Astrophysical $S_{17}(0)$ factor from a measurement of the ^{2}H(^{7}Be,^{8}B)n reaction at $E_{c.m.} = 4.5$ MeV

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Angular distribution measurements of ^{2}H(^{7}Be,^{7}Be)^{2}H and ^{2}H(^{7}Be,^{8}B)n reactions at $E_{c.m.} \sim 4.5$ MeV were performed to extract the astrophysical $S_{17}(0)$ factor using the asymptotic normalization coefficient (ANC) method. For this purpose a pure, low emittance ^{7}Be beam was separated from the primary ^{7}Li beam by a recoil mass spectrometer operated in a novel mode. A beam stopper at 0° allowed for the use of a higher ^{7}Be beam intensity. Measurement of the elastic scattering in the entrance channel using kinematic coincidence, facilitated the determination of the optical model parameters needed for the analysis of the transfer data. The present measurement significantly reduces errors in the extracted ^{7}Be(p, γ) cross section using the ANC method. We get S_{17} (0) = 20.7 ± 2.4 eV b.

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Recently, the Sudbury Neutrino Observatory (SNO) group discovered, in a simultaneous measurement of the electron neutrino flux and the sum of three active neutrino fluxes, that a large fraction of the high energy electron neutrinos emitted in the β^{+} decay of ^{8}B in the Sun is transformed into other active neutrino flavors on their way to detectors on the Earth [1]. Together with the observation that the reactor produced antineutrinos also oscillate [2], it seems that a solution of the solar neutrino problem is at hand. To ascertain more accurately if there is a transformation of solar electron neutrinos into sterile neutrinos the precision of both experimental measurements and theoretical predictions must be improved [3]. In order to make more accurate theoretical predictions of the ^{8}B neutrino flux, the rate [or the related zero energy astrophysical S-factor, $S_{17}(0)$] of the reaction ^{7}Be(p, γ)^{8}B that produces ^{8}B in the Sun must be better determined [4].

Recent precision ^{7}Be(p, γ) measurements have yielded values of $S_{17}(0)$ which are clustered around 18.5 eV b [5] and 22.0 eV b [6] and are not consistent with each other within the quoted errors. In view of this discrepancy the determination of $S_{17}(0)$ by other methods, with different systematic errors, is necessary. One kind of indirect measurement uses the Coulomb dissociation of ^{8}B [7] where the latest experiment has yielded a $S_{17}(0)$ of 18.6 eV b [8]. The other technique uses the (^{7}Be,^{8}B) transfer reaction to extract the magnitude of the asymptotic radial wave function, characterized by the asymptotic normalization coefficient (ANC), of the proton in ^{8}B. This is then used to calculate the value of $S_{17}(0)$ [9]. The ANC method has been experimentally validated through the agreement of the measured ^{16}O(p,γ) cross section and that derived from the data on ^{16}O(^{3}He,d)^{17}F reaction [10]. Recently, the $S_{17}(0)$ has been extracted from the transfer reactions ^{10}B(^{7}Be,^{8}B)^{9}Be and ^{14}N(^{7}Be,^{8}B)^{13}C yielding values of 17.8 ± 2.8 and 16.6 ± 1.9 eV b, respectively [11].

Because of the precise knowledge of the proton wave function in the deuteron and a simpler exit channel (which makes it more amenable to continuum discretized coupled channel (CDCC) methods [12]), the d(^{7}Be,^{8}B)n reaction may still be an attractive choice for the extraction of $S_{17}(0)$ with the ANC method provided the data are taken at beam energies where this reaction is peripheral. It has been shown [13] that for entrance channel center of mass (c.m.) energies around or below 6.0 MeV this condition is fulfilled for this reaction. Liu *et al.* [14] have reported a $S_{17}(0)$ of 27.4 ± 4.4 eV b from the analysis of their d(^{7}Be,^{8}B)n experiment done at $E_{c.m.} =$ 5.8 MeV. However, it has been pointed out [13,15] that there may be a large uncertainty in the value of $S_{17}(0)$ extracted from this experiment due to lack of the knowledge of the entrance and exit channel optical model parameters (OMP) as the corresponding elastic scattering data are not available.

