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Anisotropy in the pion angular distribution of the reaction $pp \rightarrow pp\pi^0$ at 400 MeV

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The reaction $pp \rightarrow pp\pi^0$ was studied with the WASA detector at the CELSIUS storage ring. The center of mass angular distribution of the π^0 was obtained by detection of the γ decay products together with the two outgoing protons and found to be anisotropic with a negative second derivative slope, in agreement with the theoretical predictions from a microscopic calculation.

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I. INTRODUCTION

The first high precision measurements of single neutral pion production in nucleon-nucleon collisions, using storage ring technology, were carried out more than a decade ago. Still, the theoretical interpretation of the dominant production mechanism remains uncertain. The magnitude of the total cross section of the $pp \rightarrow pp\pi^0$ reaction in the threshold region, where only angular momenta equal to zero are important in the final state, was measured [1] to be about five times larger [2,3] than what was predicted by the theoretical models available at the time. However, the energy dependence was found to be consistent with the widely accepted Koltun and Reitan model [4] based on s-wave pion production and rescattering [2,3]. The experimental result was confirmed and expanded even closer to threshold [5] whereas the large theoretical activity that was triggered by the new high precision data brought conflicting, not yet settled results.

The first successful remedy to fill in the discrepancy between experiment and theory was to take into account the exchange of heavy mesons [6,7]. The off-shell pion rescattering (together with the Born term) was also suggested to fill in the gap in the cross section [8]. Both these theories cannot be right unless there are some other additional effects. Furthermore, approaches using chiral perturbation effective field theory (ChPT) reached a different conclusion than meson field theory; the interference between the direct term and the pion rescattering was found to be destructive [9,10]. Improved calculations carried out in momentum-space increased the rescattering amplitude for the ChPT treatment by a factor of three [11]. Considerable progress has since been made developing the ideas of Ref. [9], using an ordering scheme that takes into account the large momentum transfer typical for meson production in NN collisions [12–15]. Within this scheme it was possible to describe the reaction $pp \rightarrow d\pi^+$ near threshold [16] and a corresponding study of the π^0 production is under way [17].

A calculation taking into account the exchange of two different heavy mesons, pion rescattering, and the $P_{11}(1440)$ nucleon resonance reproduced the total cross section numbers [18]. Relativistic effects were studied in the impulse approximation [19]. The exchange of the mesons π, ρ, ω, and σ, with the nucleon and the $\Delta(1232)$ isobar as intermediate states, using a relativistic treatment in a covariant one-boson exchange model over an energy range from near threshold to 2 GeV, gave reasonable agreement with the data [20]. The effects of the resonances $P_{11}(1440)$, $S_{11}(1535)$, and $D_{13}(1520)$ were studied together with the impulse and the pair diagram terms [21].

The possible influences on the differential cross sections due to contributions from higher partial waves, including d waves, were investigated experimentally at CELSIUS [22]. Recently angular distributions as well as total cross sections were measured from threshold up to 10 MeV above by the TOF collaboration using an extracted beam [23]. As expected close to threshold the angular distributions were isotropic. The magnitude of the total cross section was about 50% larger than what was obtained by the IUCF [1] and the CELSIUS data [5]. The large deviation compared to the previous storage ring experiments was suggested to be due to a significant loss of events in the internal target experiments, where the very

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forward going protons escape down the beam pipe undetected. At threshold a strong final state interaction could cause the loss of a large number of protons that would not properly be accounted for. The data set was drastically increased when the reaction $\vec{p}\vec{p} \to pp\pi^0$ was measured at beam energies between 325 and 400 MeV by the PINTEX collaboration at IUCF [24–27]. All possible polarization observables were deduced in the kinematically complete experiment and a general formalism was developed from a partial wave analysis to obtain an expansion of the observables in terms of a complete set of functions mapping the angular dependence [27]. Thus an analysis method was realized with all the physics information contained in the deduced coefficients. The only theoretical model that so far has been compared to these data is the microscopic model developed by the Jülich group [28,29]. The phenomenology of the model includes direct production, s- and p-wave rescattering of the pion, pair diagrams, and excitation of the $\Delta(1232)$. Angular momenta up to $L_p, l_q \leqslant 2$ between the two protons and the pion with respect to the nucleon-nucleon subsystem are included. The same group has recently performed a partial wave analysis using the data and the assumptions of Ref. [27] and compared the extracted quantities to those of their meson-exchange model [30]. Most of the amplitudes are shown to be reproduced fairly well by the model, except for the amplitude ${}^3P_1 \to {}^3P_0 p$ that deviates significantly from what is extracted from the data. For a quantitative assessment of $pp \to pp\pi^0$, it also turns out that the Δ excitation plays a major role. For a summary on near threshold meson production experiments see Ref. [31]. The status of the theoretical field is reviewed in Ref. [32].

