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Differential cross section and analysing power of the $pp \to \{pp\}_s\pi^0$ reaction at 353 MeV

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ABSTRACT

The differential cross section $d\sigma/d\Omega$ and analysing power A_y of the $\vec{p}p \to \{pp\}_s\pi^0$ reaction have been measured at COSY-ANKE at 353 MeV. The final proton pair was detected at very low excitation energy, leading to an S-wave diproton, denoted here as $\{pp\}_s$. The angular dependence of both $d\sigma/d\Omega$ and A_y can be described in terms of s- and d-wave pion production. By using phase information from elastic pp scattering, unique solutions are derived for the corresponding amplitudes only as a result of the combined analysis of both experimental observables. The large d-wave term thus obtained is important for the tests of the current state-of-the-art chiral perturbation theory approach. The amplitudes will also help towards determining the isospin dependence of pion production in nucleon–nucleon collisions with diproton formation.

There is a programme at the COSY-ANKE facility of the Forschungszentrum Jülich to perform a complete set of measurements on $NN \to \{pp\}_s\pi$ at low energy [1]. Here the $\{pp\}_s$ denotes a proton–proton system with very low excitation energy, E_{pp}. At ANKE we select events with $E_{pp} < 3$ MeV and, under these conditions, the diproton is overwhelmingly in the $^1S_0$ state with antiparallel proton spins. This simplifies enormously the spin structure: a partial wave analysis for $pp \to pp\pi^0$ without the E_{pp} cut would require twelve additional P-wave final pp spin-triplet states [2–4]. The cut also allows one to extract the full information on the production amplitudes without having to make measurements of the final proton polarisations. As the first part of this larger programme, we report here on measurements of the cross section and proton analysing power in the $pp \to \{pp\}_s\pi^0$ reaction at $T_p = 353$ MeV.

Interest in pion production in nucleon–nucleon collisions was revitalised twenty years ago when new, high precision $pp \to pp\pi^0$ data became available [5]. In the following decade many phenomenological mechanisms were proposed to explain the results. The most popular models involved heavy meson exchange or off-shell pion nucleon rescattering (see e.g., the review [4]), but no consensus was reached as to which approach was correct.

In parallel to the phenomenological approaches, Chiral Perturbation Theory (ChPT) has been developed further for this class of reaction; see for example [6,7]. The central new finding of these works is that pion loops are numerically important. In particular, it is found that the contributions generated by the pion loops at next-to-next-to-leading order (NNLO) are comparable in size

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with the most important short-range contributions emerging in phenomenological models from heavy meson exchanges [7]. Meanwhile, all loop diagrams identified with pion rescattering in the isoscalar channel cancel exactly, whereas the tree level rescattering contribution is known to be strongly suppressed by chiral symmetry. These results therefore raise doubts about phenomenological mechanisms and show the importance of getting new data that would provide stringent tests for both these and the ChPT evaluations.

For a spin-singlet diproton, the spin structure of the $pp \to \{pp\}_s\pi^0$ or $np \to \{pp\}_s\pi^-$ reaction is that of $\frac{1}{2}^+\frac{1}{2}^+ \to 0^+0^-$. Parity and angular momentum conservation require that the initial nucleon–nucleon pair to have spin $S = 1$. The pion orbital angular momentum ℓ and the initial nucleon–nucleon isospin I are then linked by $\ell + I = \text{odd}$ so that, for the $pp \to \{pp\}_s\pi^0$ reaction, only even pion partial waves are allowed. As a consequence, the unpolarised cross section for π^0 production, and this times the proton analysing power A_y, must be of the form

$$\left(\frac{d\sigma}{d\Omega}\right)_0 = \frac{k}{4p}\left(a_0 + a_2\cos^2\theta_\pi + a_4\cos^4\theta_\pi + \cdots\right), \tag{1}$$

$$A_y\left(\frac{d\sigma}{d\Omega}\right)_0 = \frac{k}{4p}\sin\theta_\pi\cos\theta_\pi\left(b_2 + b_4\cos^2\theta_\pi + \cdots\right), \tag{2}$$

where θ_π is the pion c.m. production angle with respect to the direction of the polarised proton beam. Here p is the incident c.m. momentum and k that of the produced pion which, at 353 MeV, have values $p = 407$ MeV/c and $k \approx 94$ MeV/c, where the latter represents an average over the 3 MeV E_{pp} range.

The only detailed measurements of the $pp \to \{pp\}_s\pi^0$ differential cross section over the whole angular range were carried out with the PROMICE-WASA apparatus at CELSIUS at a series of energies from 310 to 450 MeV, using the same standard 3 MeV cut on E_{pp} [8]. Throughout this energy range, significant anisotropies were found in the angular distributions which were attributed to interferences between pion s and d waves. On the other hand, there were no corresponding measurements of the proton analysing power, which might also be driven by a similar strong s–d interference.

