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Determination of S_{17} from the ^{7}Be$(d,n)^8$B reaction

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The astrophysical factor S_{17} for ^{7}Be$(p,\gamma)^8$B reaction is reliably extracted from the transfer reaction ^{7}Be$(d,n)^8$B at $E=7.5$ MeV with the asymptotic normalization coefficient method. The transfer reaction is accurately analyzed with CDCC based on a three-body model. This analysis is free from uncertainties of the optical potentials having been crucial in the previous DWBA analyses.

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The solar neutrino problem is a central subject in neutrino physics [1]. The major source of the high-energy neutrinos observed by solar neutrino detectors is ^{8}B produced by the ^{7}Be$(p,\gamma)^8$B reaction. The astrophysical factor S_{17} for the reaction, however, is one of the most poorly determined reaction rates in the standard solar model; the latest recommendation for the factor S_{17} at zero energy, $S_{17}(0)$, based on recent direct measurements, is 19^{+4}_{-2} eV b [2], i.e., 10–20 % error exists. This is far from our goal of determining $S_{17}(0)$ within 5% error required in order to determine the neutrino oscillation parameters: the mass difference between ν_e and ν_μ and their mixing parameter. The main difficulty in the direct measurement comes from ambiguities of determining the effective target thickness. Thus, indirect measurements of $S_{17}(0)$ are expected to be essential for determining $S_{17}(0)$ accurately.

As an example of such indirect measurements, intensive measurements of ^{8}B Coulomb breakup are being made [3–5] that provide rather small $S_{17}(0)$ of about 17–20 eV b. Alternatively, one-proton pickup (removal) process by ^{7}Be (^{8}B) is also an important tool to determine $S_{17}(0)$ [6–8]; once the asymptotic normalization coefficient (ANC) of the overlap function between the ^{7}Be and ^{8}B ground states is determined from the data of the proton-transfer reaction, $S_{17}(0)$ can be accurately derived from the ANC, as long as the reaction is peripheral [9]. We here take up the transfer reaction ^{7}Be$(d,n)^8$B at $E=7.5$ MeV, which has been used to extract the ANC with the distorted wave Born approximation (DWBA) [10]. The $S_{17}(0)$ obtained there is 27.4 ± 4.4 eV b, leading to inconsistency with the recommended value. Although the reaction is found with DWBA to be indeed peripheral [11,12], distorting potentials used in DWBA are quite ambiguous, which prevent one from extracting $S_{17}(0)$ accurately. In particular, uncertainties of the d-^{7}Be optical potential bring about large errors for $S_{17}(0)$, typically 30% in magnitude. The origin of the large ambiguity of distorting potentials is that these are derived from proton and deuteron optical potentials for different targets and/or energies.

In the present Rapid Communication, we analyze ^{7}Be$(d,n)^8$B at 7.5 MeV with the three-body model, $p+n+^7$Be, assuming ^{7}Be to be an inert core. An advantage of this analysis is that we do not need the ambiguous $d+^7$Be optical potential in the entrance channel and the ambiguous $n+^8$B one in the exit channel as shown below.

The three-body dynamics in the entrance channel are explicitly treated by means of continuum-discretized coupled-channels (CDCC) method [13,14], the theoretical foundation of which is given in Ref. [15]. This theory has been established as a method of solving the three-body system with good accuracy, and extensively applied for various reactions [13,16]. Previous CDCC calculation showed that explicit treatment of breakup channels is essential in describing deuteron induced reactions [13]. The CDCC thus provides a precise description of the wave function in the entrance channel, i.e., d-^{7}Be system.

The effective Hamiltonian for the entrance channel based on the three-body model contains the optical potential between N (p or n) and ^{7}Be. Data of the neutron elastic scattering are available for target ^{7}Li, the mirror nucleus of ^{7}Be, at 4 MeV, approximately half the deuteron energy considered here [17]. First the n-^{7}Li potential is determined accurately from the data. The potential is then used as an input in CDCC calculation for deuteron elastic scattering on ^{7}Li at 8 MeV, and the numerical result is compared with the experimental data [18]. This is a good test for the neutron optical potential determined above, which is only an input in CDCC calculation for the entrance channel. As for the exit channel, the three-body dynamics are treated with the adiabatic approximation, after testing its accuracy with CDCC calculation. The ANC is then obtained with reliable distorted wave functions in both the entrance and exit channels.