Despite the vast interest in the reaction $pp \to pp\pi^0$ during the last 15 years, the reports on the pion angular distributions at energies below 1 GeV suffer from low statistics and/or small acceptance. We have measured the unpolarized angular cross section of the π^0 at 400 MeV, with the aim to resolve ambiguities from previous experiments concerning the slope parameter b and to complement the information obtained from the polarized data.

II. MEASUREMENT

The experiment was done using the WASA 4π detector facility [33] situated in the CELSIUS accelerator and storage ring at Uppsala, Sweden. A stored circulating proton beam of energy 400 MeV was allowed to interact with a stream of small ($\phi \sim 30\,\mu$m) frozen hydrogen pellets. All three outgoing particles from the reaction $pp \to pp\pi^0$ were detected. The protons were fully stopped either both in the Forward Detector (FD) or one in the FD and one in the Central Detector (CD). The FD consists of a stack of scintillator and wire chamber planes, primarily adapted to measure the four momenta of recoiling nuclei. The CD is constructed for measuring meson decay products and comprises the Scintillating Electromagnetic Calorimeter (SEC) made up of 1012 CsI detector elements, a Plastic Barrel (PB) for charged particle detection, and a Mini Drift Chamber (MDC) for measuring the momenta of charged particles. In the current experiment only the FD and the SEC were used for energy measurement and the PB was used for the rejection of charged particles.

The geometrical acceptance for detection of the outgoing protons from the reaction $pp \to pp\pi^0$ is shown in Fig. 1. The angular coverage was 3°–17° and 20°–155° for the FD and the CD, respectively. Because there were no triggers set for the case when both protons are emitted at $\theta_{\text{lab}} > 17^\circ$, these events escaped the current analysis. However, the full range of the proton relative momentum (p) is covered by the experiment, (cf. the right panel of Fig. 1), which is crucial from the physics interpretation point-of-view.

The event selection was handled using two different sets of criteria based on two different track types, which were either both protons detected in the FD (*2FD-type*) or one in the FD and one in the CD (*1FD1CD-type*). The requirements were coincident fast signals from either two hits in one scintillator layer of the FD or one hit in the FD and one hit in the forward part of the PB. These triggers gave an unbiased acceptance of the CD but yielded very high count rates, which is why prescaling was necessary.

The basic condition for an accepted event of the *2FD-type* was particle identification of the protons in the FD done by

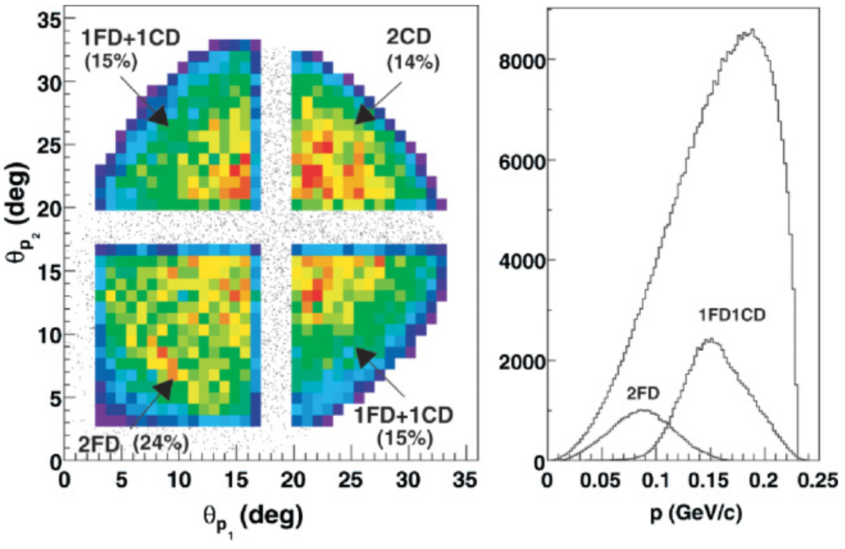

FIG. 1. (Color online) (Left panel) Scatter plot of the two proton polar angles in the laboratory system obtained from a simulation of phase space distributed $pp \to pp\pi^0$ events. The geometrical coverage of the WASA detector is shown by the overlaid histogram. (Right panel) The relative proton momentum (p) distribution obtained from a phase space generated event sample is shown by the unlabeled curve. The labeled curves represent the p distributions for two forward prong events (*2FD*) and for one forward plus one central prong event (*1FD1CD*), respectively, in a full simulation of the detector setup. The two trigger conditions used in the experiment are of the types *2FD* and *1FD1CD* (see Sec. II).

