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

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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 corelike 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 $S_{17}(0)=18.7\pm1.9$ eV b. 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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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 [1] at the end of the *pp* III chain. The recent results from SuperKamiokande [2] and SNO Collaboration [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, Refs. [6,7] 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 [8], 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 [9–13] to determine the astrophysical factor S_{17}. The calculations presented in Ref. [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 [11–13]. 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.

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 γ 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 core states (from the coincidences with γ rays). Typically, the experimental results are compared with calculations using Glauber models. The integrated cross sections have been used to extract absolute spectroscopic factors [7] or the ANC [4]. We have shown that the latter approach has the advantage that it is independent of the geometry of the proton binding potential, an important feature for exotic nuclei for which the geometry of the mean field is not necessarily well known. The ANC C^B_{Ap} for the nuclear system $A+p\leftrightarrow B$ specifies the amplitude of the tail of the overlap function of the bound state *B* in the two-body channel (Ap) [8]. This ANC is enough to determine the direct (nonresonant) contribution to the astrophysical *S* factor for the radiative proton capture reaction $A(p,\gamma)B$ which is a highly peripheral process due to the Coulomb barrier and the low

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energies in the entrance channel. Using this strategy we described the breakup of ^{8}B in terms of an extended Glauber model. The ^{8}B projectile (made of a proton and the ^{7}Be core) is moving on a straight line trajectory and each part is interacting independently with the target. The breakup cross sections depend on the proton-target and core-target interactions and on the relative *p*-core motion.

The wave function of the ground state of ^{8}B is a mixture of $1p_{3/2}$ and $1p_{1/2}$ orbitals, around a ^{7}Be core:

$$|^8\mathrm{B(g.s.)}\rangle = A_{p_{3/2}}[^7\mathrm{Be}(3/2^-) \otimes p_{3/2}]_{2^+} + A_{p_{1/2}}[^7\mathrm{Be}(3/2^-) \otimes p_{1/2}]_{2^+} + A_e[^7\mathrm{Be}^*(1/2^-) \otimes p_{3/2}]_{2^+} + \cdots, \quad (1)$$

where A_i are the spectroscopic amplitudes of the various components. The first two terms represent the proton in the $1p_{3/2}$ and $1p_{1/2}$ orbitals, respectively, coupled to the ground state of ^{7}Be. The third term corresponds to the proton being coupled to the first excited state of the ^{7}Be core, at $E^*=0.429$ MeV. Basic shell model arguments suggest that the $1p_{3/2}$ term dominates, and only a small $1p_{1/2}$ admixture exists. Recently, in the study of its mirror nucleus ^{8}Li, we disentangled for the first time these two contributions and found their ratio to be $A^2_{p_{1/2}}/A^2_{p_{3/2}}=C^2_{p_{1/2}}/C^2_{p_{3/2}}=0.13(2)$ [14]. Only these two terms contribute in the radiative capture process. However, all three terms contribute in the breakup process, with the third one identified in ^{8}B breakup through coincidences with γ rays [13]. It does not contribute in the radiative capture, but its contribution has to be evaluated and subtracted from all the other inclusive breakup data. From the breakup cross section to the excited state in ^{7}Be, $\sigma(\mathrm{exc})=12(3)$ mb and $\sigma(\mathrm{tot})=94(9)$ mb measured at 936 MeV/nucleon, we found $C^2_e/C^2_{\mathrm{tot}}=0.16(4)$, a value consistent with that found in the original analysis in Ref. [13] and which, subsequently, was used to correct for the contribution of core excitation in all other breakup data analyzed here. These two findings together establish the wave function of the ground state of ^{8}B, up to an overall multiplicative factor.

The calculated one-proton removal cross sections and the momentum distributions are given, in first-order perturbation theory, by the incoherent superposition of the single-particle contributions from the different parts of the wave function weighted by the respective spectroscopic factors [15]

$$\sigma_{-1p} = \sum S(c,nlj)\sigma_{sp}(nlj). \quad (2)$$

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 [16]

$$\sigma_{sp} = \int_0^\infty 2\pi b db[P_{\mathrm{str}}(b) + P_{\mathrm{diff}}(b)] + \sigma_{\mathrm{Coul}}. \quad (3)$$

These terms were calculated using the extended Glauber model detailed elsewhere [17,18]. *S*-matrix elements have been calculated in the eikonal approximation up to the second order [19] 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 [20].

