arXiv:nucl-ex/0609003v1 5 Sep 2006

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

P. Thörngren Engblom,* S. Negasi Keleta, F. Cappellaro, B. Höistad, M. Jacewicz,
T. Johansson, I. Koch, S. Kullander, H. Pettersson, K. Schönning, and J. Zlomańczuk
*Department of Nuclear and Particle Phsyics,*
*Uppsala University, Box 535, 751 21 Uppsala, Sweden*

H. Calén, K. Fransson, A. Kupść, P. Marciniewski, and M. Wolke
*The Svedberg Laboratory, Uppsala, Sweden*

C. Pauly, L. Demirörs, and W. Scobel
*Hamburg University, Hamburg, Germany*

J. Stepaniak and J. Zabierowski
*Soltan Institute of Nuclear Studies, Warzaw and Lodz, Poland*

M. Bashkanov, H. Clement, O. Khakimova, F. Kren, T. Skorodko
*Physikalisches Institut der Universität Tübingen, D-72076 Tübingen, Germany*

(Dated: February 7, 2008)

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 $\pi^0$ was obtained by detection of the $\gamma$ 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.

PACS numbers: 13.60.Le, 13.75.Cs, 21.45.+v, 25.10.+s

## I. INTRODUCTION

The first high precision measurements of single neutral pion production in nucleon-nucleon collisions, using storage ring technology, were done 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 and found the interference between the direct term and the pion rescattering 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 [9], using an ordering scheme that takes into account the large momentum transfer typical for meson production in $NN$ collisions [12, 13, 14, 15]. Within this scheme it was possible to describe the reaction $pp \rightarrow d\pi^+$ near threshold [16] and a corresponding study of the $\pi^0$ 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 in Ref. [19]. The exchange of the mesons $\pi$, $\rho$, $\omega$ and $\sigma$, 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 data [20]. The effect of the resonances $P_{11}(1440)$, $S_{11}(1535)$ and $D_{13}(1520)$ together with the impulse and pair diagram terms were studied in Ref.[21]

The possible influence on the differential cross sections due to contributions from higher partial waves, including $d$-waves, was studied experimentally at CELSIUS [22]. Angular distributions as well as total cross sections were recently measured from threshold up to 10 MeV above, by the TOF collaboration using an extracted beam [23].

---

*Electronic address: pia.thorngren@tsl.uu.se

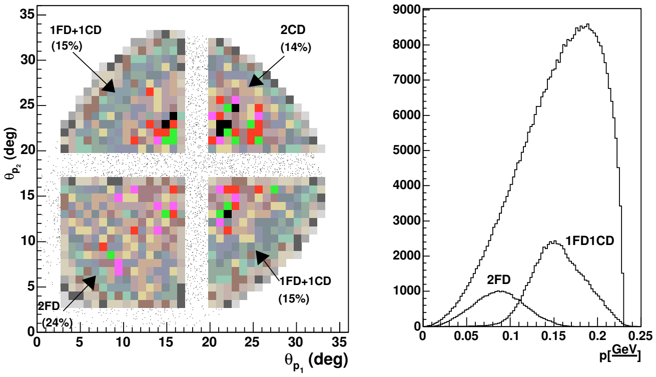

FIG. 1: *Left panel :* Scatter plot of the two proton polar angles in the laboratory system, obtained from a monte carlo simulation of phase space distributed $pp \to pp\pi^0$ events. The geometrical coverage of the WASA detector is shown by the overlaid histogram. *Right panel :* The relative proton momenta ($p$ from a simulation according phase space. The labelled curves represent different ranges of $p$ corresponding to their detection in a full-blown simulation of the detector setup: two forward prongs (2FD), one forward and one central (1FD+1CD). The two trigger conditions used in the experiment are of the types $2FD$ and $1FD + 1CD$ (see sec. II A).

The angular distributions were isotropic as expected close to threshold. The total cross section obtained was about 50 % larger than the IUCF [1] and CELSIUS data [5]. The reason for the large deviation compared to the previous storage ring experiments was suggested to be due to a significant loss of events in the internal experiments, where the very forward going protons escape down the beampipe undetected. At threshold a strong final state interaction could cause the loss of a large number of protons that would not be properly accounted for.

