Breakup of $^8$B and the $S_{17}$ astrophysical factor revisited

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Existing experimental data for the breakup of $^8$B at energies from 30 to 1000 MeV/nucleon on light through heavy targets are analyzed in detail in terms of an extended Glauber model. The predictions of the model are in excellent agreement with independent reaction data (reaction cross sections and parallel momentum distributions for core like fragments). Final state interactions have been included in the Coulomb dissociation component. We extract asymptotic normalization coefficients (ANC) from which the astrophysical factor $S_{17}(0)$ for the key reaction for solar neutrino production, $^7$Be$(p,\gamma)^8$B, can be evaluated. Glauber model calculations using different effective interactions give consistent, though slightly different results. The differences give a measure of the precision one can expect from the method. The unweighted average of all ANCs extracted leads to $S_{17}(0) = 18.7 \pm 1.9$ eVb. The results of this new analysis are compared with the earlier one. They are consistent with the values from most direct measurements and other indirect methods.

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I. INTRODUCTION

The major source of the high-energy neutrinos observed by the solar neutrino detectors is $^8$B, produced in the $^7$Be$(p,\gamma)^8$B reaction at the end of the $pp$ III chain. The recent results from Superkamiokande$^2$ and SNO$^3$ shift the interest for a precise determination of the rate of this reaction from the problem of the existence of the solar neutrino deficit and of the neutrino oscillations to that of putting stringent constraints on the different scenarios that explain them. There were many recent determinations of $S_{17}$, but its precise value is still controversial. In particular, there is a discrepancy between the value found in one direct measurement and most of the results from indirect measurements.

Recently we have proposed an indirect method to extract astrophysical S factors from one-nucleon-removal (or breakup) reactions of loosely bound nuclei at intermediate energies$^4,5$. It is based on the recognition that the structure of halo nuclei is dominated by one or two nucleons orbiting a core (see for example$^4,5$ and references therein). Consequently, we use the fact that the breakup of halo or loosely bound nuclei is essentially a peripheral process, and therefore the breakup cross-sections can give information about the wave function of the last proton at large distances from the core. More precisely, we determine asymptotic normalization coefficients (ANCs) from a comparison of the experimental data with calculations. Then, these ANCs are sufficient to determine the astrophysical S factors for radiative proton capture reactions. The approach offers an alternative and complementary technique to extracting ANCs from transfer reactions$^6$, an alternative particularly well adapted to rare isotope beams produced using fragmentation.

In this paper we discuss the use of existing experimental data on $^8$B breakup at energies between 30 and 1000 MeV/nucleon$^3,4,7,8$ to determine the astrophysical factor $S_{17}$. The calculations presented in$^4$ on this subject were extended and refined. First, the Coulomb part of the dissociation cross section was modified by including the final state interaction into the calculations. Second, new data on the breakup of $^8$B are analyzed$^3,7,8$. Third and most important, a new set of calculations for the breakup of $^8$B were made using different effective nucleon-nucleon (NN) interactions. Each of the new effective interactions considered, which do not involve any new parameters, give consistent results for all experiments, but the average ANCs found are slightly different from one interaction to another. We interpret these differences as a measure of the accuracy of the present (and possibly other) indirect method(s). Finally, a brief comparison with results of direct measurements and of other determinations of $S_{17}$ using indirect methods is made.

II. FROM BREAKUP CROSS SECTIONS TO ANCS

In the breakup (one-nucleon removal reactions) of loosely bound nuclei at intermediate energies, a nucleus $B = (Ap)$, where $B$ is a bound state of the core $A$ and the nucleon $p$, is produced by fragmentation from a primary beam, separated and then used to bombard a secondary target. In inclusive measurements, the core $A$ is detected, measuring its parallel and transverse momenta and eventually the gamma-rays emitted from its deexcitation. Spectroscopic information can be extracted from these experiments, such as the orbital momentum of the relative motion of the nucleon and the contribution of different orbitals (from the momentum distributions) and the contribution of different core states (from the coin-
superposition of the single particle contributions from the different parts of the wave function weighted by the respective spectroscopic factors. 

\[ \sigma_{-1p} = \sum S(c, nlj) \sigma_{sp}(nlj). \]  