In calculations we assume a structure of the projectile given by Eq. (1), 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

$$\sigma_{-1p} = (S_{p_{3/2}} + S_{p_{1/2}})\sigma_{sp} = (C^2_{p_{3/2}} + C^2_{p_{1/2}})\sigma_{sp}/b^2_p, \quad (4)$$

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, $S_p=0.137$ 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 σ_{sp}. The sum of the spectroscopic factors or the sum of the asymptotic normalization coefficients $C^2_{tot}=C^2_{p_{3/2}}+C^2_{p_{1/2}}$ can thus be extracted by comparing the experimental one-proton-removal cross sections with the calculations. The ^{8}B ANC, C^2_{tot}, is extracted from existing breakup data at energies between 30 and 1000 MeV/nucleon and on different targets ranging from C to Pb [9–13]. Figure 1(a) 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.

Two approaches were used to evaluate the *S* matrices needed in the calculations. The first is a potential approach. 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 densities carefully adjusted to correctly reproduce the experimental binding energy of each nucleus. In an extensive study of the elastic scattering of loosely bound *p*-shell nuclei around 10 MeV/nucleon [22], we found that renormalized double folded potentials with this effective 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 calculations we assume that no renormalization of the imaginary part is needed at all energies. We used the JLM interaction for energies below 285 MeV/nucleon only.

Before comparing the experimental and calculated integrated cross sections, we checked that we can reproduce all other available experimental observables with our model. This was crucial before proceeding with the calculations. In Fig. 2 we show that parallel momentum distributions measured at 41 MeV/nucleon on one low *Z* (Be) and one high *Z* (Au) target [23] and on the ^{12}C target at 936 MeV/nucleon (calculated with appropriate technique for high energy, as discussed below) are well reproduced. Similarly, the trans-

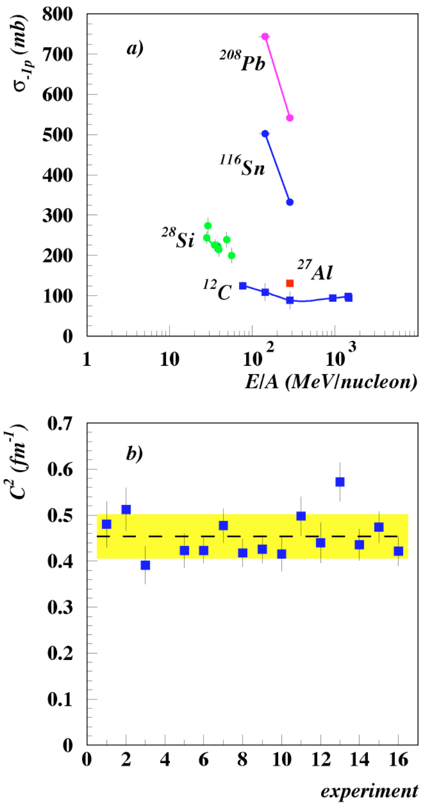

FIG. 1. (Color online) (a) The cross sections determined from the breakup of ^{8}B at 30–1000 MeV/nucleon on C, Al, Sn, and Pb targets at various energies [9–13] used in this study. (b) The ANCs determined from the breakup of ^{8}B using the JLM effective interaction. The error bars of the individual points contain the experimental and theoretical uncertainties. The dashed line shows the average and the hatched area isthe standard deviation.