The present work is a significant improvement over the earlier work of Liu *et al.* [14]. The ^{7}Be beam was produced by operating the existing recoil mass spectrometer, HIRA [16], in a novel optical mode leading to a beam of superior quality (purity >99.9%, beam spot size ≈3 mm, angular divergence of ±1°). This allowed for the use of a stopper in the beam path enabling the use of a higher intensity (by a factor of ≈10) beam thus reducing the statistical errors significantly. In a separate experiment, to obtain the entrance channel OMP, the elastic scattering angular distribution was measured using kinematic coincidence to eliminate the background from other target elements. These have allowed a more precise measurement of the $d(^7\mathrm{Be},^8\mathrm{B})n$ angular distribution at the lowest energy of $E_{\mathrm{c.m.}} = 4.5$ MeV and the determination of $S_{17}(0)$ by the ANC method.

The measurements were made at Nuclear Science Centre, New Delhi, using a radioactive ion beam of 21.0 ± 0.5 MeV ^{7}Be incident on a 1.05 mg/cm^2 deuterated polyethylene $(CD_2)_n$ target. The ^{7}Be was produced through the $p(^7\mathrm{Li},^7\mathrm{Be})n$ reaction at E(^{7}Li) = 25 MeV using a pulsed ^{7}Li beam (intensity $\sim 3 \times 10^{10}$/s) from the 15UD Pelletron, at a 4 MHz repetition rate and FWHM ~2 nsec, to obtain an average ^{7}Be intensity of 3000/s. The deterioration of the production target, a 20 μm polyethylene $(CH_2)_n$ foil, was minimized by automated linear and rotary motions. The forward going ^{7}Be particles were selected using the recoil mass spectrometer, HIRA, operated in a new ion optical mode optimized for such inverse kinematic reactions [17]. In this mode the reaction products of interest were focused through a slit placed at the center of the magnetic dipole to reject the primary beam. The selected secondary ion beam was refocused at the target such that the beam spot was a replica of that at the production target. Two silicon telescopes placed at $\pm 30^\circ$ with respect to the beam direction were used in the primary target chamber to measure the recoil protons. The ratio of counts in the recoil proton peak from the production target to the counts of ^{7}Be in the secondary reaction chamber was monitored and kept constant to ensure an identical and reproducible trajectory of ^{7}Be through HIRA. A 3 mm diameter graphite collimator placed 86 mm upstream of the target was used to limit any unforeseen wandering of the beam spot. The X-Y profile of the ^{7}Be beam was monitored using a multiwire proportional counter (MWPC) placed ~90 mm behind the target. The MWPC had entrance and exit windows of 1.5 μm polyethylene and was operated using isobutane gas at a pressure of 5 mbar. A 4 mm diameter tantalum disk mounted on a thin (0.25 mm ϕ) wire, at a distance of 114 mm from the target, stopped the main beam. This reduced the beam flux incident on the downstream detector telescope by a factor of ~8. The detector telescope consisted of a ΔE gas ionization chamber (IC) followed by a 50×50 mm^2 two dimensional position sensitive Si-E detector (PSSD). The IC had an opening of 55×55 mm^2, active depth of 60 mm, and was operated at a pressure of 50 mbar. The position and energy resolutions of the PSSD and IC were measured to be <2 mm, 200 keV and 200 keV, respectively, using a ^{241}Am alpha source. The energy, position, pileup parameter (generated from the zero crossover time of the bipolar E pulse) and time of flight (TOF) with respect to the timing reference of the beam pulsing system together with the scaled down monitor detector energy signals were recorded in an event by event mode. The MWPC energy output was recorded independently in a multichannel analyzer to minimize the dead time in the data acquisition system. This was used to obtain the integrated ^{7}Be beam intensity. A 10 Hz precision pulser was used to monitor the dead time of the data acquisition system as well as the electronic gain of, and noise in, the detector system. The response of the detector telescope was continuously monitored using a weak ^{229}Th alpha source. The count rate in the detector