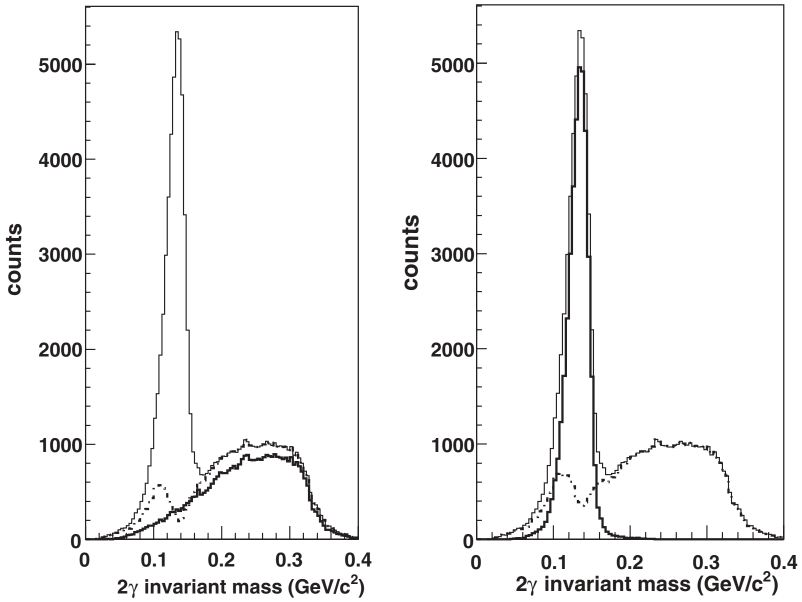

FIG. 2. The invariant mass distribution of the two γ's selected by the *1FD1CD-type* trigger. (Left panel) The dashed line represents the events that are excluded due to the constraint that the summed γ energy is within the kinematical limits for π^0 production. The bold line depicts what events are cut out based on the relation between the opening angle and the planarity of the two γ's, representing largely background from elastic scattering (accidentals). (Right panel) The combination of the two cuts is shown by the dashed line and the final resulting invariant mass of the two γ's is drawn by the bold line.

$\Delta E - E$ technique and the presence in the CD of two neutral tracks. Additional constraints were based on the comparison of the reconstructed polar and azimuthal laboratory angles, plus cuts in the center of mass energy, with respect to the missing mass of the two protons and the invariant mass of the two γ's from the π^0 decay. The conditions applied were $|\theta_{Mx} - \theta_{\mathrm{IM}}| < 15^\circ$, $|\phi_{Mx} - \phi_{\mathrm{IM}}| < 15^\circ$, and $|E_{Mx} - E_{\mathrm{IM}}| <$ 30 MeV, where *Mx* is the missing mass of the two protons and *IM* the invariant mass of the two γ's.

The selection of event candidates for the type of events with one forward and one central prong (*1FD1CD-type*) was done by particle identification of the FD proton. Additional constraints were applied on the opening and planarity angles of the two γ's, and the sum of the their energies being within the kinematical limits for π^0 production, i.e., $135 < \Sigma E_\gamma <$ 238 MeV. The consistency of the π^0 angle reconstructed from the missing mass and the invariant mass, respectively, for the *2FD-type* events was investigated. The two approaches agreed, and because the energy and angular resolutions for protons were relatively poor in the CD, the final analysis was based on the detection of the $\pi^0 \to 2\gamma$ decay using CD information only. The π^0 peak obtained from the invariant mass of the two γ's, before and after track requirements are fulfilled, is shown in Fig. 2.

The two sets of selected $pp\pi^0$ events were weighted together according to their relative trigger prescaling factor. The experimental angular distribution of the π^0 in the center of mass, uncorrected for acceptance, is seen in Fig. 3. Displayed are also simulations using either isotropically distributed events according to phase space or events weighted with the theoretical calculation of the Jülich model by Hanhart *et al.* [28,29]. More details on the data reduction procedure can be found in Ref. [34].

