New Measurement and Analysis of the ^{7}Be$(p,\gamma)^8$B Cross Section

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Cross sections for the ^{7}Be$(p,\gamma)^8$B reaction have been measured for $E_{\rm c.m.} = 0.35-1.4$ MeV using radioactive ^{7}Be targets. Two independent measurements carried out with different beam conditions, different targets, and detectors are in excellent agreement. A statistical comparison of these measurements with previous results leads to a restricted set of consistent data. The deduced zero-energy S factor $S(0)$ is found to be 15%–20% smaller than the previously recommended value. This implies a ^{8}B solar neutrino flux lower than previously predicted in various standard solar models. [S0031-9007(97)05137-5]

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The ^{8}B produced in the solar interior via the reaction ^{7}Be$(p,\gamma)^8$B is the major (or unique) source of high energy neutrinos detected in many solar-neutrino experiments now operating or in development (Homestake, Kamiokande, Super-Kamiokande, SNO, etc. [1]). The observed deficit of ^{8}B solar neutrinos when compared to the predictions of solar models [1,2] might have its origin, at least partly, in the value of the ^{7}Be$(p,\gamma)^8$B cross section at very low energy (~20 keV) since the magnitude of the ^{8}B solar neutrino flux is directly proportional to the rate of this reaction. Moreover, the interpretation of the various experiments in terms of neutrino oscillations depends on the reliability of the measured cross sections. For instance, it has been argued [3] that the prediction for the charged to neutral current ratio in SNO is strongly dependent on the estimation of the ^{8}B neutrino flux.

There are six direct measurements of the ^{7}Be$(p,\gamma)^8$B cross section [4–9] using radioactive ^{7}Be targets and proton beams, the most recent dating back to 1983. In addition, a result [10] was obtained in 1994 studying the Coulomb dissociation of ^{8}B at 50 MeV/u energy. The four most precise measurements [5–7,9] are grouped in two distinct pairs which are in agreement with regard to the energy dependence but in disagreement with regard to the absolute value. Zero-energy S factors [$S(E_{\rm c.m.}) = \sigma(E_{\rm c.m.})E_{\rm c.m.}e^{2\pi\eta}$, and $\eta = e^2 Z_1 Z_2/\hbar v$] $S(0)$ are deduced from measurements by an extrapolation based on theoretical calculations of the energy dependence of the cross section. The resulting $S(0)$ are found to disagree by as much as 40%, making this quantity the most uncertain input to solar models. Therefore, it appears highly desirable to perform new measurements of the ^{7}Be$(p,\gamma)^8$B cross section.

In this Letter, we report measurements of the ^{7}Be$(p,\gamma)^8$B cross section for $0.35 \leq E_{\rm c.m.} \leq 1.4$ MeV using radioactive ^{7}Be targets. Special attention was devoted to checking the internal consistency of the measurements and to reducing the uncertainties with the aim of restricting the available data for ^{7}Be$(p,\gamma)^8$B to a set of consistent measurements.

The experiment was performed at the Bordeaux 4 MV Van de Graaff accelerator. The targets, produced via the ^{7}Li$(p,n)^7$Be reaction using the same accelerator, consisted of ^{7}Be oxide deposited on Pt disk. Details of the target preparation will appear elsewhere [11]. The ^{7}Be$(p,\gamma)^8$B cross section was measured by detecting the delayed α particles following the β^+ decay of ^{8}B. The bombard-count cycle was as follows: the target was irradiated for 1.54 s with the detectors protected against the flux of backscattered protons by a metallic iris diaphragm. The beam was then deflected off the target (transit time = 0.24 s) via an electrostatic device for 1.52 s. During this phase, a mechanical shutter stopped neutral hydrogen. The iris diaphragm was then opened and a time window of 1.34 s was defined for α counting before going back to the irradiation position (transit time = 0.21 s). The target was fixed so that it could be efficiently water cooled which was not the case in the previous experiments [5–9] where a rotating arm was used to transfer the target from the bombarding chamber to the counting chamber. In consequence, we were able to use currents of typically 25 μA without noticeable degradation of the target. A liquid nitrogen cooled copper plate was positioned very close to the target to reduce carbon buildup. The beam was collimated to a spot of approximately 4 by 4 mm at the target by passing through two diaphragms (8 and 6 mm in diameter) 1.5 m apart. In addition, a third insulated collimator (7 mm diameter) was placed 1 cm in front of the target. The negligible currents measured in all runs on this collimator gave evidence for the absence of significant instability in the beam position at the target during a run. The data were recorded event by event. Because of the low data acquisition rate, special precautions were taken against spurious events using a veto signal which inhibited the acquisition when an extra detector located outside the reaction chamber was triggered by a rare electrical noise signal. Moreover, in the data analysis, events in which more than one detector fired were rejected. Beam currents on all collimators and on the target were measured, digitized, and recorded on a computer system for off-line analysis. To suppress secondary electron emission the large insulated copper plate acting as LN_2 cold trap in front of the target and the last collimator were biased at -300 V. In addition, the beam current was measured in a Faraday cup before and after each run and found to be in good agreement with measurements on the target to within 2%.