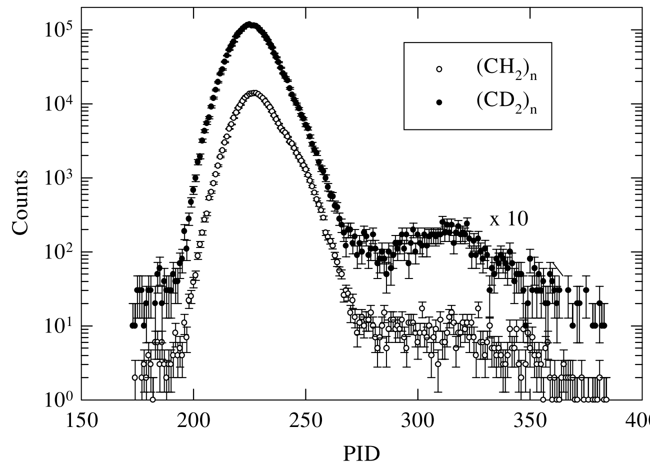

FIG. 1. (a) Particle identification (PID) spectrum for the polyethylene target with suitable energy, pileup and TOF cuts (see text) for a integrated ^{7}Be flux of 1.65×10^8 particles. (b) PID spectrum for deuterated polyethylene target.

was kept constant to within $\pm 10\%$ so as to keep the pileup fraction similar for different runs.

The beam profile was maintained within $\pm$ 0.25 mm during the runs for an accurate angular definition. The stopper allowed a tenfold increase in the ^{7}Be intensity as compared to that of Liu *et al.* [14] for a similar pileup rate. HIRA was rotated to 2° and the scattered ^{7}Li, ^{7}Be, and ^{12}C ions were selected to calibrate the particle identification (PID) of the detector telescope in situ. This was essential in choosing the ΔE-E two dimensional (2D) gates for ^{8}B in conjunction with a SRIM [18] calculation. The $(CD_2)_n$ and $(CH_2)_n$ data with (without) stopper were taken for 4×10^8 (8×10^7) and 1.5×10^8 (2×10^7) ^{7}Be incident particles, respectively. The PID parameter was calculated in the standard way using the ΔE-E information [19]. Typical PID spectra after gating on the pileup, time-of-flight, and particle energy (to remove the elastically scattered ^{7}Be from the target) are shown in Fig. 1. The ^{8}B events were selected using suitable gates on PID, pileup parameter and TOF. The angular distribution was obtained using the position information from the PSSD. The position response of the latter was measured offline using an alpha source and a mask placed on the detector. An overall angular resolution of 0.9° was estimated taking into account the angular divergence, transverse beam profile, angular straggling in the target and gas, and the position resolution of the PSSD. The ^{8}B yields were corrected for small dead time losses and transmission loss in the MWPC.

Elastic scattering for the $^7\mathrm{Be} + d$ system was also measured at 20.3 ± 0.5 MeV using the same $(CD_2)_n$ target. The schematic of the experimental setup is shown in Fig. 2(a). In an elastic scattering event, the recoiling deuteron is detected in the annular detector (A2) and ^{7}Be in the forward detector telescope ΔE(gas)-Si 2D. The ^{7}Be particles reaching the detector telescope as a result of scattering from the collimator and ^{12}C [in $(CD_2)_n$ target] and from the beam halo have no coincident events in A2 and were eliminated. Although the inelastic contribution from the 429 keV state in ^{7}Be could not be resolved, its contamination to the elastic scattering yield is expected to be small (also supported by low energy