The transition amplitude for the transfer reaction, based on the three-body model ($p+n+^7$Be), is

$$T_{\rm fi}=S_{\rm exp}^{1/2}\langle\Psi_{\rm f}^{(-)}|V_{np}|\Psi_{\rm i}^{(+)}\rangle. \tag{1}$$

The three-body wave function $\Psi_{\rm i}^{(+)}$ is a solution of the Schrödinger equation $(H_{\rm i}-E)\Psi_{\rm i}^{(+)}=0$ for the three-body Hamiltonian

$$H_i=K_{np}+K_{d\rm Be}+V_{np}(r_{np})+U, \tag{2}$$

with $U=U_{n\rm Be}(\mathbf{r}_{n\rm Be})+U_{p\rm Be}(\mathbf{r}_{p\rm Be})$. Here $\mathbf{r}_{XY}$ is the coordinate of nucleus X relative to nucleus Y. The potential V_{np} is

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the interaction between n and p, $U_{p\mathrm{Be}}$ ($U_{n\mathrm{Be}}$) is the proton (neutron) optical potential for the target ^{7}Be at half the deuteron incident energy, and K_{np} and $K_{d\mathrm{Be}}$ show kinetic energy operators for two-body systems denoted by the subscripts. The nuclear part of $U_{p\mathrm{Be}}$ is assumed to be the same as $U_{n\mathrm{Be}}$. The Coulomb part of $U_{p\mathrm{Be}}$ is treated approximately by replacing the coordinate $\mathbf{r}_{p\mathrm{Be}}$ by $\mathbf{r}_{d\mathrm{Be}}$. Effects of Coulomb breakup of the deuteron, not included in the usual treatment above, are found to be quite small in the present system.

The wave function $\Psi_{\mathrm{i}}^{(+)}$ is obtained with CDCC, that is, by solving the Schrödinger equation in a model space. In CDCC, deuteron breakup states are classified with linear and angular momenta, k and ℓ, and truncated into $0 \leqslant k \leqslant k_{\max}$ and $0 \leqslant \ell \leqslant \ell_{\max}$, respectively. The k continuum $[0, k_{\max}]$ is further divided into bins with a common width Δ. The total wave function is expanded, in terms of the deuteron ground state and the discretized breakup states, into $\Psi_i^{(+)} = \Sigma_{i=0}^{i_{\max}} \phi_i(\mathbf{r}_{np}) \chi_i(\mathbf{r}_{d\mathrm{Be}})$, where ϕ_0 is the deuteron ground state and ϕ_i ($i \neq 0$) is the ith discretized breakup state obtained by averaging continuous breakup states in the ith bin. The coefficient χ_i represents a center-of-mass motion of n-p pair in the ith state. Inserting this form into the three-body Schrödinger equation leads to a set of coupled differential equations,

$$(E_i - K_{d\mathrm{Be}})\chi_i = \sum_j F_{ij}\chi_j, \tag{3}$$

with $F_{ij} = \langle \phi_i | U | \phi_j \rangle_{\mathbf{r}_{np}}$ and $E_i = E - e_i$, where e_i is an intrinsic energy of the ith n-p state. The coupled equations are soluble, since they have a compact kernel in its integral equation form. The precise formulation of CDCC is shown in Ref. [14]. The present model space is $k_{\max} = 1.7$ fm^{-1}, $\ell = 0$, 2 and $\Delta = 1.7/40$ fm^{-1}. The CDCC solution converges at these values, as the model space is enlarged.

The exit channel is also treated in the three-body model, that is, the exit channel wave function $\Psi_f^{(-)}$ is determined by the three-body Hamiltonian

$$H_f = K_{p\mathrm{Be}} + K_{n\mathrm{B}} + V_{p\mathrm{Be}}(\mathbf{r}_{p\mathrm{Be}}) + U_{n\mathrm{Be}}(\mathbf{r}_{n\mathrm{Be}}). \tag{4}$$

In the three-body model, ^{8}B is treated by the two-body ($p + ^7$Be) model with the potential $V_{p\mathrm{Be}}$. The spectroscopic factor S_{exp} in Eq. (1) is introduced by taking account of the incompleteness of the model. It should be noted that H_f does not contain V_{np} since the interaction is already treated as a transition operator in Eq. (1). In general, the distorting potential $U_{n\mathrm{Be}}$ between an outgoing neutron and ^{7}Be differs from the corresponding one in H_i, since an outgoing neutron has a different velocity from an incoming deuteron in the (d,n) reaction.