Two independent measurements were carried out. For the first run, referred to as (95), the target activity was 10.4 ± 0.4 mCi and the detector consisted of a set of four passivated implanted silicon counters, with a total active surface of 12 cm^2 and a 100 μm depletion depth. For the second experiment, referred to as (96), the target activity was increased to 26.9 ± 0.5 mCi, and four surface barrier detectors 30 μm thick were used. With this improved setup, cross sections were measured at ten energies ($E_{\mathrm{c.m.}}$) ranging from 0.35 to 1.4 MeV. Only comments on the analysis of (96) are given here. The analysis of (95) was very similar with, however, slightly larger error bars mainly due to the deconvolution process of the α spectra. Cross sections were obtained from the integrated α particle yields in a manner similar to that described in Ref. [9]. Two typical spectra of delayed α particles taken at different energies are shown in Fig. 1. The small thickness of the detector and its segmentation into four sectors strongly reduced the pileup events seen as a dashed steep line extending up to 0.760 MeV in the figure and due to photoelectrons created by the 478 keV γ rays. In deducing cross sections, counts in the range from 0.76 to 5 MeV were integrated and a small correction factor for energy cutoffs (typically 1.05 ± 0.01) was calculated from a curve fitted to the data in the same energy range. This curve was deduced from the actual α spectrum shape given in Ref. [12] after correction of energy loss and energy straggling of the emitted α particles (fluctuations in the range of the recoiling ^{8}B were also considered). As shown in Fig. 1, very good agreement is obtained without introducing any free parameters into the analysis except the normalization factor. It was checked that the same corrected number of counts within statistical error bars was obtained when varying the value of the low-energy cut. The same procedure applied equally well to $^7\mathrm{Li}(d,p)^8\mathrm{Li}$ (see below). The background was determined in an extensive series of measurements alternating between beam off and beam on. It contributed from $\leq 2\%$ of the α yield at $E_{\mathrm{c.m.}} \geq 0.5$ MeV to $\sim 7\%$ at the lowest energies. In addition, the background due to a possible deuteron contamination of the H^+ beam was found to be less than 0.1% at all energies. Effective reaction energies were determined from measurements of the target thickness (4.0 ± 0.4 keV at a proton energy of 441 keV) and of the carbon buildup by consistent Rutherford backscattering measurements and (d,p) reaction analysis of ^{12}C, ^{16}O performed many times during the course of the experiment. The overall corrections for target thickness and carbon buildup lead to an effective energy uncertainty of less than 0.3%. The beam energy was calibrated to $\pm 0.1\%$ from thick target yield curves at resonances in the $^{19}\mathrm{F}(p,\alpha\gamma)^{16}\mathrm{O}$ [$^{27}\mathrm{Al}(p,\gamma)^{28}\mathrm{Si}$] reaction at proton energies of 340.46 and 871.11 keV [632.6 keV, 991.8 keV].