III. RESULTS

The acceptance corrected center of mass angular distribution of the π^0 is shown together with the prediction by the Jülich model in Fig. 4. The experimental data points and the theoretical curve are normalized to $\sigma_{\mathrm{tot}} = 93 \pm 7.2$ μb from Ref. [22].

The systematic uncertainties dominate, primarily emanating from the acceptance varying with the central detector's geometry. To estimate the magnitude of this effect the outermost layers in the forward and the backward parts, respectively, were excluded by ±10–15 degrees in the analysis, and the resulting deviation is included in the error. The dependence of the event sample on the resolution of the calorimeter was investigated using a wide gate, $100 < \Sigma E_\gamma < 250$ MeV, for the summed γ energies. The latter systematic uncertainty contributed mostly in the extreme forward direction. The final error limits were formed by adding in quadrature the effects of the systematic and the statistical uncertainties.

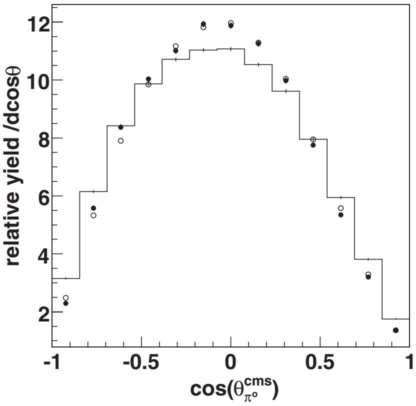

FIG. 3. The experimental center of mass π^0 angular distribution, arbitrarily normalized. The black markers represent the data and the unfilled markers correspond to the predicted histogrammed values from a simulation weighted according the microscopic calculation by Hanhart *et al.* [28,29]. The line shows the result of a simulated phase space generated isotropic distribution of the $pp \to pp\pi^0$ after passing through the detector system.

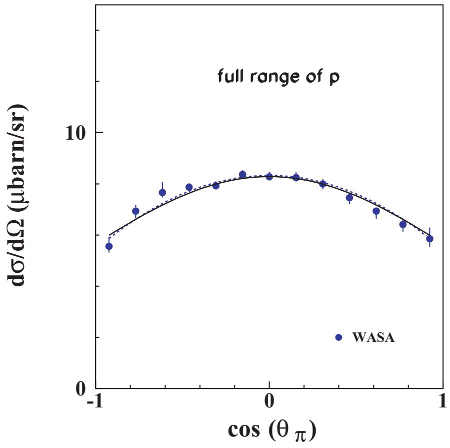

FIG. 4. (Color online) Acceptance corrected center of mass π^0 angular distribution, normalized to $\sigma_{\rm tot} = 92.3 \pm 7.2$ μb [22]. The uncertainites are dominated by systematic effects. The solid (black) line corresponds to the microscopic calculation by Hanhart *et al.* [28,29]. The dashed (blue) line represents a fit of the dependence on $\cos^2\theta_\pi$, taking only the statistical errors into account.

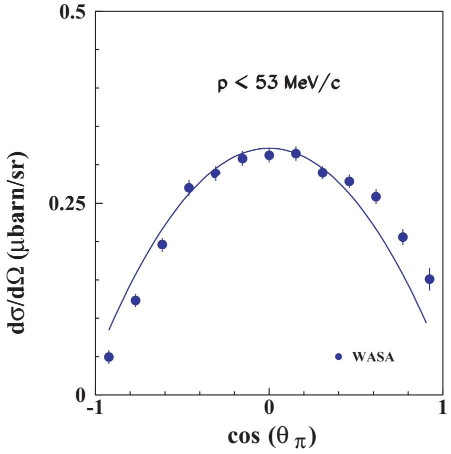

FIG. 6. (Color online) Acceptance corrected center of mass π^0 angular distribution, for $p < 53$ MeV/c, normalized to the cross sections of Ref. [22]. The line represents a fit of the data points to the dependence on $\cos^2\theta_\pi$.

