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Direct measurement of the absolute cross section of $p(^7Be,\gamma)^8B$

F. Terrasi[a*], L. Gialanella[b], G. Imbriani[bc], F. Strieder[d], L. Campajola[b], A. D'Onofrio[a], U. Greife[e], G. Gyurky[f], C. Lubritto[a], A. Ordine[b], V. Roca[b], C. Rolfs[d], M. Romano[b], D. Rogalla[d], C. Sabbarese[a], E. Somorjai[f], H.P. Trautvetter[d]

[a]Dipartimento di Scienze Ambientali, Seconda Universitá di Napoli, Caserta and INFN, Napoli, Italy

[b]Dipartimento di Scienze Fisiche, Universitá Federico II, Napoli and INFN, Napoli, Italy

[c]Osservatorio Astronomico di Capodimonte, Napoli, Italy

[d]Institut fur Physik mit Ionenstrahlen, Ruhr-Universität Bochum, Bochum, Germany

[e]Colorado School of Mines, Golden, Colorado, USA

[f]Institute of Nuclear Research (ATOMKI), Debrecen, Hungary

A new direct measurement of the absolute cross section of the $^1H(^7Be,\gamma)^8B$ reaction has been performed in inverse kinematics at $E_{cm} = 990\ keV$. A radioactive ^7Be beam ($E_{lab} = 8\ MeV$) and a windowless H_2 gas target were used; ^8B recoils were identified and counted by a recoil mass separator. The reaction cross section was derived by normalization to the elastic scattering cross section, measured in a separate run. The resulting value $\sigma_r = 0.40 \pm 0.12\ \mu b$ yielded an astrophysical S-factor at zero energy $S_0 = 15.3 \pm 4.5\ eV\ b$, in fair agreement with recommended values.

1. INTRODUCTION

The observed solar neutrino fluxes on the earth provide no unique picture of the microscopic processes in the sun ([1] and references therein). The so called "missing ^7Be neutrino" problem indicates that no astrophysical or nuclear solution can account for the relative value of the H_2O and Cl experiment results [2] and neutrino oscillations have been invoked to explain the discrepancy between observation and model predictions. In the framework of the MSW theory, nuclear inputs to solar models play still an important role. In particular, the value of the astrophysical S(E) factor at the Gamow energy $E_0 = 18\ keV$ of the radiative capture reaction $^7Be(p,\gamma)^8B$ ($Q = 0.14\ MeV$) constrains the acceptance region in the $\Delta m^2 - sin^2(2\theta)$ parameter plane [3]. The present knowledge of the cross section is based essentially on measurements of the β-delayed α-decay of ^8B ($T_{1/2} = 770\ ms$), performed using radioactive ^7Be targets ($T_{1/2} = 53\ d$) produced by hot chemistry [4] [5] [6] [7] [8] [9][10], and on experiments with the inverse process, i.e. ^8B coulomb dissociation ([11] and references therein). The measurements provided $\sigma(E)$ data

*terrasi@na.infn.it

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covering a wide center-of-mass energy range, which show however a considerable scatter, predominantly in the absolute values. Omitting some data sets and using different model calculations [12][13], values of $S(0) = 19^{+4}_{-2}$ eV b [14] and 21 ± 2 eV b [15] have been recommended for the astrophysical $S(E)$ factor at zero energy.

In 1995 we have started at the 3 MV tandem accelerator in Naples [16] a renewed measurement of the absolute $\sigma(E)$ value of $p(^7Be,\gamma)^8B$ (inverted kinematics) in the non-resonant energy region, i.e. at $E_{cm} = 1$ MeV ($E_{lab} = 8$ MeV). The aim of the present measurement was to determine the cross section using a different technique with respect to previous ones, thus searching for possible systematic uncertainties. The use of a radioactive ^7Be beam impinging on a windowless H_2 gas target avoided the problems of ^7Be target stoichiometry. The detection of the ^8B recoils by a recoil mass separator allowed an unambiguous identification of the reaction products on the basis of their energy and $\Delta E - E$ characteristics (using a telescope placed at the end of the separator). Finally, the ^8B yield was measured concurrently with the $^7Be + p$ elastic scattering yield. As the elastic scattering cross section was measured independently by comparison with the $^7Be + Ar$ elastic scattering, the method related ultimately $\sigma(E)$ to the Rutherford cross section, thus yielding a model-independent absolute normalization. Details of the equipment and experimental procedures have been described previously [16] [17] and first results have also been reported [17] [18] . In the following section we briefly summarize the experimental procedure and describe the present status of this novel approach.

2. RESULTS AND DISCUSSION

A ^7Be radioactive ion beam with an energy of 8 MeV in the 4^+ charge state and an average intensity of 30 pA bombarded a differentially pumped gas target operated with H_2 at 5 $mbar$ with an effective length $l_B = 376 \pm 8$ mm. The effective energy, at the center of the gas target, was $E_{eff} = 7.920 \pm 0.004$ MeV, i.e. $E_{cm} = 990.0 \pm 0.5$ keV), estimated using the calibration of the analysing magnet [17] and the energy loss calculations performed by the SRIM2000 program [19]. The charge state distribution of the emerging ^8B recoils was deduced as described in [17] and the mean value of the relevant 5^+ charge state is $\Phi_{5+} = (65 \pm 2)\%$, derived from integration of the $q = 5^+$ curve. The 5^+ ^8B recoils were identified and counted in the recoil separator including a magnetic quadrupole triplet, a 30° switching magnet, a magnetic quadrupole doublet, a Wien filter, and a conventional $\Delta E - E$ ionization chamber [17]. The transmission of the separator was found to be $\epsilon_B = (100 \pm 3)\%$.