In principle, H_f allows transitions between the ground and continuum states of the $p + ^7$Be system in the exit channel. However, effects of the transitions are quite small and simply estimated with the adiabatic approximation, since the ground state of ^{8}B has a binding energy (0.137 MeV) considerably smaller than an energy (4.18 MeV) of outgoing neutron. Following Johnson and Soper [19], we replace the Hamiltonian of the $p + ^7$Be system by the binding energy of ^{8}B. Errors of the adiabatic approximation are estimated with CDCC in the exit channel scattering, $^8\mathrm{B}(n,n)^8\mathrm{B}$, at $E = 4.18$ MeV. The breakup effect is indeed small and errors of the approximation are about 3% at forward angles (below 60°). It should be noted that the breakup effect of ^{8}B on the elastic scattering is not always the same as that on the transfer process. It was reported in Ref. [20], however, that the latter is much smaller than the former. We thus conclude that the error of our calculation about the adiabatic approximation for the exit channel is less than 3%. The Johnson-Soper approximation leads to a simple form $\Psi_f^{(-)} = \chi_{n\mathrm{B}}^{(-)} \phi_{p\mathrm{Be}}$, where $\phi_{p\mathrm{Be}}$ is the wave function of ^{8}B in its ground state and $\chi_{n\mathrm{B}}^{(-)}$ is the wave function of outgoing neutron distorted by the potential $U_{n\mathrm{Be}}(r_{n\mathrm{B}} \cdot 8/7)$, where the zero-range approximation is made to the transition amplitude (1). We discuss the use of this approximation below. It should be noted that in DWBA $\chi_{n\mathrm{B}}^{(-)}$ is determined by the elastic scattering of neutron from ^{8}B, of which no measurement has been done so far. On the other hand, the three-body model approach can avoid this difficulty, as in the entrance channel.

The transfer reaction $^7\mathrm{Be}(d,n)^8\mathrm{B}$ is calculated with the zero-range approximation with its finite-range correction [21]. The integration over $\mathbf{r}_{p\mathrm{Be}}$ in T is made up to a large value 40 fm, since the transferred proton is very weakly bound in ^{8}B. The finite-range correction for the transition amplitude (1) including deuteron ground and breakup channels is straightforward; the resultant correction for the ith channel keeps the standard form by regarding F_{ii} and e_i as the potential and the intrinsic energy of the entrance channel. This prescription is tested by doing finite-range DWBA calculation [22] for the deuteron ground channel which is a main component of the transition amplitude (1). The result of the prescription above agrees with that of the full finite-range calculation within 2% error at forword angles.

The wave function $\phi_{p\mathrm{Be}}$ is calculated with four types of $V_{p\mathrm{Be}}$ [23–26]. We determine the spectroscopic factor S_{exp} comparing the calculated $^7\mathrm{Be}(d,n)^8\mathrm{B}$ cross section with the experimental one, for every type of the four potentials. The astrophysical factor $S_{17}(0)$ at zero energy is then obtained from the S_{exp} with $S_{17}(0) = S_{\mathrm{exp}}\alpha^2/0.026$ in the ANC

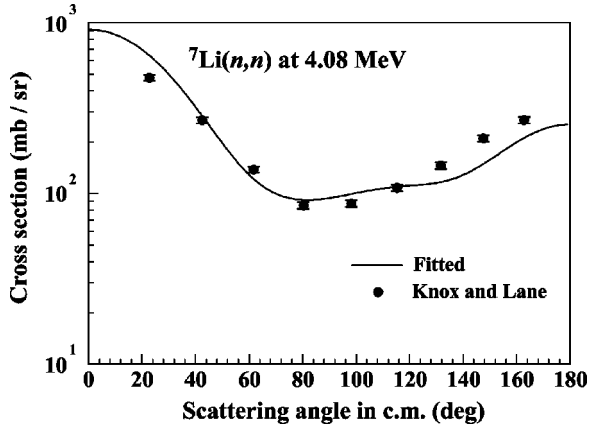

FIG. 1. Results of the optical potential search for neutron elastic scattering at 4.08 MeV from ^{7}Li. Experimental data are taken from Ref. [17].