In previous experimental reports [23,35–41] concerning the angular distribution, the slope parameter b was defined according to $\frac{d\sigma}{d\Omega} \propto \frac{1}{3} + b\cos^2\theta_\pi$; see Fig. 5 for a compilation of measurements below 1 GeV. There is a large spread of the values, probably mainly due to the varying coverage of p in the measurements. One recent experiment [22] yielded a negative b up to 360 MeV beam energy but at 400 MeV the slope was reported to be positive in discrepancy with the present result $b = -0.116 \pm 0.010^{+0.018}_{-0.016}$. However, the acceptance of Ref. [22] was limited with respect to p, with a coverage similar to the *2FD-type* events, and a model dependence was introduced by extrapolating into unmeasured regions of phase space. It should be noted that events with *both* proton angles larger than 17° were not detected within the current acceptance (see Fig. 1). There are indications that the inclusion of such events would flatten the distribution [42].

A selection of only S-wave protons can be accomplished by a cut in the relative momentum p between the protons. In Fig. 6 events with $p < 53$ MeV/c have been selected, yielding a fitted $b = -0.29 \pm 0.03$, taking only statistical errors into account. At 800 MeV beam energy using the same cut in p, an even larger negative second derivative was found [43], which was also predicted by a phenomenological calculation [44].

To compare the present experiment with the expansion in terms of angular functions obtained by the double polarization data [27], one integrates over all variables but the pion polar angle, which reduces Eq. (11a) of Ref. [27] to $\sigma_0 = E + F_1 + H_0^{00} + (H_1^{00} + I)(3\cos^2\theta_\pi - 1)$, where the sum $E + F_1 + H_0^{00}$ represents the spin averaged total cross section. For the correspondence between the slope parameter b and the term $H_1^{00} + I$, see Table I. One should keep in mind that these coefficients for the unpolarized cross section expansion were obtained solely from the polarized data of Ref. [27], and thus a large uncertainty is propagated to the error of b.

By using the recently developed analysis method for three-particle final states, the *sampling method* [45], that enables the integration of the prediction of a theoretical model over the experimentally accessible phase space region, a

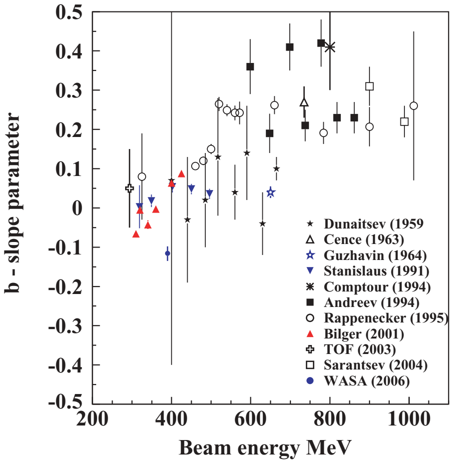

FIG. 5. (Color online) A compilation of measurements of the slope parameter b below 1 GeV is shown. The definition of b differs by a factor of three in Ref. [22], which is why the values given by that reference have been divided by three for consistency. (The large error bar at 400 MeV is from Ref. [35], and the location of the present data point at the same energy is shifted horizontally by 10 MeV to make it visible).

TABLE I. Correspondence between $H_1^{00} + I$ and b.

	WASA	[22]	[27](pol)
$H_1^{00} + I$	-0.131 ± 0.030	0.059 ± 0.003	0.084 ± 0.053
b	-0.116 ± 0.020	0.063 ± 0.003[a]	0.09 ± 0.18

[a] Published value is divided by three.

direct comparison can be made between experimental data and a theoretical calculation. Such a study is in progress but is outside the scope of this article. With all the data available, both polarized and unpolarized, in conjunction with the *sampling method*, we anticipate for the development of the ChPT approach that is under way [17] that detailed realistic constraints will be supplied. The goal is a complete characterization of the amplitudes of the fundamental reaction $pp \to pp\pi^0$ at low energy.

