its precision. In addition to differently treating previous data [8] in the fit, Refs. [13,14] employed large germanium detectors in close geometry, enhancing the detection efficiency but incurring true coincidence summing-in corrections of 100–250% for the ground state data, which, in turn, lead to considerable systematic uncertainty.

The aim of the present work is to address the conflicting extrapolations [13,14] with a precision cross section measurement. To minimize the uncertainties, the analysis is limited to the ratio of the cross sections for capture to the ground state and to the 6792 keV state. An energy range above the 259 keV resonance, where the fits for ground state capture pass through a sensitive minimum [10], has been selected [17]. A second sensitive energy region lies below the 259 keV resonance. Because the cross section is a factor 100 lower there, the latter energies were not probed in the present work. The experiment was performed at the Laboratory for Underground Nuclear Astrophysics (LUNA) at the Gran Sasso National Laboratory (Italy), which has an ultra-low γ-ray laboratory background [18]. A Clover detector was used, reducing the summing-in correction by a factor of 30 (Table II).

The H$^+$ beam of $E_p = 359$, 380, and 399 keV and 0.25–0.45 mA intensity from the LUNA2 400 kV accelerator [19] impinged on a sputtered TiN target, with 55 keV thickness measured on the $E = 259$ keV resonance. The γ rays from the reaction to be studied were detected in a Eurisys Clover-BGO detection system [20]. The front end of the Clover crystals was positioned at 9.5 cm distance from the target, at an angle of 55° with respect to the beam axis. The output signal from each of the four Clover segments was split into two branches; of these branches, one branch was recorded separately, and the four spectra were summed in the offline analysis (singles mode). The second branches of the four signals were added online in an analog summing unit (addback mode). For experiments off the 259 keV resonance, the addback mode data were recorded in anticoincidence with the BGO anti-Compton shield.

The γ-ray detection efficiency was obtained using ^{137}Cs and ^{60}Co radioactive sources calibrated to 1.5 and 0.75%, respectively. The efficiency curve was extended to high energy based on spectra recorded at the 259 keV resonance, using the known 1:1 γ-ray cascades for the excited states at 6172 and 6792 keV. The γ rays from the decay of this 1/2$^+$ resonance are isotropic, and their angular correlations are well known [22]. The calculated summing-out correction in addback mode is 2.9%, with an assumed relative uncertainty of 20%, consistent with a GEANT4 [23] simulation showing $(4.5 \pm 1.8)\%$ correction. As a check on the quality of the efficiency curve, the experimental cascade ratio for the 5181 keV excited state (not used in the fit) was found to be reproduced within 1% statistics.

The branching ratio for decay of the 259 keV resonance to the ground state was found to be $(1.56 \pm 0.08)\%$ in addback mode and $(1.53 \pm 0.06)\%$ in singles mode, taking into account (42 ± 2) and $(7.4 \pm 0.3)\%$ summing-in corrections, respectively. This confirms that the summing-in correction for the addback mode is accurate. Furthermore, the GEANT4 simulation showed (40.2 ± 1.4) and $(7.8 \pm 0.9)\%$ summing-in correction for addback and singles, respectively, in good agreement with the above data. The branching ratio is in good agreement with the previous LUNA value [15] and in fair agreement with the TUNL value [14].

Off resonance, the spectra (Fig. 2, rows 1–3) show some on-resonance contribution due to the tail of the target profile. The secondary γ ray from the decay of the 6792 keV level (Fig. 2, middle column) therefore contains 13–55% on-resonance capture, and it was rescaled with the on/off-resonance ratio obtained from the primary γ rays (Fig. 2, left column). Subsequently, the cross section ratio

$$R_{\rm GS/6792}(E) = \frac{\sigma_{\rm GS}(E)}{\sigma_{6792}(E)}, \tag{2}$$

with $\sigma_{\rm GS}(E)$ and $\sigma_{6792}(E)$ the cross sections for capture to the ground state and to the 6792 keV state in ^{15}O, respectively, was calculated for each bombarding energy (Table II). The addback and singles mode data for $R_{\rm GS/6792}$ were found to be in agreement. Because of their lower statistical uncertainty, the addback data were adopted for the further analysis.

The systematic uncertainty for $R_{\rm GS/6792}$ (Table II) depends on (1) the summing-in correction for the ground state γ ray (up

TABLE I. Measured quantities used to obtain an extrapolated $S_{\rm GS}(0)$ (keV barn) in recent studies.