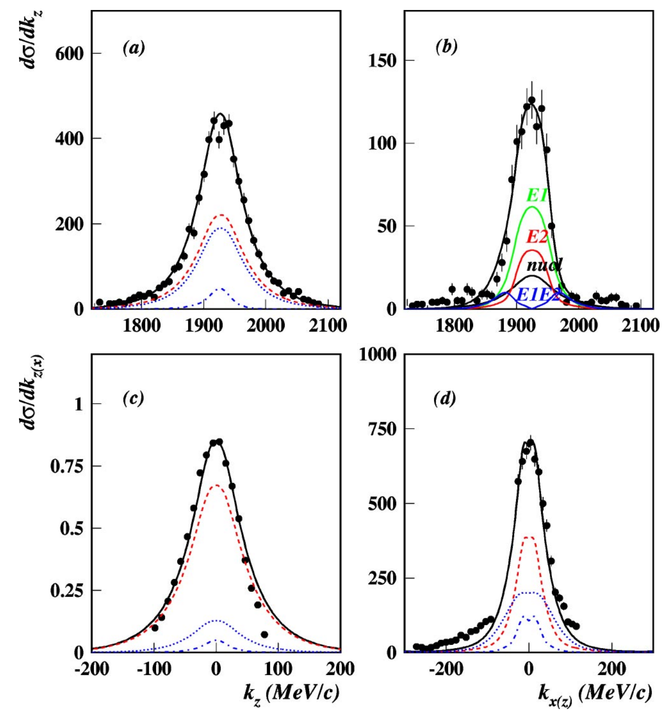

FIG. 2. (Color online) The parallel momentum distributions determined from the breakup of ^{8}B on (a) Be and (b) Au targets at 41 MeV/nucleon [23] and on (c) C at 936 MeV/nucleon [13]. In panel (d) the transverse momentum distribution measured in Ref. [23] on Be at 41 MeV/nucleon is compared with the calculations. The units for the ordinate axes are (counts) for (a), (b), and (d) and (mb/MeV c) for (c). For calculations the total (full lines) and the components are shown: stripping (dashed) and diffraction (dotted), Coulomb (dash-dotted), or as labeled on each curve in panel (b).

verse momentum distributions are well reproduced and an example is shown in the right bottom panel for the case of ^{9}Be target and 41 MeV/nucleon (data from Ref. [23]). More details will be published later [18]. The model also reproduces well the relative fraction of stripping/diffraction dissociation disentangled first by Negoita *et al.* [9] on Si targets at 28–38 MeV/nucleon (as can be seen in Fig. 6 of that reference) and more recently by Enders *et al.* on C at 76 MeV/nucleon [11]. For the latter the calculations give $\sigma_{\rm str}=80$ mb, $\sigma_{{\rm diff}+C}=50$ mb, to compare with the experimental results $\sigma_{\rm str}=93(16)$ mb, $\sigma_{{\rm diff}+C}=37(13)$ mb. In Fig. 3 we show, for the case of the breakup of ^{8}B on C targets that the reaction is essentially peripheral. The stripping and the nuclear diffraction dissociation probabilities as a function of the proton impact parameter s are calculated at four energies. While these probabilities are peaked outside the radius of the ^{7}Be core (vertical line) in all cases, it is clear that the interior contributes and should be carefully considered. The figure also shows the variation with energy of the relative importance of the two nuclear mechanisms: the diffraction dissociation (dashed line) is dominant at lower energies and its role decreases with increasing energy where stripping (full line) becomes dominant. The comparison of the results of the present calculations with the results of the simpler black disk model shows that the interior plays the crucial role in describing correctly the wings of the parallel momentum distributions (see Fig. 3 of Ref. [4]). An analysis like the one presented in Fig. 2 of Ref. [4] shows that there is an energy window $E/A=25$–150 MeV/nucleon for which the breakup of ^{8}B is mostly peripheral even on the lightest targets. For the heavier targets this is always the case, due to the dominance of the Coulomb component.

The data considered were taken on C targets at 76 [11], 142, 285 [10], and 936A MeV [13] (expt. no. 1–4, in order), on Al at 285A MeV ([10], expt. no. 5), on Si at 28, 35, 38 ([9], expt. no. 6,8,9), 29, 39, 49, and 56A MeV ([12], expt. no. 7, 10–12), on Sn at 142A and 285A MeV ([10], expt. no. 13,14), and on Pb targets at 142A and 285A MeV ([10], expt. no. 15, 16).

From the analysis with the JLM interaction of all experiments up to 285A MeV we find ANCs consistent with a constant value [Fig. 1(b)] with an average $C^2_{\rm tot}$(JLM) $=0.454\pm0.048$ fm^{-1}. Compared with Ref. [4], we include the newer measurements in Refs. [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 $p+{}^7$Be final channel for the calculation of the matrix elements. The distorted waves were calculated numerically in the same poten-