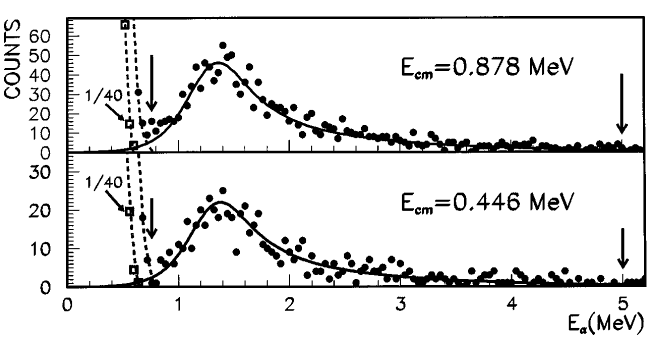

FIG. 1. Delayed α-particle spectrum from decay of ^{8}B at two different energies. The α particle yields were integrated from the energy cutoffs indicated by the arrows. The solid curve is a fit to the data as explained in the text. The dashed line is a fit to the low-energy background due to pileup events. For squares, the y scale is divided by 40.

The product of initial ^{7}Be areal density and efficiency of the α detector, $N_{^7\mathrm{Be}}(0) \times \epsilon$, was measured by two methods as initiated in Ref. [9]. In the first method, the total activity of ^{7}Be was determined several times by measuring the yield of the 478 keV γ ray with a Ge detector and using the known branching ratio of $(10.53 \pm 0.036)\%$ for the electron capture of ^{7}Be to the first excited state of ^{7}Li [13]. The detector efficiency was obtained using standard γ ray sources calibrated to within 1% uncertainty. After fitting the ^{7}Be decay function to the various measurements ($\chi^2 = 0.43$), we found an initial total activity of 26.9 ± 0.5 mCi. For the whole duration of the experiment no loss of activity due to beam impact was observed as indicated by the excellent fit to the data. The target surface was measured by computer scanning of a photographic enlargement of the target where the ^{7}Be deposit clearly appears. Furthermore, γ-activity scanning of the target was performed with a Ge detector collimated with a 0.85 mm diameter aperture in a 15 cm thick lead absorber. This measurement gave the degree of target uniformity of the ^{7}Be density and a total target area which was consistent with the previous one ($S = 0.47 \pm 0.02$ cm^2). The beam position at the target was systematically determined before and after each run and found stable at each energy. The ^{7}Be areal density at the target spot was finally determined ($\pm 5\%$ uncertainty) run by run by averaging the results of the γ-ray scan over the beam spot dimensions and normalizing to the total activity per surface unit. An extensive and consistent series of measurements was made to determine the efficiency ϵ of the α detector, using calibrated ^{241}Am sources of different diameters and different centerings deposited onto Pt backings identical to those used in the experiment and with the same source-detector geometry. We found $\epsilon = 0.107 \pm 0.002$. In the second method, $N_{^7\mathrm{Be}}(t) \times \epsilon$ was independently determined with the same experimental setup from the delayed α yield of the reaction $^7\mathrm{Li}(d,p)^8\mathrm{Li}$. Averaging over five measurements of this reaction yielded a value for $N_{^7\mathrm{Be}}(0) \times \epsilon$ very close to the same quantity as measured directly. Specifically, the ratio is 1.01 ± 0.08 using a value of 147 ± 11 mb [14] for $^7\mathrm{Li}(d,p)^8\mathrm{Li}$ at the 0.61 MeV resonance. Hence, both methods gave identical results for the cross section with, however, lower error bars for the first one owing to the extensive and consistent series of measurements devoted to obtaining the detector efficiency and the target activity at the beam spot, as explained above.

Results in the form of astrophysical S factors are given in Fig. 2 (see also Fig. 3). No measurements were carried out in the region of the resonance at $E_{\mathrm{c.m.}} = 0.660$ MeV which has no significant contribution to the cross section in the energy range $E_{\mathrm{c.m.}} = 0{-}0.5$ MeV and $E_{\mathrm{c.m.}} = 0.85{-}1.4$ MeV where our measurements were concentrated. In that region, the $E1$ direct capture process is largely dominant. At $E_{\mathrm{c.m.}} = 0.88$ MeV, four independent proton bombardments were made, three [one] of them with the experimental setup (96) [(95)]. The four experiments were found to be in excellent agreement with a reduced $\chi^2 = 1.1$. The same excellent agreement was observed for two independent measurements at $E_{\mathrm{c.m.}} = 0.497$ MeV. The consistency of the whole set of independent measurements made with different beam conditions, different targets, and detectors strongly supports the reliability of the data (and the correct evaluation of the uncertainties) and experimental bias negligible compared to the quoted errors.