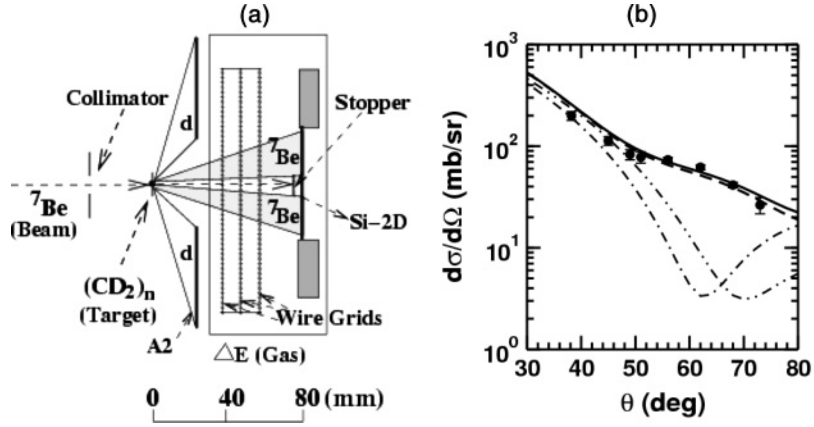

FIG. 2. (a) Schematic of detector setup used for elastic scattering measurement. (b) Angular distribution for the elastic scattering of deuteron on ^{7}Be at $E_{c.m.} = 4.4$ MeV. Curves are fits to the data using optical potentials S1 (solid). Results obtained from potential sets of S2 and S4 are not distinguishable from those shown. The dot-dashed and dot-dot-dashed lines represent the cross sections obtained with potential sets 1 and 2, respectively, of Ref. [14].

^{7}Li + ^{12}C scattering measurements) [20]. This has been checked by performing a calculation for the inelastic excitation cross section to the first excited state in ^{7}Be as discussed below. Figure 2(b) shows the experimental elastic differential cross sections.

These data were fitted in a standard optical model analysis using the code SNOOPY8Q [21]. The depths of the real and imaginary parts of the d-OMP were constrained by the method described in Ref. [22] where the d-OMP was calculated by folding the nucleon optical potentials corresponding to half the deuteron energy so as to resolve the discrete ambiguity in the d-OMP. Following Ref. [23], the radius parameters of both real and imaginary parts were varied in the range of 3.5 to 4.5 fm. In the fitting procedure, we applied an additional constraint that the total reaction cross section (σ_R) be close to $\sim$1.2 b which is obtained by calculations done with the OMP of Ref. [23] for the $d + {}^{7}$Li system at comparable energies and also from the measurements of σ_R reported for the $d + {}^{9}$Be system [24]. Four sets of best fit potentials obtained from a χ^2 minimization analysis of the data are shown in Table I. The fit to the elastic angular distributions obtained with potential S1 is shown in Fig. 2(b) (dashed line). Also shown in this figure is the sum of the elastic and inelastic (to the first excited state in ^{7}Be at 427 keV) cross sections (solid line). The latter has been calculated using the same set of d-^{7}Be OMP and β_2 of 0.6 [25]. Results obtained with sets S2-S4 are similar and cannot be distinguished from these curves. This figure also shows that the potentials sets 1 and 2 of Ref. [14] provide very poor fits to our elastic data. Similar poor fits are obtained using the potential sets given in Refs. [13,15]. While the fits could be improved upon by performing measurements with better statistics and having more data points, the present data on elastic scattering angular distribution can clearly discriminate between the different deuteron optical potentials and the potential sets extracted by us are the only ones which provide any reasonable fit to these data.

The measured $d(^{7}\text{Be},^{8}\text{B})n$ angular distribution (shown in Fig. 3) has been analyzed within the finite range distorted wave Born approximation (FRDWBA) using the code DWUCK5 [26] (with full transition operator) which has been modified to include external form factors (FF). The FF for the deuteron-neutron overlap has been obtained from the deuteron wave function (including both s and d states) corresponding to the Reid soft core potential. A two-body model for the p-^{7}Be system has been assumed where the proton occupies a single particle state $n\ell j$ and the ^{8}B (p-^{7}Be) overlap function is written

TABLE I. Parameters of the Woods-Saxon optical model potentials extracted from the analysis of the present $d + {}^{7}$Be ($E_{c.m.} = 4.4$ MeV) elastic scattering data. A spin orbit term with $V_{so} = 8.60$ MeV, $r_{so} = 2.17$ fm, and $a_{so} = 0.61$ fm, has been added to all the potential sets. The optical potential is defined as that in Ref. [27] with the light convention for the radius.