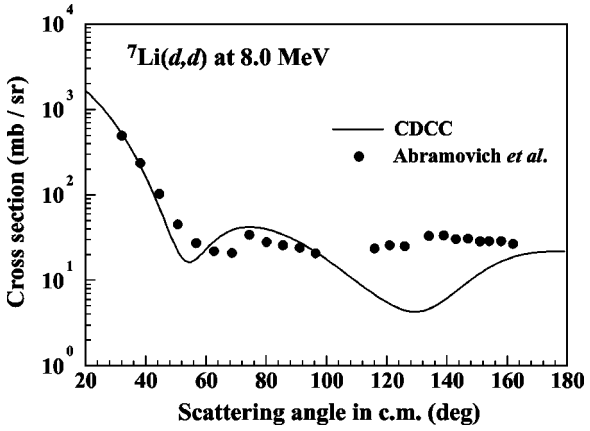

FIG. 2. Comparison between the CDCC calculation and the experimental data [18] for ^{7}Li$(d,d)^7$Li at 8.0 MeV.

method [9], where α is defined with the Whittaker function W as $\phi_{p\mathrm{Be}}(r_{p\mathrm{Be}})=\alpha W(r_{p\mathrm{Be}})$ at $r_{p\mathrm{Be}}$ larger than the range of the nuclear force $V_{p\mathrm{Be}}$ between p and ^{7}Be. It should be noted that if the reaction is peripheral, ANC should be stable against the change of the ^{8}B internal wave functions, i.e., that of the parameter set of single-particle potentials. Thus, one can estimate the error of the ANC calculation from the deviation of ANC (or S_{17}) with four different models of ^{8}B above.

Figure 1 shows the result of the optical potential search for neutron scattering at 4.08 MeV from ^{7}Li, the mirror nucleus of ^{7}Be. The resultant potential shows a good agreement with data [17]. The optical potential is then applied for deuteron scattering at 8.0 MeV from ^{7}Li. The CDCC calculation with the potential again gives a good agreement with data [18] at angles $\theta<60°$, as shown in Fig. 2. The potential is shown to be reliable especially at the forward angles; we use it in H_i and obtain the proper wave function for the entrance channel. As for the exit channel, on the other hand, we need the optical potential of the $n+^7$Li scattering at $E=4.18$ MeV to determine H_f. The data are available at $E=4.26$ MeV that is closest to the proper energy. Figure 3 shows the result of the optical potential search for the scattering. The resulting potential well reproduces the data [27] at forward angles.

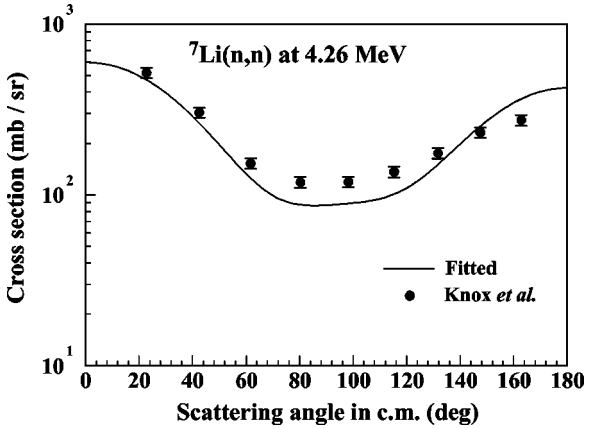

FIG. 3. Results of the optical potential search for neutron elastic scattering at 4.26 MeV from ^{7}Li. Experimental data are taken from Ref. [27].