A comparison of our measurements with existing data is shown in Fig. 2. In a previous analysis, Johnson *et al.* [15] used the results of Refs. [5–7,9] in the averaging process for determining $S(0)$ despite the fairly large spreading of the data. However, the present work provides an additional strong constraint on the consistency of the various experiments (see Fig. 2). To be quantitative, we have performed a χ^2 test on the $S(0)$ deduced by a least squares normalization of the same $S(E)$ curve calculated by Descouvemont *et al.* [16] to each of the data sets considered. The used experimental values were in the energy range from 0.11 to 0.5 MeV and 0.87 to 1.4 MeV in which the resonance contributes no more than 3.4% to the data (the corresponding small contributions were substracted using results of Ref. [9]). Such a fit is shown in Fig. 3 for our data. Note that the fits were performed for each experiment using relative error bars. The resulting uncertainty in $S(0)$ was then combined in quadrature with "systematic" uncertainties applied on the same footing to every energy point of a given experiment. The obtained $S(0)$ and associated error bars are given in Table I. Since most of the experiments rely on normalization to ^{7}Li content in target via the $^7\mathrm{Li}(d,p)^8\mathrm{Li}$ cross section, we applied the χ^2 test to the $S(0)$ corresponding to such analyses for all experiments including our own and that of Filippone. As we used the same value $\sigma_{dp} = 147 \pm 11$ mb [14] for the normalization of all the experiments, the contribution to the uncertainty related to σ_{dp} was not included in the error bars for the χ^2 test. On this basis, the consistency of the five sets of data is ruled out at 99.9% C.L. By way of precaution, we checked that the above conclusion does not depend closely on the estimation of the error bars. Specifically, when increasing the uncertainties by a factor

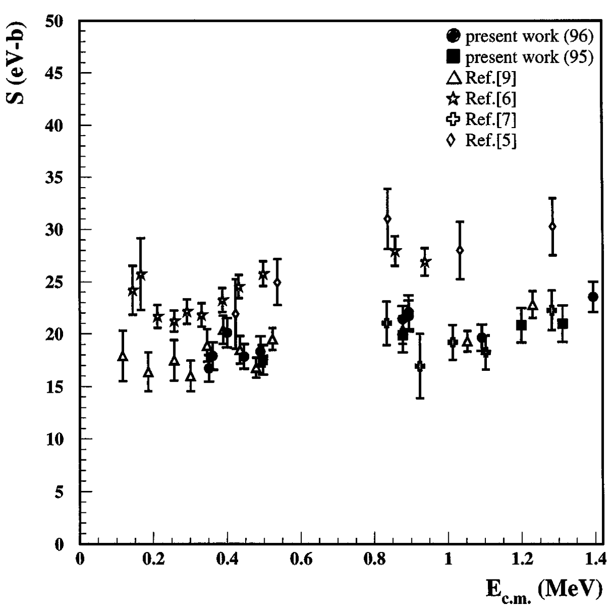

FIG. 2. The $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ S factors obtained from our two series of measurements together with existing data shown at energies outside the $M1$ resonance. The data were renormalized using $\sigma = 147 \pm 11$ mb [14] for $^7\mathrm{Li}(d,p)^8\mathrm{Li}$ at $E_{\mathrm{c.m.}} = 0.61$ MeV. The error bars represent only the relative uncertainties in the points.