Pot.	V_0 (MeV)	r_0 (fm)	a_0 (fm)	$4W_s$ (MeV)	r_s (fm)	a_s (fm)
S1	103.12	2.23	0.62	79.03	2.37	0.17
S2	107.87	2.17	0.61	58.84	2.28	0.25
S3	92.54	2.41	0.57	117.50	2.45	0.14
S4	121.49	1.97	0.66	54.88	2.38	0.28

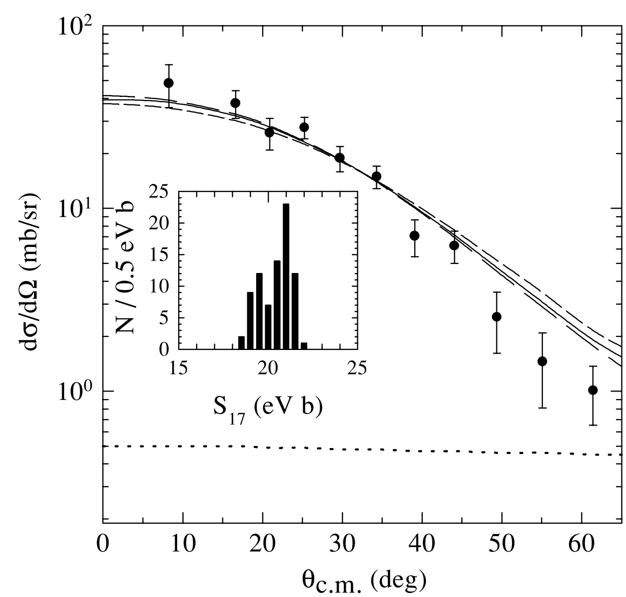

FIG. 3. Measured $d(^{7}\text{Be}, {}^{8}\text{B})n$ angular distribution together with the folded FRDWBA + CN cross sections shown as solid, short-, and long-dashed lines (see text). The calculated compound nuclear contributions are shown by the dotted line. The inset shows a histogram plot of the extracted $S_{17}(0)$ using the various combinations of d-^{7}Be, n-^{8}B OMP and p-^{7}Be bound state potentials (see text).

as $\mathcal{S}^{1/2}u_{n\ell j}(r)$. Here $u_{n\ell j}(r)$ is the normalized single particle radial wave function and $\mathcal{S}$ is the spectroscopic factor which is directly related to the ANC [9] and subsequently to the $S_{17}(0)$ factor. While the results obtained with the proton in the $0p_{3/2}$ orbital are given here, those calculated using the $0p_{1/2}$ proton configuration separately are almost identical. Five sets [27] of the neutron OMPs were used in the FRDWBA transfer calculations. These were obtained from the global parametrizations given in Ref. [28] (used extensively in Hauser-Feshbach calculations), from fits to $n + {}^{10,11}$B scattering at 9.72 MeV (two sets) and to $p + {}^9$Be scattering at 5 and 6 MeV (two sets). The compound nuclear (CN) contributions were calculated using a Hauser-Feshbach code HAFEST [29]. As can be seen from Fig. 3, these contributions are small ($\approx$7.5% at 44° and $\approx$1% at 8°). The uncertainty in the CN contributions was estimated to be around 50% (which, however, adds only about 1% to the overall theoretical uncertainty). This has been included in the systematic error of the extracted $S_{17}(0)$. The calculated transfer angular distributions have been folded using a Monte Carlo simulation which took into account the spatial, angular, and energy spread of the beam, the finite thickness of the target and the position resolution of the detector. The measured transfer angular distribution below 45° was used to extract the $S_{17}(0)$. This was done to (a) minimize the error arising from the contributions of CN and higher order processes which may affect the extracted $S_{17}(0)$ and (b) use the forward angle data to the maximum extent in order to reduce the statistical errors. These theoretical calculations at forward angles ($\theta_{\mathrm{c.m.}} \leqslant 45°$) were scaled to find the best fit to the data (from which the CN contribution is subtracted) yielding $\mathcal{S}$ which has been used to calculate $S_{17}(0)$ by the procedure discussed in Ref [9].

We have verified that the peripheral condition of the transfer reaction is fulfilled at our beam energy by two ways: (1) by using four different sets of bound state potentials for the p-^{7}Be system (given in Refs. [30–33]) which lead to a variation of the ANC by only ±3.5% whereas the calculated transfer cross sections changed by about 30%, and (2) by introducing a lower cutoff in the radial integrals where it was found that results (at the forward angles) obtained with a lower cutoff of up to 4.0 fm were almost identical to those obtained with no lower cutoff. It should also be noted that the multistep processes (inelastic excitation + transfer, breakup fusion) and core excitation in ^{8}B have negligible effect on these cross sections [34]. While calculating the S-factor the correction arising from the p-^{7}Be scattering length has been included [35].