The data set was drastically increased when the reaction $\overrightarrow{p}\,\overrightarrow{p} \to pp\pi^0$ was measured at beam energies between 325 and 400 MeV by the PINTEX collaboration at IUCF [24, 25, 26, 27]. All possible polarization observables were deduced in the kinematically complete experiment and a general formalism was developed from a partial wave analysis, in order 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. However, contributions from $Ds$ and $Sd$ to the final state were not taken into account. 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 $L_p, l_q \leq 2$ between the two protons and the pion with respect to the NN subsystem, are included. The same group has recently performed a partial wave analysis using the data and the assumptions of [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 $\Delta$ excitation plays a major role. For a summary on near threshold meson production experiments see [31]. The status of the theoretical field is reviewed in [32].

In spite of the interest in the reaction $pp \to pp\pi^0$ during the last 15 years, the reports on the pion angular distributions at energies up to 400 MeV, suffer from low statistics and/or small acceptance. We have measured the unpolarized angular cross section of the $\pi^0$ at 400 MeV, with the aim to resolve some of the ambiguities and complement the partial wave analysis based solely on polarized data.

## II. MEASUREMENT

The experiment was done using the WASA $4\pi$ detector facility [33] situated in the CELSIUS accelerator and storage ring at Uppsala, Sweden. A stored circulating proton beam of energy 400 MeV was let 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 elmeents, 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 for the rejection of charged particles. Since the energy and angular resolution for protons was relatively poor in the CD, the final analysis was based on the detection of the $\pi^0 \to 2\gamma$ decay in the CD.

### A. Data Analysis

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 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

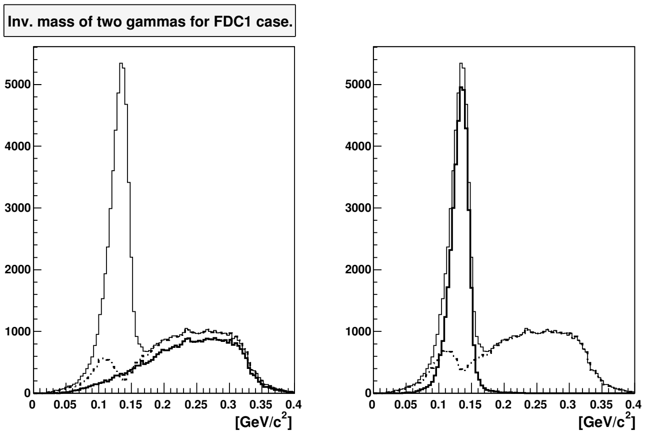

FIG. 2: The invariant mass of of the two $\gamma$'s selected by the *1FD1CD-type* trigger. *Left panel :* The cut based on the constraint that the sum of the energies of the two $\gamma$'s is within the kinematical limits for $\pi^0$ production, is shown by the dashed line. The bold line depicts what is cut out based on the relation between the opening angle and the planarity of the two $\gamma$'s, representing largely background from elastic scattering. *Right panel :* The combination of the two cuts is shown by the dashed line and the final resulting invariant mass of the two $\gamma$'s, is drawn by the bold line.

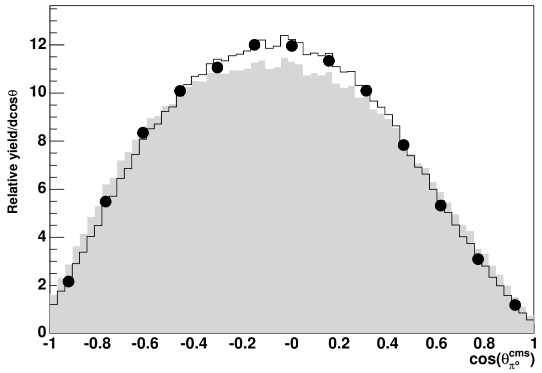

FIG. 3: The experimental center-of-mass $\pi^0$ angular distribution, arbitrarily normalized. The shaded area is the result of a simulated phase space generated isotropic distribution of the $pp \to pp\pi^0$ after passing through the detector system. The solid line corresponds to the predicted histogrammed values from a simulation weighted with the microscopic calculation by Hanhart et al. [28, 29]. The statistical uncertainties are negligible.

high countrates, why prescaling was necessary. The main background reactions present in the trigger were $pp \to d\pi^+$ and $pp$ elastic scattering.