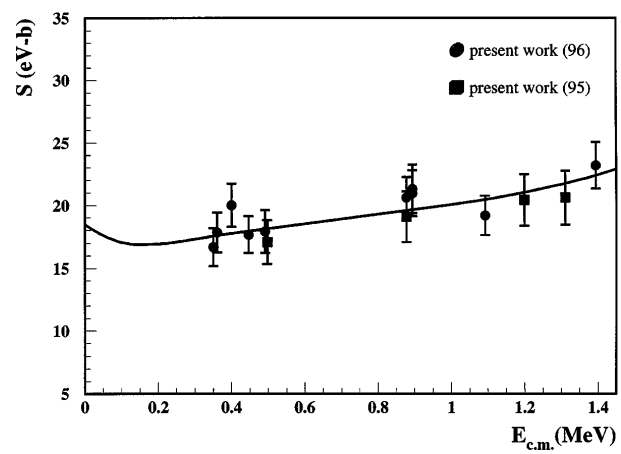

FIG. 3. S factors from the present work and typical fit using theoretical curve of Descouvemont *et al.* [16] for the nonresonant capture (their resonant $M1$ contribution has been substracted). The only free parameter in the fit is a normalization factor. Overall error bars corresponding to the first method of analysis (see text) are drawn.

TABLE I. Extrapolation of the S factors to zero energy using the energy dependence of Descouvemont *et al.* [16]. All the experiments labeled (a) were normalized with $\sigma_{dp} = 147 \pm 11$ mb for ^{7}Li$(d,p)^8$Li. The uncertainties given in the second column are overall uncertainties (see text). The uncertainty in σ_{dp} must be substracted when comparing the experiments labeled (a).

Experiment	$S(0)$ (eV b)	Reduced χ^2
Ref. [5][a]	25.8 ± 2.2	0.55
Ref. [6][a]	24.3 ± 2.0	0.74
Ref. [7][a]	17.4 ± 1.6	0.75
Ref. [9][a]	18.4 ± 2.2[c]	1.1
Ref. [9][b]	18.4 ± 2.4[c]	1.1
Present[a]	18.5 ± 1.7	0.65
Present[b]	18.5 ± 1.0	0.65

[a]Cross section determined from the ^{7}Li$(d,p)^8$Li cross section.
[b]Cross section determined from γ-ray activity.
[c]Error bar deduced from that given in Ref. [9], assuming that the random error arising from the fit is similar in Ref. [9] and in the present analysis.

of 2 (3) the consistency of the data is still ruled out at 99.5% (95%) C.L. On the contrary, a complete consistency is found (reduced $\chi^2 = 0.5$) with the actual errors when considering only our data and those of Filippone and Vaughn. The above analysis is independent of the fitted curve so long as the fits are good for all sets of data. The latter point is clearly verified as shown by the obtained reduced χ^2 given in Table I.

The consistent $S(0)$ values of this work and of Filippone and Vaughn have been averaged taking into account that some of the experiments were normalized to the same value of σ_{dp} (the uncertainty in σ_{dp} was then treated as an overall systematic uncertainty). For our experiment we took the uncertainty in $S(0)$ quoted in Table I which arises from the normalization procedure via direct measurement of ^{7}Be activity. The final result is $\langle S(0)\rangle = 18.3 \pm 0.8$ eV b, very close to the value of 18.5 ± 1.0 obtained with our data alone. A similar averaged value of 18.5 ± 1.0 eV b is found when the fits are restricted to the maximum energy of 0.5 MeV using our data and those of Ref. [9] (note that the goodness of individual fits to each set of data is found to be excellent whatever the energy range considered [17]). The same analysis, when performed with the curve calculated by Johnson *et al.* [15], leads to a value of 18.3 ± 1.0 eV b.

The present value for $\langle S(0)\rangle$ is significantly lower than the previously recommended value of 22.4 ± 2.1 eV b given by Johnson *et al.* [15]. The reason is essentially that we did not consider the results of Refs. [5,6] in our averaging process in contrast to Johnson *et al.* (an additional reduction arises from the different values adopted for σ_{dp}).

Finally, the obtained $\langle S(0)\rangle$ value implies a significant reduction of 15%–20% in the ^{8}B solar neutrino flux. We are presently developing experiments at lower energies to further reduce the overall uncertainty on the zero-energy S factor for this reaction.

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