Group	Quantity used [taken from]	$S_{\rm GS}(0)$
TUNL [9]	γ width [9]	0.12–0.45
Brussels [10]	Cross section [8]	$0.08^{+0.13}_{-0.06}$
Texas A&M [11]	ANC [11], cross section [8]	0.15 ± 0.07
LUNA [13]	Cross section [8,13][a]	0.25±0.06
TUNL [14]	Cross section [14]	0.49±0.08

[a] Reference [8] data have been corrected [13] for summing-in.

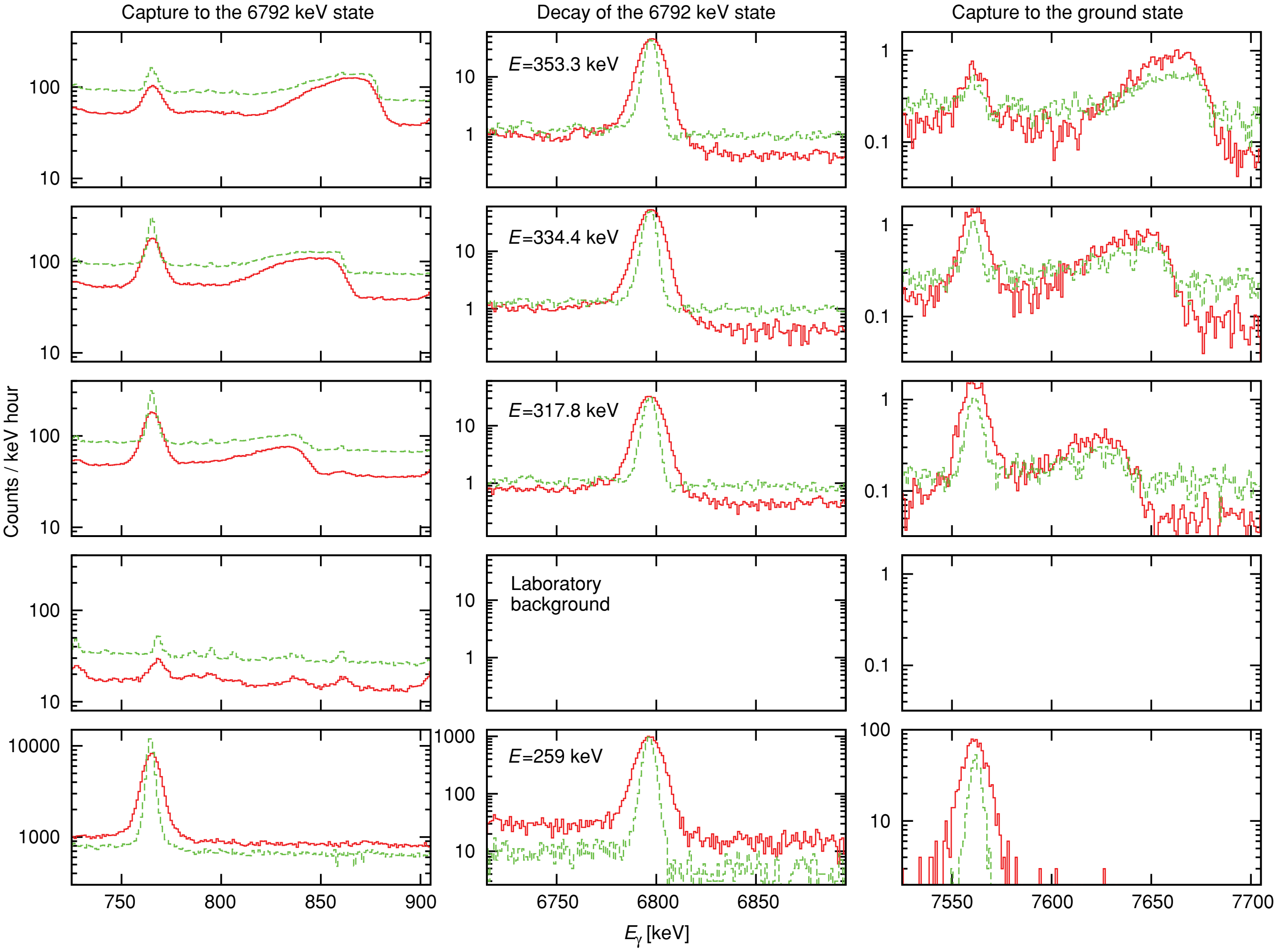

FIG. 2. (Color online) Solid red (dashed green) line: γ-ray spectra for addback (singles) mode. First three rows: off-resonance data. Fourth row: laboratory background, negligible at high γ energy. Fifth row: data at the $E = 259$ keV resonance.