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 $3^\circ - 17^\circ$ and $20^\circ - 155^\circ$, for the FD and the CD respectively. Since there were no triggers set for the case when both protons are emitted at $\theta_{lab} > 17^\circ$, these events escape the current analysis. However, the full range of the relative momenta of the two protons is covered by the experiment, (c.f. the right panel of Fig. 1), which is crucial from the physics interpretation point-of-view.

The basic condition for an accepted event of the $2FD - type$ was particle identification of the protons in the FD done by $\Delta E - E$ technique, and the presence in the CD of two neutral tracks from the decay of $\pi^0 \to 2\gamma$. 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 $\gamma$'s from the $\pi^0$ decay. The conditions applied were: $|\theta_{Mx} - \theta_{IM}| < 15^\circ$, $|\phi_{Mx} - \phi_{IM}| < 15^\circ$ and $|E_{Mx} - E_{IM}| < 30$ MeV, where $Mx$ is the missing mass of the two protons and $IM$ the invariant mass of the two $\gamma$'s. The consistency of the $\pi^0$ angle reconstructed from the missing mass and the invariant mass, respectively, was investigated. The two approaches agreed and thus the conclusion was drawn that analysis of the *1FD1CD-type* prongs could be done using CD information only.

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. Furthermore, for the two $\gamma$'s a cut was based on the relation between the opening and planarity angles. An additional constraint applied was that the sum of the energies of the two $\gamma$'s was within the kinematical limits for $\pi^0$ production, i.e. $135 < \Sigma E_\gamma < 238$ MeV, The $\pi^0$ peak obtained from the invariant mass of the two $\gamma$'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 $\pi^0$ 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 [34].

## III. RESULTS

The acceptance corrected $\pi^0$ angular distribution is shown together with the prediction by the Jülich model in Fig. 4. The experimental data points and the theoretical curve are normalized to $\sigma_{tot} = 93 \pm 7.2$ $\mu$barn from [22]. The systematic uncertainties dominate, primarily emanating from the acceptance varying with the central detector's geometry. In order to obtain an estimate of the magnitude of this error the outmost layers in the forward and the backward parts respectively, were excluded in the analysis.

In previous experimental reports [23, 35, 36, 37, 38, 39, 40, 41] concerning the angular distribution a slope parameter $b$ was defined according $\frac{d\sigma}{d\Omega} \propto \frac{1}{3} + b\cos^2\theta_\pi$, see

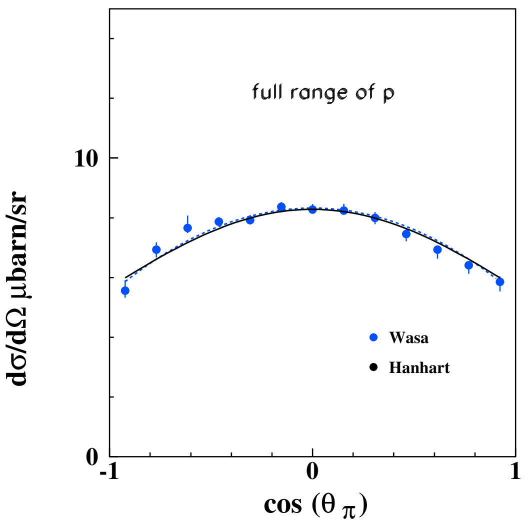

FIG. 4: Acceptance corrected center-of-mass $\pi^0$ angular distribution, normalized to $\sigma_{tot} = 92.3 \pm 7.2$ $\mu$barn [22]. The uncertainites are dominated by systematic effects. The solid line corresponds to the microscopic calculation by Hanhart et al. [28, 29]. The dashed line represents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

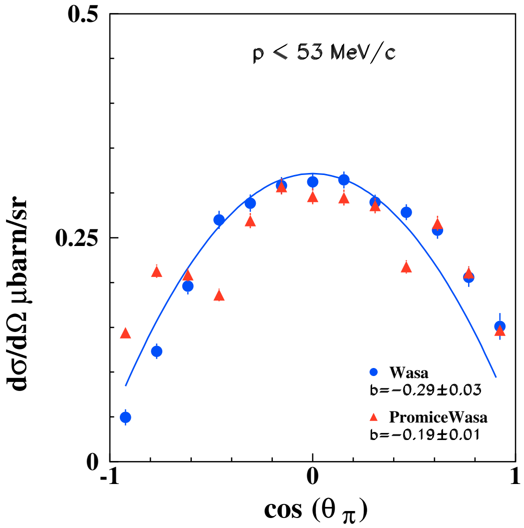

FIG. 6: Acceptance corrected center-of-mass $\pi^0$ angular distribution, for $p < 53$ MeV/c, compared and normalized to [22]. The solid line represents a fit of the WASA data points to the dependence on $\cos^2\theta_\pi$, taking only the statistical errors into account.