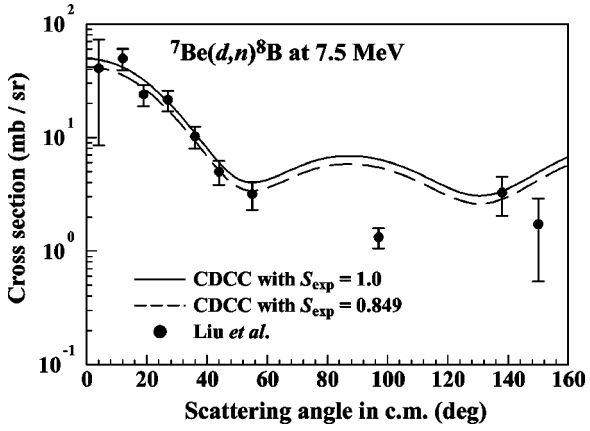

FIG. 4. The calculated cross sections for ^{7}Be$(d,n)^8$B at 7.5 MeV with $S_{\mathrm{exp}}=1.0$ (solid line) and 0.849 (dashed line), compared with the experimental data [10].

Figure 4 shows our result for the ^{7}Be$(d,n)^8$B cross section using $V_{p\mathrm{Be}}$ of Kim *et al.* [23], compared with the experimental data [10]. The solid and dashed lines represent the calculated results with $S_{\mathrm{exp}}=1.0$ and 0.849, respectively. Parameter sets of the optical potentials at 4.08 and 4.26 MeV and the single-particle potential of Kim *et al.* used in the calculation are listed in Table I together. At forward angles $\theta<60°$, the calculated cross section well reproduces the data [10] with the spectroscopic factor $S_{\mathrm{exp}}=0.849$, leading to $S_{17}(0)=21.36$ eV b. It was found that deuteron breakup states play important roles not only in determining distorting potentials but also in the transfer process. In fact, when the deuteron breakup component is set to zero in $\Psi_i^{(+)}$, the resultant transfer cross section is reduced by 10% at the forward angles and, more seriously, the angular distribution cannot be reproduced correctly. The components are obviously not included in the framework of the standard DWBA. We thus conclude that the three-body model approach is inevitable.

We show in Table II the list of calculated S_{exp}, α, and $S_{17}(0)$ for different V_pBe. One sees that the calculated values of $S_{17}(0)$ are almost consistent, which shows that, as mentioned above, the present reaction is peripheral and the ANC method works well. Taking account of the theoretical errors of ANC, the adiabatic approximation (AD) and the finite-range correction (FRC)

TABLE I. Parameters for the optical potentials between neutron and ^{7}Li at $E_n=4.08$ (a) and 4.26 MeV (c) corresponding to the initial and final channels for ^{7}Be$(d,n)^8$B at $E_d=7.5$ MeV, respectively. The single particle potential between p and ^{7}Be in ^{8}B of Kim *et al.* [23] (b) is also shown.

	V_0	r_0	a_0	W_d	r_i	a_i	V_{so}	r_{so}	a_{so}
a	46.57	2.07	0.49	0.82	1.87	0.22	5.50	1.15	0.50
b	32.12	1.54	0.52	—	—	—	8.24	1.54	0.52
c	60.97	1.47	0.58	0.31	3.57	0.22	9.0	2.39	0.55

TABLE II. Results of $S_{\rm exp}$, α, and $S_{17}(0)$ with different ^{8}B single particle models.

	$S_{\rm exp}$	α	$S_{17}(0)$
Kim *et al.* [23]	0.849	0.809	21.36
Tombrello [24]	0.882	0.784	20.87
Robertson [25]	0.864	0.794	20.93
Esbensen and Bertsch [26]	1.097	0.700	20.67

and of thesystematic error of the experimental data [10] on the ^{7}Be$(d,n)^8$B cross section, we obtain $S_{17}(0) = 20.96^{+0.4}_{-0.3}(ANC)\pm 0.63(AD)\pm 0.42(FRC)\pm 2.7$(expt) eV b, consistent with both the recommended values [2] and the recent result $S_{17}(0) = 22.3 \pm 1.2$ eV b of accurate direct measurement [28]. Very recently, it was reported that a significant $1/2^-$ ^{7}Be excited state component of order 10% presents within the ^{8}B ground state [29]. It suggests the possibility that reorientation in ^{8}B has a definite role in the transfer process considered here and so $S_{17}(0)$. Further investigation on this effect is highly expected.