The value of $S_{17}(0)$ and the systematic errors arising from the uncertainties in the $d + {}^7$Be OMP, $n + {}^8$B OMP parameters and the bound state wave function of the proton in ^{8}B have been estimated from four, five and four choices, respectively, for each of these inputs. Each of these 80 combinations was used to derive the best fit to the experimental transfer angular distribution and hence the corresponding $S_{17}(0)$. The range in which our calculated angular distributions lie can be seen from Fig. 3 (short and long dashed lines). The calculated angular distributions agree well with the data within the experimental uncertainty. The inset of Fig. 3 shows a histogram for the number of occurrences/0.5 eV b (N) for the $S_{17}(0)$ which ranges from 18.8 eV b to 22.1 eV b with a calculated mean and rms deviation of 20.7 eV b and 0.9 eV b, respectively. The distribution of these derived S-factors should give a reasonable estimate of the theoretical uncertainties considering the large number of combinations for the potentials used. The total systematic error after including the uncertainty in target thickness (±2% by weighing samples from the same stock of target material) is ±1.0 eV b. The statistical error estimated from these fits is ±1.4 eV b.

If the above exercise is carried out using the first three, five, and all 11 data points, starting from the most forward angles, the extracted $S_{17}(0)$ turns out to be 22.3 ± 2.7 eV b, 22.7 ± 1.9 eV b, and 18.5 ± 1.6 eV b, respectively. The mean S-factor from the analysis using these data sets and the eight data point set used earlier is 20.6 eV b. We may use this to estimate an additional error arising from the different choices of data points. This is probably a very conservative estimate of the error since it is expected that using the larger angle data makes it prone to contributions from higher order processes and uncertainties in compound nuclear contributions while use of only the most forward data points increases the statistical error while not making optimal use of the data. Nevertheless if this spread of 1.7 eV b is added in quadrature to the statistical and systematic errors mentioned earlier the overall error increases to 2.4 eV b. Since the systematic error alone contributes about 70% to the total error there is scope for reducing it. This would require a higher statistics elastic scattering and transfer measurement covering a larger angular range and the more elaborate CDCC calculations.

In conclusion, we have measured, for the first time, both the $d(^7\mathrm{Be},^8\mathrm{B})n$ transfer and the entrance channel elastic differential cross sections at the lowest beam energy hitherto using a high quality ^{7}Be beam from a recoil mass spectrometer operated in a novel optical mode. The extracted $^7\mathrm{Be}(p,\gamma)$ $S_{17}(0)$-factor, 20.7 ± 2.4 eV b is in good agreement with the latest direct capture measurements [6] and those determined from the CDCC analysis of the ^{8}B breakup reaction [36]. Thus the disagreement in the values of $S_{17}(0)$ determined by direct and indirect methods is reduced (see also Ref. [37]). This experiment, therefore, clearly demonstrates that the ANC method can be used for reasonably precise measurements of other (p,γ) S-factors involving short-lived nuclei, where direct capture measurements may be very difficult, if not impossible.