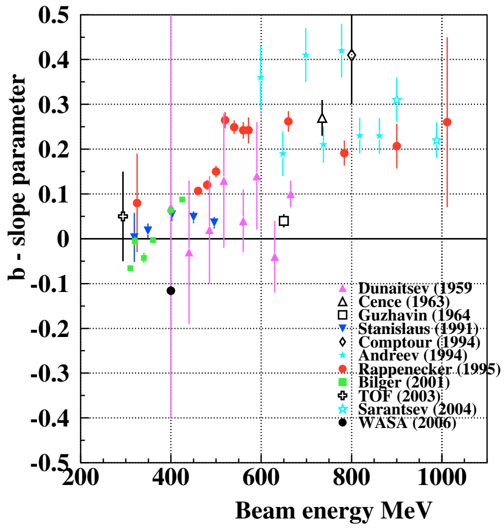

FIG. 5: A compilation of measurements of the slope parameter below 1 GeV is shown. The definition of $b$ differs by a factor of three in [22] why the values given by that reference have been divided by three for consistency. (The large error bar at 400 MeV is from [35]).

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

| | WASA | [22] | [27](pol) |
|---|---|---|---|
| $H_1^{00} + I$ | $-0.131 \pm 0.012$ | $0.055 \pm 0.007$ | $0.084 \pm 0.053$ |
| $b$ | $-0.116 \pm 0.010$ | $0.063 \pm 0.003^a$ | $0.09 \pm 0.18$ |

$^a$Published value is divided by three

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] yield 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 $b = -0.116 \pm 0.010$. However the acceptance of [22] was limited with respect to $p$, with a coverage similar to the $2FD - type$ case, 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 slightly flatten the distribution [42]. Whereas the $\pi^0$ angular distribution integrated over all $p$ displays discrepancies among the different experiments, a selection of $S$-wave protons might shed some light. At very low relative momenta between the protons, $p < 53$ MeV/c, the two CELSIUS measurements agree at least qualitatively, see Fig. 6. 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].

A direct comparison between the present experiment and the expansion deduced from the double polarization data [27] can be done by using the *sampling method* [45], that allows to integrate the prediction of a theoretical model over the experimentally accessible phase space region, see Fig. 7. The coefficient combination $H_1^{00} + I$ and the dependency on the $\cos^2(\theta_\pi)$-term (Eq. 11 [27]), have been taken into account, all other variables are ignored. See Table I for the correspondence between the slope parameter $b$ and $H_1^{00} + I$.

The prospect of improving the accuracy of certain co-

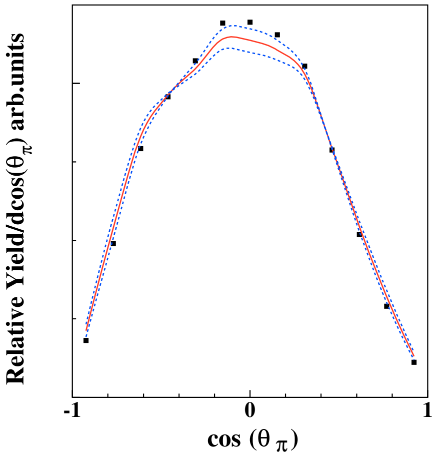

FIG. 7: Using the sampling method [45] for direct comparison between the experimental data and the expansion developed in [27]. The dashed lines correspond to the uncertainty ($1\sigma$) in the determination of the coefficient combination $H_1^{00} + I$.

efficients, as well as pinning down the only remaining undetermined coefficient, $H_3^{00}$, using the present experimental event sample, is now a highly feasible plan for the immediate future. Thus another advancement has been made towards a complete characterization of the amplitudes of the fundamental reaction $pp \to pp\pi^0$ at low energy. With all the data available, both polarized and unpolarized, in conjunction with the *sampling method*, we anticipate that all amplitudes can be determined individually. For the future development of ChPT, detailed realistic constraints will be supplied.