In inclusive measurements, such as those analyzed here, the proton is not detected, therefore the calculated cross sections \( \sigma_{sp}(nlj) \) contain a stripping term (the loosely bound proton is absorbed by the target and the \(^7\)Be core is scattered and detected), a diffraction dissociation term (the proton is scattered away by the target, the \(^7\)Be core is scattered by the target and is detected) and a Coulomb dissociation term.

\[ \sigma_{sp} = \int_0^\infty 2\pi b db (P_{str}(b) + P_{diff}(b)) + \sigma_{Coul} \]  

These terms were calculated using the extended Glauber model detailed elsewhere. S-matrix elements have been calculated in the eikonal approximation up to the second order to assure convergence. This convergence was checked with calculations for other quantities, for example proton-target reaction cross sections as a function of energy, and compared with data available from literature.

### III. RESULTS USING DIFFERENT NN INTERACTIONS

In calculations we assume a structure of the projectile given by Eq. with the spectroscopic factors, or the ANCs, to be determined from the comparison of the measured cross sections (from which the contribution of the \(^7\)Be core excitation was removed as described above) with those calculated as an incoherent superposition of single particle cross sections.

\[ \sigma_{-1p} = (S_{p1/2} + S_{p1/2}) \sigma_{sp} = (C_{p1/2}^2 + C_{p1/2}^2) \sigma_{sp}/b^2, \]  

where \( b_{nlj} \) are the asymptotic normalization coefficients of the normalized single particle radial wave functions \( \varphi_{nlj}(r) \) calculated in a spherical Woods-Saxon potential of a given geometry and with the depth adjusted to reproduce the experimental proton binding energy of \(^8\)B, \( S_p = 0.137 \text{ MeV} \). They are essentially equal for the \( 1p_{3/2} \) and \( 1p_{1/2} \) orbitals \( (b_p) \), as are the single particle breakup cross sections \( \sigma_{sp} \). The sum of the spectroscopic factors or the sum of the asymptotic normalization coefficients \( C_{tot}^2 = C_{p1/2}^2 + C_{p1/2}^2 \) can thus be extracted by comparing the experimental one-proton removal cross sections with the calculations. The \(^8\)B ANC, \( C_{tot}^2 \), is extracted from existing breakup data at energies between 30-1000 MeV/nucleon and on different targets ranging from C to Pb. Figure shows the one-proton removal cross sections for various targets and incident energies. One can notice the large range of cross sections and the variation with the energy for different targets.
ized double folded potentials with this effective interac-
nuclei around 10 MeV/u [22], we found that renormal-
study of the elastic scattering of loosely bound
mental binding energy of each nucleus. In an extensive
sities carefully adjusted to correctly reproduce the exper-
Mahaux (JLM) [21] and Hartree-Fock-Bogolyubov den-
nucleon-nucleon interaction of Jeukenne, Lejeune and
approach. To obtain the folded potentials for the proton-
needed in the calculations. The first is a potential ap-
atched area is the standard deviation.
ertainties. The dashed line shows the average and the
points contain the experimental and theoretical uncer-
effective interaction. The error bars of the individual
ANCs determined from the breakup of
gets at various energies [9-13] used in this study. b)The
breakup of
b) using the JLM
interaction provide a good description of the data. We found
there that a large renormalization is needed for the real
part of the potential, but no renormalization is needed for
the imaginary part of the potential. In the present calcula-
tions we assume that no renormalization of the imagi-
ary part is needed at all energies. We used the JLM
interaction for energies below 285 MeV/nucleon only.

Before comparing the experimental and calculated in-
tegrated cross sections, we checked that we can repro-
duce all other available experimental observables with
our model. This was crucial before proceeding with the
calculations. In Figure 2 we show that parallel momen-
tum distributions measured at 41 MeV/nucleon on one
low Z (Be) and one high Z (Au) target [23] and on the
12
3
28
76

FIG. 1: a) The cross sections determined from the
breakup of B at 30-1000 MeV/u on C, Al, Sn and Pb tar-
gets at various energies [9-13] used in this study. b)The
ANCs determined from the breakup of B using the JLM
effective interaction. The error bars of the individual
points contain the experimental and theoretical uncer-
tainties. The dashed line shows the average and the
hatched area is the standard deviation.