to 4.6 and 0.9% effect on $R_{\mathrm{GS}/6792}$ for the addback and singles mode, respectively, taking into account the calculated [7] angular correlation) and (2) the slope of the detection efficiency curve over the energy range $E_\gamma = 6792$–7650 keV (known to 0.8%). For the cascade 6792 keV γ-ray, (3) the anticoincidence efficiency (1.2% effect) and (4) the summing-out correction (0.6% effect) contribute to the systematic uncertainty for $R_{\mathrm{GS}/6792}$. The effects of, e.g., target composition and profile, stopping power, beam intensity, and absolute γ-ray detection efficiency cancel out in the relative experiment. The effective energy E was determined from the centroids of the γ lines for capture to the ground state and to the 6792 keV state and leads to 2.0%–2.4% uncertainty.

The absolute cross section for the ground state transition obtained from the present data was determined by the ratios given in Table II normalized with the weighted average

TABLE II. Cross section ratio $R_{\mathrm{GS}/6792}(E)$ and relative uncertainty. The size of the summing-in correction is also given.

E (keV)	Mode	$R_{\mathrm{GS}/6792}(E)$ (10^{-2})	Stat. Uncertainty	Syst. Uncertainty	Summing-in correction
317.8 ± 1.5	Addback	4.71	5.9%	5.4%	30%
	Singles	4.67	14%	2.7%	4.3%
334.4 ± 1.5	Addback	5.00	5.1%	3.9%	21%
	Singles	5.07	13%	2.5%	3.4%
353.3 ± 1.5	Addback	5.30	3.6%	3.5%	19%
	Singles	5.15	10%	2.3%	3.2%

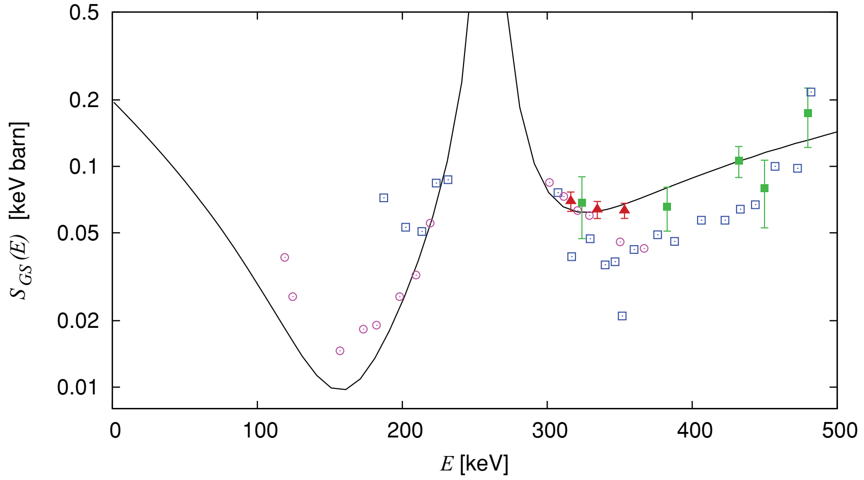

FIG. 3. (Color online) S factor for capture to the ground state. (Solid triangles) Present data. (Solid squares) Ref. [8]. (Line) Present best R-matrix fit. Data from Refs. [13,15] (empty circles) and Ref. [14] (empty squares) are shown for comparison but were not used in the fit; their error bars have been omitted for clarity.