In summary, the present analyses based on the three-body model are free from uncertainties of the optical potentials in both the entrance and exit channels which were the most essential problems in the previous DWBA analyses. The deuteron breakup process in the incident channel is significant for determining $S_{17}(0)$ within 5% error required from the neutrino physics. We then conclude that the three-body model approach is essential and necessary. The present analyses provide a precise value $S_{17}(0) = 20.96^{+1.4}_{-1.3}$(theor) ± 2.7(expt) eV b; the theoretical ambiguity of $S_{17}(0)$ is 6–7 % slightly beyond the required accuracy. However, we can reduce the theoretical error to $\sim$2% coming from ANC only, if we do the finite-range calculation with accurate $\Psi_i^{(+)}$ and $\Psi_f^{(-)}$ derived by CDCC. Such full-fledged calculations are highly expected. In the present analyses, however, the experimental error (13%) is even larger than the theoretical one. It is expected that the peripheral properties, essential for the ANC method, become insufficient, as the incident energy increases [12]. Thus, accurate measurements on ^{7}Be$(d,n)^8$B and ^{7}Li$(d,d)^7$Li at about a few tens of MeV and on ^{7}Li$(d,d)^7$Li at the half the corresponding deuteron incident energy are highly expected; the proton and deuteron elastic scattering are necessary to determine the nucleon optical potential accurately.

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[1] J. N. Bahcall *et al.*, Astrophys. J. **555**, 990 (2001), and references therein.
[2] E. G. Adelberger *et al.*, Rev. Mod. Phys. **70**, 1265 (1998).
[3] T. Motobayashi *et al.*, Phys. Rev. Lett. **73**, 2680 (1994).
[4] N. Iwasa *et al.*, Phys. Rev. Lett. **83**, 2910 (1999).
[5] B. Davids *et al.*, Phys. Rev. Lett. **86**, 2750 (2001).
[6] A. Azhari *et al.*, Phys. Rev. C **60**, 055803 (1999).
[7] A. Azhari *et al.*, Phys. Rev. Lett. **82**, 3960 (1999).
[8] L. Trache *et al.*, Phys. Rev. Lett. **87**, 271102 (2001).
[9] H. M. Xu *et al.*, Phys. Rev. Lett. **73**, 2027 (1994).
[10] Weiping Liu *et al.*, Phys. Rev. Lett. **77**, 611 (1996).
[11] C. A. Gagliardi *et al.*, Phys. Rev. Lett. **80**, 421 (1998).
[12] J. C. Fernandes *et al.*, Phys. Rev. C **59**, 2865 (1999).
[13] M. Kamimura *et al.*, Prog. Theor. Phys. Suppl. **89**, 1 (1986); N. Austern *et al.*, Phys. Rep. **154**, 125 (1987).
[14] R. A. D. Piyadasa *et al.*, Phys. Rev. C **60**, 044611 (1999).
[15] N. Austern *et al.*, Phys. Rev. Lett. **63**, 2649 (1989); Phys. Rev. C **53**, 314 (1996).
[16] J. A. Tostevin *et al.*, Phys. Rev. C **66**, 024607 (2002), and references therein.
[17] H. D. Knox and R.O. Lane, Bull. Am. Phys. Soc. **23**, 942 (1978).
[18] S. N. Abramovich *et al.*, Izv. Ross. Akad. Nauk, Ser. Fiz. **40**, 842 (1974).
[19] R. C. Johnson and P. R. J. Soper, Phys. Rev. C **1**, 976 (1970).
[20] A. M. Moro *et al.*, Phys. Rev. C **66**, 024612 (2002).
[21] J. A. Buttle and L. J. B. Goldfarb, Proc. Phys. Soc. London **83**, 701 (1964).
[22] M. Igarashi, Program TWOFNR (unpublished).
[23] K. H. Kim *et al.*, Phys. Rev. C **35**, 363 (1987).
[24] T. A. Tombrello, Nucl. Phys. **71**, 459 (1965).
[25] R. G. H. Robertson, Phys. Rev. C **7**, 543 (1973).
[26] H. Esbensen and G. F. Bertsch, Nucl. Phys. **A600**, 66 (1996).
[27] H. D. Knox *et al.*, Nucl. Sci. Eng. **69**, 223 (1979).
[28] A. R. Junghans *et al.*, Phys. Rev. Lett. **88**, 041101 (2002).
[29] D. C. -Gil *et al.*, Phys. Lett. B **529**, 36 (2002).