Two approaches were used to evaluate the S-matrices
needed in the calculations. The first is a potential ap-
proach. To obtain the folded potentials for the proton-
target and core-target interactions we used the effective
nucleon-nucleon interaction of Jeukenne, Lejeune and
Mahaux (JLM) [21] and Hartree-Fock-Bogolyubov densi-
ties carefully adjusted to correctly reproduce the experi-
mental binding energy of each nucleus. In an extensive
study of the elastic scattering of loosely bound p-shell
nuclei around 10 MeV/u [22], we found that renormal-
ized double folded potentials with this effective interac-
were taken in the calculation, except that distorted waves, not plane waves, component of the one-proton removal cross section. E1 interaction in the calculation of the Coulomb dissociation [4], we include the newer measurements by [11, 12].  

Consistent with a constant value (Fig. 1b) with an average \( C_{\text{tot}}^2 (JLM) = 0.454 \pm 0.048 \text{ fm}^{-1} \). Compared with Ref. [4], we include the newer measurements by [11, 12]. Another distinction is that we have included the final state interaction in the calculation of the Coulomb dissociation component of the one-proton removal cross section. E1 and E2 amplitudes have been included as in the earlier calculation, except that distorted waves, not plane waves, were taken in the \( p+^7\text{Be} \) final channel for the calculation of the matrix elements. The distorted waves were calculated numerically in the same potential that was used to bind the proton \( p \) around the \(^7\text{Be} \) core in the ground state of \(^8\text{B} \). Differences occur between the calculated amplitudes with the two approaches especially for low relative momenta, but their influence on the final integrated result is relatively small due to the extra \( q^2 \) factor that weights their contribution to the integrated cross section. However, the inclusion of distorted waves increases the asymmetry in the parallel momentum distribution due to an increased E1-E2 interference effect as can be seen in the upper right panel in Fig. 2. It has been suggested [24] that asymmetries observed in the fragment parallel momentum distributions in the Coulomb dissociation of \(^8\text{B} \) on heavy targets could be reproduced with an overall renormalization of 1.22 and of 0.7 for the E2 matrix elements calculated in first order perturbation theory. We have, therefore, performed calculations using bare amplitudes resulting from perturbation theory [27], as well as renormalized E2 and E1 amplitudes. No significant differences were found in the extracted ANCs with these two versions, and the values reported here are those obtained without any renormalization. The Coulomb term in the breakup cross section is particularly important for heavy targets where it becomes dominant. The value found above for the ANC is in very good agreement with that determined before using the peripheral proton transfer reactions \(^{10}\text{B}(^7\text{Be},^8\text{B})^9\text{Be} \) and \(^{14}\text{N}(^7\text{Be},^8\text{B})^{13}\text{C} \) at 12 MeV/nucleon [26] \( C_{\text{tot}}^2 (p) = 0.449 \pm 0.045 \text{ fm}^{-1} \) and with that obtained from the study of the mirror neutron transfer reaction \((^7\text{Li},^8\text{Li}) \) \( C_{\text{tot}}^2 (n) = 0.455 \pm 0.047 \text{ fm}^{-1} \) [14]. They agree very well, in spite of the differences in the energy ranges and in the reaction mechanisms involved. The ANC extracted with JLM leads to the astrophysical factor \( S_{17}(0) = 17.5 \pm 1.8 \text{ eV} \cdot \text{b} \) for the key reaction for solar neutrino production \(^7\text{Be}(p,\gamma)^8\text{B} \).

FIG. 2: The parallel momentum distributions determined from the breakup of \(^7\text{B} \) on Be and Au targets at 41 MeV/u [23] and on C at 936 MeV/u [13] for the both g.s. and core excitation components. Final state interaction is included in the Coulomb calculations. The total (full lines) and the components are shown: stripping (dashed) and diffraction (dotted), Coulomb (dash-dotted), or as labelled on each curve.

FIG. 3: The breakup probability profiles as a function of the impact parameter \( s \) for the breakup of \(^8\text{B} \) on C targets at four different energies. The stripping (full lines) and the diffraction dissociation (dashed lines) components are shown. The vertical line shows the position of the \(^7\text{Be} \) core rms radius.
nucleons. The total NN cross sections and the scattering amplitudes are taken from literature. Calculations were done for all the experiments in the energy range 50-1000 MeV/nucleon using a constant ("standard") finite range of 1.5 fm, as well as specific ranges in each NN channel as suggested by Ray [30]. No new parameters were adjusted. For details on the procedure see [5]. For all the effective

FIG. 4: The ANCs determined from the breakup of $^8$B at 30-1000 MeV/μ on C, Al, Sn and Pb targets, using three NN effective interactions: JLM (squares), "standard" (circles) and "Ray" (triangles). See text for details. The dashed, dotted and dash-dotted lines are the average of the JLM, "standard" and "Ray" values, respectively.