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[1] Q. R. Ahmad *et al*., Phys. Rev. Lett. **92**, 181301 (2004).
[2] K. Eguchi *et al*., Phys. Rev. Lett. **90**, 021802 (2003).
[3] J. N. Bahcall, M. H. Pinsonneault, and J. Basu, Astrophys. J. **555**, 990 (2001).
[4] E. G. Adelberger *et al*., Rev. Mod. Phys. **70**, 1265 (1998).
[5] F. Hammache *et al*., Phys. Rev. Lett. **86**, 3985 (2001).
[6] A. R. Junghans, E. C. Mohrmann, K. A. Snover, T. D. Steiger, E. G. Adelberger, J. M. Casandjian, H. E. Swanson, L. Buchmann, S. H. Park, and A. Zyuzin, Phys. Rev. Lett. **88**, 041101 (2002); Phys. Rev. C **68**, 065803 (2003); L. T. Baby *et al*., Phys. Rev. Lett. **90**, 022501 (2003).
[7] T. Motobayashi, Nucl. Phys. **A718**, 101c (2003) and references therein.
[8] F. Schumann *et al*., Phys. Rev. Lett. **90**, 232501 (2003).
[9] H. M. Xu, C. A. Gagliardi, R. E. Tribble, A. M. Mukhamedzhanov, and N. K. Timofeyuk, Phys. Rev. Lett. **73**, 2027 (1994).
[10] C. A. Gagliardi *et al*., Phys. Rev. C **59**, 1149 (1999).
[11] A. Azhari, V. Burjan, F. Carstoiu, H. Dejbakhsh, C. A. Gagliardi, V. Kroha, A. M. Mukhamedzhanov, L. Trache, and R. E. Tribble, Phys. Rev. Lett. **82**, 3960 (1999); A. Azhari, V. Burjan, F. Carstoiu, C. A. Gagliardi, V. Kroha, A. M. Mukhamedzhanov, X. Tang, L. Trache, and R. E. Tribble, Phys. Rev. C **60**, 055803 (1999).
[12] K. Ogata, M. Yahiro, Y. Iseri, and M. Kamimura, Phys. Rev. C **67**, 011602(R) (2003).
[13] J. C. Fernandes, R. Crespo, F. M. Nunes, and I. J. Thompson, Phys. Rev. C **59**, 2865 (1999).
[14] W. Liu *et al*., Phys. Rev. Lett. **77**, 611 (1996).
[15] C. A. Gagliardi, A. M. Mukhamedzhanov, R. E. Tribble, and H. M. Xu, Phys. Rev. Lett. **80**, 421 (1998).
[16] A. K. Sinha *et al*., Nucl. Instrum. Methods A **339**, 543 (1994).
[17] J. J. Das *et al*., J. Phys. G **24**, 1371 (1998).
[18] J. F. Zeigler, see the URL http://www.srim.org/
[19] F. S. Goulding, in *Treatise on Heavy-Ion Science*, Vol. 7, edited by D. A. Bromley (Plenum, New York, 1984).
[20] S. Kailas (private communication).
[21] P. Schwandt, SNOOPY8Q optical model code, Indiana University (unpublished).
[22] G. L. Wales and R. C. Johnson, Nucl. Phys. **A274**, 168 (1976).
[23] H. G. Bingham, A. R. Zander, K. W. Kemper, and N. R. Fletcher, Nucl. Phys. **A173**, 265 (1971).
[24] A. Auce, R. F. Carlson, A. J. Cox, A. Ingemarsson, R. Johansson, P. U. Renberg, O. Sundberg, and G. Tibell, Phys. Rev. C **53**, 2919 (1996).
[25] F. M. Nunes *et al*., Nucl. Phys. **A615**, 69 (1997).
[26] P. D. Kunz, University of Colarado report, 1978 (unpublished).
[27] C. M. Perey and F. G. Perey, At. Data Nucl. Data Tables **17**, 1 (1976).
[28] D. Wilmore and P. E. Hodgson, Nucl. Phys. **55**, 673 (1964).
[29] M. A. Eswaran, S. Kumar, E. T. Mirgule, and N. L. Ragoowansi, Phys. Rev. C **39**, 1856 (1989).
[30] F. C. Barker, Aust. J. Phys. **33**, 177 (1980).
[31] T. A. Tombrello, Nucl. Phys. **71**, 459 (1965).
[32] H. Esbensen and G. F. Bertsch, Nucl. Phys. **A600**, 66 (1996).
[33] R. G. H. Robertson, Phys. Rev. C **7**, 543 (1973).
[34] A. M. Moro, R. Crespo, F. M. Nunes, and I. J. Thompson, Phys. Rev. C **67**, 047602 (2003); F. M. Nunes and A. M. Mukhamedzhanov, *ibid*. **64**, 062801(R) (2001).
[35] D. Baye, Phys. Rev. C **62**, 065803 (2000); C. Angulo *et al*., Nucl. Phys. **A716**, 211 (2003).
[36] K. Ogata, S. Hashimoto, Y. Iseri, M. Kamimura, and M. Yahiro, arXiv:nucl-th/0505007.
[37] H. Esbensen, G. F. Bertsch, and K. A. Snover, Phys. Rev. Lett. **94**, 042502 (2005).