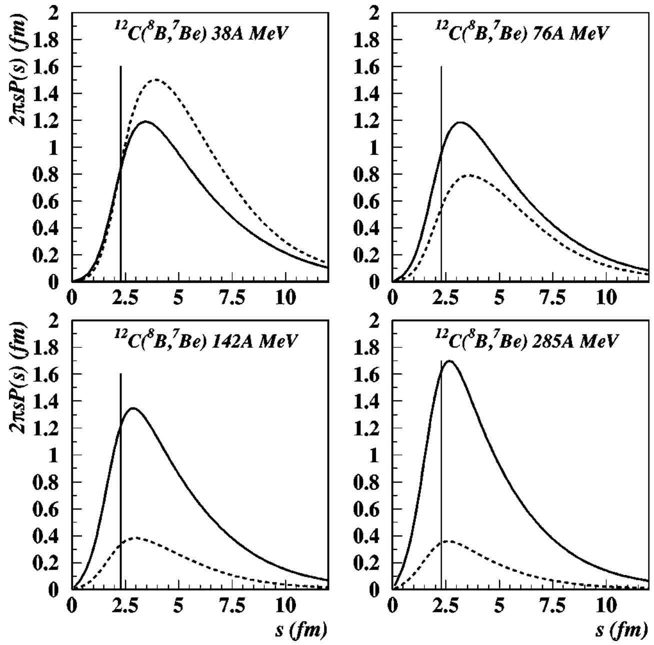

FIG. 3. The breakup probability profiles as a function of the impact parameter s for the breakup of ^{8}B on C targets at four different energies. The stripping (full lines) and the diffraction dissociation (dashed lines) components are shown. The vertical line shows the position of the ^{7}Be core rms radius.

tial that was used to bind the proton p around the ^{7}Be core in the ground state of ^{8}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}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 (not renormalized) amplitudes resulting from perturbation theory [25], 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. Overall, assuming a ±10% variation of the Coulomb breakup cross section would result in changes in the extracted ANC values that range from 0.2% for the C targets to a maximum of 6.4% for the Pb target at 285 MeV/nucleon. The value found above for the ANC is in very good agreement with that determined before using the peripheral proton transfer reactions ^{10}B(^{7}Be, ^{8}B)^{9}Be and ^{14}N(^{7}Be, ^{8}B)^{13}C at 12 MeV/nucleon [26] $C^2_{\mathrm{tot}}(p)=0.449\pm0.045$ fm^{-1} and with that obtained from the study of the mirror neutron transfer reaction (^{7}Li, ^{8}Li) $C^2_{\mathrm{tot}}(n)=0.455\pm0.047$ fm^{-1} [14]. They agree very well, in spite of the differences in the energy ranges and in the reaction mechanisms involved. The ANC

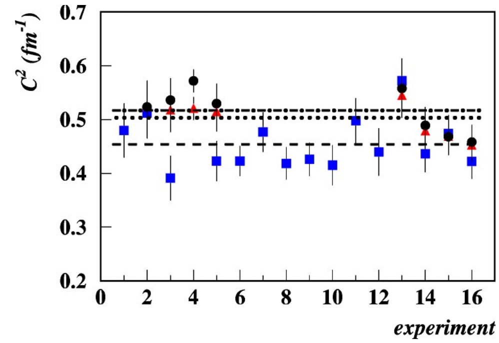

FIG. 4. (Color online) The ANCs determined from the breakup of ^{8}B at 30–1000 MeV/nucleon on C, Al, Sn, and Pb targets, using three *NN* effective interactions: JLM (squares), "standard" (circles), and "Ray" (triangles). See text for details. The dashed, dotted, and dash-dotted lines are the average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

extracted with JLM leads to the astrophysical factor $S_{17}(0)=17.5\pm1.8$ eV b for the key reaction for solar neutrino production ^{7}Be(p,γ)^{8}B.

In a second approach, the Glauber model in the optical limit [27] was used. The breakup process is treated as multiple elementary interactions between the partners' 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 [28]. No new parameters were adjusted. For details on the procedure see Ref. [5].

For all the effective *NN* interactions we checked that they correctly describe complementary data, such as proton-target and ^{7}Be-target elastic and total reaction cross sections, where available. Data at energies higher than 50*A* MeV were selected. We did not include the measurements of Ref. [29] at 1440 MeV/nucleon and of Ref. [30] at 1471 MeV/nucleon [highest energy points in Fig. 1(a)], 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. 4), but the average values obtained are slightly different: $C^2_{\mathrm{tot}}(\mathrm{standard})=0.503\pm0.032$ fm^{-1} and $C^2_{\mathrm{tot}}(\mathrm{Ray})=0.517\pm0.041$ 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 $C^2_{\mathrm{tot}}(\mathrm{ave})=0.483\pm0.050$ fm^{-1} that leads to $S_{17}(0)=18.7\pm1.9$ 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 Ref. [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_s 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 $R_s=0.88$ 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 $R_{\text{ave}}=0.98\pm0.16$.

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 Refs. [32–35]), 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 $S_{17}(0)=18.7\pm1.9$ eV b is virtually equal with the most probable values extracted in Ref. [32] $S_{17}(0)=18.6\pm1.2(\text{stat})\pm1.0(\text{theor})$ eV b and in Ref. [33] $S_{17}(0)=18.6\pm0.4(\text{stat})\pm1.1(\text{theor})$ 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 breakup reactions, indicating that accuracies to +/−10% can be obtained.

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