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[1] H. O. Meyer, C. Horowitz, H. Nann, P. V. Pancella, S. F. Pate, R. E. Pollock, B. v. Przewoski, T. Rinckel, M. A. Ross, and F. Sperisen, Nucl. Phys. **A539**, 633 (1992).
[2] G. A. Miller and P. U. Sauer, Phys. Rev. C **44**, R1725 (1991).
[3] J. A. Niskanen, Phys. Lett. **B289**, 227 (1992).
[4] D. Koltun and A. Reitan, Phys. Rev. **141**, 1413 (1966).
[5] A. Bondar *et al*., Phys. Lett. **B356**, 8 (1995).
[6] T.-S. H. Lee and D. O. Riska, Phys. Rev. Lett. **70**, 2237 (1993).
[7] C. J. Horowitz, H. O. Meyer, and D. K. Griegel, Phys. Rev. C **49**, 1337 (1994).
[8] E. Hernandez and E. Oset, Phys. Lett. **B350**, 158 (1995).
[9] T. D. Cohen, J. L. Friar, G. A. Miller, and U. van Kolck, Phys. Rev. C **53**, 2661 (1996).
[10] B.-Y. Park, F. Myhrer, J. R. Morones, T. Meissner, and K. Kubodera, Phys. Rev. C **53**, 1519 (1996).
[11] T. Sato, T.-S. H. Lee, F. Myhrer, and K. Kubodera, Phys. Rev. C **56**, 1246 (1997).
[12] V. Bernard, N. Kaiser, and U.-G. Meißner, Int. J. Mod. Phys. E **4**, 193 (1995).
[13] V. Bernard, N. Kaiser, and U.-G. Meißner, Eur. Phys. J. A **4**, 259 (1999).
[14] C. Hanhart, U. van Kolck, and G. A. Miller, Phys. Rev. Lett. **85**, 2905 (2000).
[15] C. Hanhart and N. Kaiser, Phys. Rev. C **66**, 054005 (2002).
[16] V. Lensky, V. Baru, J. Haidenbauer, C. Hanhart, A. E. Kudryavtsev, and U. G. Meissner, Eur. Phys. J. A **27**, 37 (2006).
[17] C. Hanhart (private communication).
[18] U. v. Kolck, G. A. Miller, and D. O. Riska, Phys. Lett. **B388**, 679 (1996).
[19] J. Adam, A. K. Stadler, M. T. Peña, and F. Gross, Phys. Lett. **B407**, 97 (1997).
[20] A. Engel *et al*., Nucl. Phys. **A603**, 387 (1996).
[21] M. T. Peña, D. O. Riska, and A. Stadler, Phys. Rev. C **60**, 45201 (1999).
[22] R. Bilger *et al*., Nucl. Phys. **A693**, 633 (2001).
[23] S. A. El-Samad *et al*., Eur. Phys. J. A **17**, 595 (2003).
[24] H. O. Meyer *et al*., Phys. Rev. Lett. **81**, 3096 (1998).
[25] H. O. Meyer *et al*., Phys. Rev. Lett. **83**, 5439 (1999).
[26] H. O. Meyer *et al*., Phys. Lett. **B480**, 7 (2000).
[27] H. O. Meyer *et al*., Phys. Rev. C **63**, 064002 (2001).
[28] C. Hanhart, J. Haidenbauer, O. Krehl, and J. Speth, Phys. Lett. **B444**, 25 (1998).
[29] C. Hanhart, J. Haidenbauer, O. Krehl, and J. Speth, Phys. Rev. C **61**, 064008 (2000).
[30] P. N. Deepak, J. Haidenbauer, and C. Hanhart, Phys. Rev. C **72**, 024004 (2005).
[31] P. Moskal, M. Wolke, A. Khoukaz, and W. Oelert, Prog. Part. Nucl. Phys. **49**, 1 (2002).
[32] C. Hanhart, Phys. Rep. **397**, 155 (2004).
[33] J. Zabierowski *et al*., Phys. Scr. **T99**, 159 (2002).
[34] S. Keleta, Licentiate thesis, Uppsala University (2004).
[35] A. F. Dunaitsev *et al*., JETP **9**, 1179 (1959).
[36] R. J. Cence, D. L. Lind, G. D. Mead, and B. J. Moyer, Phys. Rev. **131**, 2713 (1963).
[37] S. Stanislaus, D. Horvath, D. F. Measday, A. J. Noble, and M. Salomon, Phys. Rev. C **44**, 2287 (1991).
[38] C. Comptour *et al*., Nucl. Phys. **A579**, 369 (1994).
[39] V. Andreev *et al*., Phys. Rev. C **50**, 15 (1994).
[40] G. Rappenecker *et al*., Nucl. Phys. **A590**, 763 (1995).
[41] V. Sarantsev *et al*., Eur. Phys. J. A **21**, 303 (2004).
[42] S. A. El-Samad *et al*., Eur. Phys. J. A **30**, 443 (2006).
[43] Dymov *et al*., Phys. Lett. **B635**, 270 (2006).
[44] J. Niskanen, Phys. Lett. **B642**, 34 (2006).
[45] J. Kuroś-Żołnierczuk *et al*., Few-Body Syst. **34**, 259 (2004).