The elastic scattering of ^7Be on H target nuclei was measured concurrently, by detection of H recoils in four collimated Si detectors placed at 30°, +45°, −45° and 60° with respect to the beam axis. From the collimator geometry a value of $l_H\Omega_{lab} = 11.3 \pm 0.4$ mm msr was deduced for the product of the effective length seen by the +45° detector times the subtended solid angle. From the number of counts in the final detector of the separator, $N_B = 13 \pm 4$, and the number of recoils counted in the 45° detectors, $N_H = 365 \pm 11$, one can calculate the reaction cross section:

$$\sigma_r(E_{cm}) = \frac{N_B}{N_H}\frac{l_H\Omega_{lab}(\Omega_{cm}/\Omega_{lab})}{(\Phi_{5+}\varepsilon_B)}\,\sigma_{cm}(45^\circ, E_{cm}) \quad (1)$$

The elastic scattering cross section $\sigma_{cm}(45^\circ, E_{cm})$ was measured in the following way.

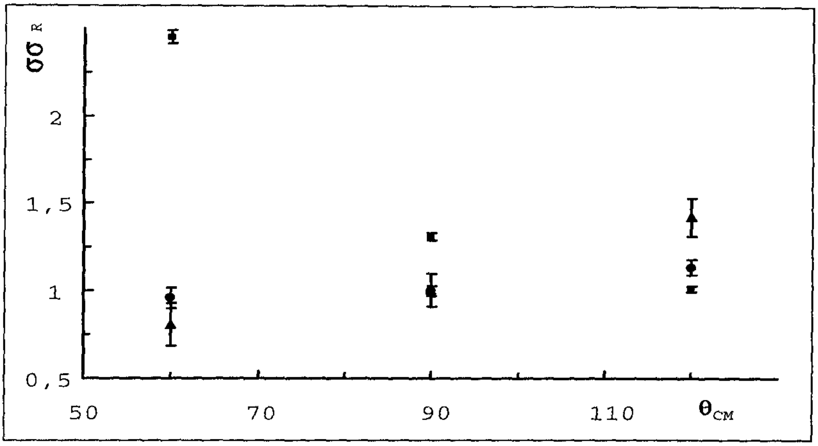

Figure 1. Absolute elastic scattering cross sections for ^7Li+p at $E_{cm}=975\ keV$ (squares) and for ^7Be+p at $E_{cm}=954\ keV$ (triangles) and relative cross section for ^7Be+p at $E_{cm}=990\ keV$ (dots).

First, ^7Li beams of 2, 3 and 8 MeV were guided in the gas target operated with an $Ar-H$ mixture. From the measured yields of ^7Li ions scattered by Ar and of H recoils from ^7Li+H elastic scattering at 2 and 3 MeV, where both reactions follow the Rutherford law, the relative $l_H\Omega_{lab}(\theta)$ for the 30°, −45° and 60° detectors were deduced, as well as the ratio of H to Ar number densities, N_H/N_{Ar}. From the yields measured at 8 MeV incident energy, the absolute values of $\sigma_{cm}^{Li}(\theta, E_{cm}^{Li})$ at 30°, 45° and 60° were deduced, with $E_{cm}^{Li}=975\ keV$, as calculated taking into account the energy loss in the target. They are reported, after normalization to the Rutherford cross section, in Fig. 1 (squares). Then two runs were performed bombarding the same $Ar-H$ mixture with an 8 MeV ^7Li beam and an 8 MeV ^7Be beam. The ratios of elastic scattering yields in the two runs provided the absolute elastic scattering cross section $\sigma_{cm}^{Be}(\theta, E_{cm}^{Be})$ at $E_{cm}^{Be}=954\ keV$. The latter is plotted in Fig. 1 (triangles). Note that the deduced values are not affected by the fact that $E_{cm}^{Be}\neq E_{cm}^{Li}$, but they refer to a c.m. energy which is slightly different from that of the reaction cross section measurement. The difference in the σ/σ_R values between the two energies can be attributed to the different importance of the interference with the 39 keV broad resonance at $E_R=632\ keV$. This effect is expected to decrease with increasing energy above the resonance and to be absent at $\theta_{cm}=90°$ ($\theta_{lab}=45°$), due to the p-wave character of the resonant term and the predominance of s-waves in the non resonant scattering channel. Indeed, this is confirmed by the comparison of the absolute σ/σ_R values measured at $E_{cm}^{Be}=954\ keV$ with the relative ones deduced from the data at $E_{cm}^{Be}=990\ keV$, also shown in Fig.1 (dots) after normalization to $\sigma/\sigma_R=1$ at $\theta_{cm}=90°$.

We have then assumed $\sigma_{cm}^{Be}(45°, 990keV)=\sigma_{cm}^{Be}(45°, 954keV)$ and used this value in eq. 1 to extract the reaction cross section. The resulting value is $\sigma_r(990\ keV)=(0.40\pm 0.12)\mu\ b$, which corresponds to an astrophysical S factor $S(990\ keV)=(16.5\pm4.8)\ eV\ b$. Scaling this value with the energy dependence of [13], we obtain $S(0)=(15.3\pm4.5)\ eV\ b$.

Within the present statistical uncertainty this result is consistent with the values recommended recently [12] [13]. However, a closer comparison with individual data sets considered in the above compilations shows an agreement at the level of 1σ just with the lowest $S(0)$ values obtained in the most recent delayed activity measurements [6] [8] [9] [10].

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