(uncertainty 7.5%) of the S-factor results for the 6792 keV transition given in Refs. [8,14,15]. From such a combined fit an ANC of 4.8 fm$^{-1/2}$ was obtained for the 6792 keV state, in good agreement with Refs. [11,24] and resulting in $\gamma^2 = 0.4$ MeV for the reduced width of the subthreshold state. For the strength of the 259 keV resonance, 13.1 meV (weighted average of Refs. [14–16,21]) was adopted; for its proton width 0.99 keV [13] was used; and for the ground state branching, 1.63% (weighted average of [14,15] and the present work) was used. For all other parameters, the previous values were taken without any change [13]: ANC for ground state capture: 7.3 fm$^{-1/2}$. $E = 0.987$ MeV resonance: $\Gamma_\gamma = 26$ meV, $\Gamma_p = 3$ keV. $E = 2.187$ MeV resonance: $\Gamma_\gamma = 4.4$ eV, $\Gamma_p = 0.27$ MeV. Background pole at $E = 6$ MeV, $\Gamma_p = 8$ MeV. To limit the systematic uncertainty due to summing-in to less than the statistical error, only data with less than 50% summing-in correction were used for the R-matrix analysis, i.e., Ref. [8] (corrected [13] for summing-in) and the present data. The interference pattern around the 259 keV resonance is fixed by the results of Refs. [13–15], and the interaction radius was set to 5.5 fm [13]. The best fit (Fig. 3) varying only the γ widths of the subthreshold state and of the background pole results in $S_{\rm GS}(0) = 0.20$ keV barn with a γ width $\Gamma_\gamma = 0.9 \pm 0.2$ eV for the subthreshold state, in agreement with Coulomb excitation work [12] and with lifetime measurements [9,25]. A full R-matrix analysis including a detailed error determination for all parameters is beyond the scope of the present work. Therefore, the previous relative uncertainty of 24% in $S_{\rm GS}(0)$ [13] is adopted here, giving $S_{\rm GS}(0) = 0.20 \pm 0.05$ keV barn.

In summary, owing to the present high precision data, ground state capture now contributes less than 4% uncertainty to the total $S_{\rm tot}(0)$, instead of the previous 15%, based on a data set that is nearly free from summing problems. On the basis of the present result, $S_{\rm tot}(0) = 1.57 \pm 0.13$ keV barn is recommended, with the uncertainty including also systematic effects. For this sum, $S_{6172}(0) = 0.09 \pm 0.07$ keV barn [11,14,15,26] has been adopted. Further improvements in $S_{\rm tot}(0)$ precision would require a fresh study of this contribution. In the meantime, the present ground state data pave the way for a measurement of the solar central metallicity [4].

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[1] M. Asplund, N. Grevesse, and A. Jacques Sauval, Nucl. Phys. **A777**, 1 (2006).
[2] J. N. Bahcall, A. M. Serenelli, and S. Basu, Astrophys. J. Suppl. Ser. **165**, 400 (2006).
[3] Q. R. Ahmad *et al.*, Phys. Rev. Lett. **89**, 011301 (2002).
[4] W. Haxton, Publ. Astron. Soc. Australia **25**, 44 (2008).
[5] C. Arpesella *et al.*, Phys. Lett. **B658**, 101 (2008).
[6] M. C. Chen, Nucl. Phys. B, Proc. Suppl. **145**, 65 (2005).
[7] C. Iliadis, *Nuclear Physics of Stars* (Wiley-VCH, Weinheim, 2007).
[8] U. Schröder *et al.*, Nucl. Phys. **A467**, 240 (1987).
[9] P. Bertone *et al.*, Phys. Rev. Lett. **87**, 152501 (2001).
[10] C. Angulo and P. Descouvemont, Nucl. Phys. **A690**, 755 (2001).
[11] A. Mukhamedzhanov *et al.*, Phys. Rev. C **67**, 065804 (2003).
[12] K. Yamada *et al.*, Phys. Lett. **B579**, 265 (2004).
[13] A. Formicola *et al.*, Phys. Lett. **B591**, 61 (2004).
[14] R. C. Runkle *et al.*, Phys. Rev. Lett. **94**, 082503 (2005).
[15] G. Imbriani *et al.*, Eur. Phys. J. A **25**, 455 (2005).
[16] A. Lemut *et al.*, Phys. Lett. **B634**, 483 (2006).
[17] H.-P. Trautvetter *et al.*, J. Phys. G **35**, 014019 (2008).
[18] D. Bemmerer *et al.*, Eur. Phys. J. A **24**, 313 (2005).
[19] A. Formicola *et al.*, Nucl. Instrum. Methods A **507**, 609 (2003).
[20] Z. Elekes *et al.*, Nucl. Instrum. Methods A **503**, 580 (2003).
[21] F. Ajzenberg-Selove, Nucl. Phys. **A523**, 1 (1991).
[22] B. Povh and D. F. Hebbard, Phys. Rev. **115**, 608 (1959).
[23] S. Agostinelli *et al.*, Nucl. Instrum. Methods A **506**, 250 (2003).
[24] P. F. Bertone *et al.*, Phys. Rev. C **66**, 055804 (2002).
[25] D. Schürmann *et al.*, Phys. Rev. C **77**, 055803 (2008).
[26] S. O. Nelson *et al.*, Phys. Rev. C **68**, 065804 (2003).