## Acknowledgments

We wish to acknowledge the support of the Swedish Research Council with Grant Nos. Dnr. 629-2001-3868 and Dnr. 40313601, and the Göran Gustafsson Foundation Grant No. 01:95. The hard work of the CELSIUS crew is greatly appreciated. One of the authors, P.T.E., is grateful for clarifying discussions concerning the reaction $pp \to pp\pi^0$ with Prof. H.-O. Meyer, Dr. C. Hanhart, Prof. A. Johansson and Prof. C. Wilkin.

[1] H. O. Meyer, C. Horowitz, H. Nann, P. V. Pancella, S. F. Pate, R. E. Pollock, B. Przewoski, T. Rinckel, M. A. Ross, and F. Sperisen, Nucl. Phys. **A539**, 633 (1992).
[2] G. A. Miller and P. U. Sauer, Phys. Rev. **C44**, 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. Lee and D. O. Riska, Phys. Rev. Lett. **70**, 2237 (1993).
[7] C. J. Horowitz, H. O. Meyer, and D. K. Griegel, Phys. Rev. **C49**, 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. v. Kolk, Phys. Rev. **C53**, 2661 (1996).
[10] B.-Y. Park, F. Myhrer, J. R. Morones, T. Meissner, and K. Kubodera, Phys. Rev **C53**, 1519 (1996).
[11] T. Sato, T.-S. Lee, F. Myhrer, and K. Kubodera, Phys. Rev. **C56**, 1246 (1997).
[12] V. Bernard, N. Kaiser, and U.-G. Meißner, Int. J. Mod. Phys. **E4**, 193 (1995), [arXiv:hep-ph/9501384].
[13] V. Bernard, N. Kaiser, and U.-G. Meißner, Eur. Phys. J. **A4**, 259 (1999), [arXiv:nucl-th/9806013].
[14] C. Hanhart, U. van Kolck, and G. Miller, Phys. Rev. Lett. **85**, 2905 (2000), [arXiv:hep-th/0004033].
[15] C. Hanhart and N. Kaiser, Phys. Rev. **C66**, 054005 (2002), [arXiv:hep-th/0208050].
[16] V. Lensky, V. Baru, J. Haidenbauer, C. Hanhart, A. E. Kudryavtsev, and U. G. Meissner, Eur. Phys. J. **27**, 37 (2006), [arXiv:nucl-th/0511054].
[17] C. Hanhart, private communication.
[18] U. v. Kolk, G. A. Miller, and D. O. Riska, Phys. Lett pp. 679–685 (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. **C60**, 45201 (1999).
[22] R. Bilger, *et al.*, Nucl. Phys. **A693**, 633 (2001).
[23] S. A. Samad, *et al.*, Eur.Phys.J. **A17**, 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. **C63**, 064002 2 (2001).
[28] C. Hanhart, J. Haidenbauer, O. Krehl, and J. Speth, Phys. Lett. **B444**, 25 (1998), [arXiv:nucl-th/9808020].
[29] C. Hanhart, J. Haidenbauer, O. Krehl, and J. Speth, Phys. Rev. **C61**, 064008 (2000), [arXiv:nucl-th/0002025].
[30] P. Deepak, J. Haidenbauer, and C. Hanhart, Phys. Rev. **C72**, 024004 (2005), [arXiv:hep-ph/0503228].
[31] P. Moskal, M. Wolke, A. Khoukaz, and W. Oelert, Prog. Part. Nucl. Phys. **49**, 1 (2002), [arXiv:hep-ph/0208002].
[32] C. Hanhart, Phys. Rep. **397**, 155 (2004), [arXiv:hep-ph/0311341].
[33] J. Zabierowski, *et al.*, Phys. Scripta **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, *et al.*, Phys. Rev. **C44**, 2287 (1991).
[38] C. Comptour, *et al.*, Nucl. Phys. **A579**, 369 (1994).
[39] V. Andreev, *et al.*, Phys. Rev. **C50**, 15 (1994).
[40] G. Rappenecker, *et al.*, Nucl. Phys. **A590**, 763 (1995).
[41] V. Sarantsev, *et al.*, Eur. Phys. J. **A21**, 303 (2004).
[42] H. Clement, private communication, the TOF collaboration.
[43] Dymov, *et al.*, Phys.Lett. **B635**, 270 (2006), [arXiv:nucl-ex/0512035].
[44] J. Niskanen, [arXiv:nucl-th/0603072].
[45] J. Kuroś-Żołnierczuk, Few-Body Systems **34**, 259 (2004).