NN interactions we checked that they correctly describe complementary data, like proton-target and 7Be-target elastic and total reaction cross sections, where available. Understandably, calculations with zero-range and with 2.5 fm range give too small or too large cross sections, respectively, and were not retained. Data at energies higher than 50 A MeV were selected. We did not include the measurements of Ref. [28] at 1440 MeV/nucleon and of Ref. [29] at 1471 MeV/nucleon (highest energy points in Fig. B), because at those very large energies the breakup is no longer peripheral and the extraction of an ANC may not be the most appropriate. However, the results obtained from the analysis of these two cases are fully consistent with the others.

For each of the two NN interactions we find that all experiments give consistent ANCs (Fig. B), but the average values obtained are slightly different: $C_{12}^2$ ("standard") = 0.503±0.032 fm$^{-1}$ and $C_{12}^2$ ("Ray") = 0.517±0.041 fm$^{-1}$. These differ by 11% and 13% respectively from the JLM value. We find no argument to determine which value is best. If we take the unweighted average of all 31 determinations we find an ANC $C_{12}^2$(ave) = 0.483 ± 0.050 fm$^{-1}$ that leads to $S_{17}(0) = 18.7 ± 1.9$ eV·b. The uncertainties quoted are only the standard deviation of the individual values around the averages, with no experimental errors included. The experimental data considered here were taken in various laboratories, at different energies, with varying methods and the calculations also used different techniques. Therefore, we believe that the results form a statistical ensemble with many and randomly occurring error sources, for which the average and the standard deviation around the average give a reasonable description of the ANC and its error.

In Ref. [31] the authors study the same data of $^8$B breakup on the C target and find a larger value for the ANC than the one we published previously in [4]. They use a different strategy for the calculations where they assume a wave function for the $^8$B g.s. from nuclear structure calculations and a geometry of the proton binding potential that they do not question. Then, the comparison with the experiment gives them a quenching factor $R_q$ of unexplained origin in that paper (but of great significance if its connection with short range correlations inside nuclei is confirmed). On the other hand they compare their result for one single target with the full average from our calculations. A direct comparison with the individual ANCs or with the average of our results for the breakup on the C target only (available in Table I of our Ref. [4]) would have led to agreement. Later [11] they find full agreement with us [5] for the breakup of $^9$C where we use essentially the same techniques. Also, our examination of different theoretical reaction models above indicates that a quenching factor $R_q = 0.88$ may not be precise enough to consider it different from unity. A recent study of 23 cases of one-neutron removal cross sections at similar energies [17] found no quenching $R_{ave} = 0.98 ± 0.16$.

IV. CONCLUSIONS

In conclusion, we show that the breakup of $^8$B at intermediate energies can be used to obtain the $S_{17}$ astrophysical factor at stellar energies. Very difficult direct measurements are complemented by reactions using secondary beams of exotic nuclei obtained from fragmentation and seeking the relevant ANCs, rather than a complete knowledge of the ground state wave function of $^8$B. In addition, the indirect ANC method is subject to different systematic errors than direct measurements.

There were many recent determinations of this key astrophysical factor $S_{17}$, but its precise value is still controversial. Our result is in agreement with those from all indirect methods and with most of the direct determinations (see the discussions in [32, 33, 34, 35]), but one which stands out in its claim of a larger value and very small error [36]. The value obtained as an average of all ANCs found in the present study $S_{17}(0) = 18.7 ± 1.9$ eV·b, is virtually equal with the most probable values extracted in Ref. [32] $S_{17}(0) = 18.6 ± 1.2$ (stat) ±1.0 (theor) eV·b and in Ref. [32] $S_{17}(0) = 18.6 ± 0.4$ (stat) ±1.1 (theor) eV·b from statistical analyses of all mutually consistent results, including the reanalysis of data.
from direct measurements \[37\] with a different extrapolation at low energies. Our results from the use of different NN interactions reminds us of the fact that the precision of indirect methods depends not only on the precision of the experiments but also on the accuracy of the calculations. These findings may give a measure of the present status for break-up reactions, indicating that accuracies to +/-10% can be obtained.

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