We have previously reported measurements of the $pp \to \{pp\}_s\pi^0$ differential cross section at several energies and small angles [9,10]. Since these were carried out using the ANKE spectrometer [11] under conditions that were similar to the current ones, the description here can be quite brief. ANKE is placed at an internal beam station of the COSY cooler synchrotron. Fast charged particles, resulting from the interaction of the stored transversally polarised proton beam with the hydrogen cluster-jet target [12] and passing through the analysing magnetic field, were recorded in the forward detector (FD) system. The FD, which was the only detector used in this experiment, includes multiwire proportional chambers for tracking and a scintillation counter hodoscope for energy loss and timing measurements.

To start the identification of the $pp \to \{pp\}_s\pi^0$ reaction, proton pairs were first selected from all the registered two-track events using the measured momenta of the both particles and the difference in their time-of-flight [13]. The resolution $\sigma(E_{pp})$ in the diproton excitation energy was better than 0.6 MeV, which allowed the $E_{pp} < 3$ MeV cut to be applied reliably.

After selecting the $^1S_0$ final state, the kinematics of the $pp \to \{pp\}_sX$ process could be reconstructed on an event-by-event basis to obtain a missing-mass M_X spectrum. A two-dimensional distribution of M_X^2 versus the c.m. polar angle of the diproton θ_{pp}^{cm} is presented in Fig. 1. This demonstrates the large angular acceptance of the apparatus for the $pp \to \{pp\}_s\pi^0$ reaction at 353 MeV and shows a clean π^0 signal with an almost negligible background. Simulations indicate that the c.m. angular resolution is better than 5°.

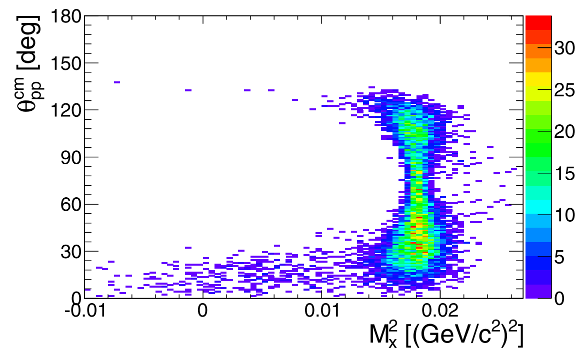

Fig. 1. Two-dimensional distribution of the missing-mass-squared M_X^2 of the $pp \to \{pp\}_sX$ reaction at 353 MeV versus the diproton c.m. polar angle θ_{pp}^{cm} for events with $E_{pp} < 3$ MeV.

The polarisation asymmetry is defined by

$$\varepsilon = \frac{N_\uparrow/L_\uparrow - N_\downarrow/L_\downarrow}{N_\uparrow/L_\uparrow + N_\downarrow/L_\downarrow}, \tag{3}$$

where $N_\uparrow$ and $N_\downarrow$ are the numbers of $pp \to \{pp\}_s\pi^0$ events with beam proton spin up and down, corrected for dead time, and $L_\uparrow$ and $L_\downarrow$ are the corresponding luminosities. The relative luminosity $L_\uparrow/L_\downarrow \approx 0.985 \pm 0.015$ was estimated using events at very small polar angles, where the polarisation asymmetry should be negligible. This procedure adds about a 3% systematic error to the values of ε.

The analysing power A_y is connected to the asymmetry through:

$$A_y = \frac{\varepsilon}{P\langle\cos\phi_{pp}\rangle}, \tag{4}$$

where P is the transverse polarisation of the beam and $\langle\cos\phi_{pp}\rangle$ the average over the diproton azimuthal angular distribution. Since the $\cos\phi_{pp}$ acceptance is concentrated near 1, all the events in the regions analysed contribute usefully to the A_y measurement.

The polarisation of the proton beam was flipped between "spin up" to "spin down" (perpendicular to the plane of the accelerator) every six minutes and no measurements were made with an unpolarised beam. The value of P was estimated from proton–proton elastic scattering and the $pp \to d\pi^+$ reaction that were measured in parallel. The analysing powers for these reactions were taken from the SAID analysis program, solutions SP07 for $pp \to pp$ and SP96 for $pp \to d\pi^+$ [14]. The results of the two methods shown in Fig. 2 agreed within measurement errors and gave an average polarisation of $P = 0.68 \pm 0.03$, where the error includes the uncertainties arising from the calibration reactions.

A simulation was undertaken of the two-dimensional acceptance in terms of the pp excitation energy E_{pp} and its c.m. polar angle θ_{pp}. This took into account the geometry of the setup and the sensitive areas of the detectors, the efficiency of the multiwire proportional chambers and the track reconstruction algorithm. In order to avoid potential problems arising near the limits of the acceptance, cuts were made around the edges of the exit window of the spectrometer magnet in both the experimental data and simulation. This is only a challenge at the larger angles, $80^\circ < \theta_\pi < 100^\circ$, where a compromise had to be made regarding the acceptance ambiguities and this introduces an extra 4% systematic uncertainty in this angular region.

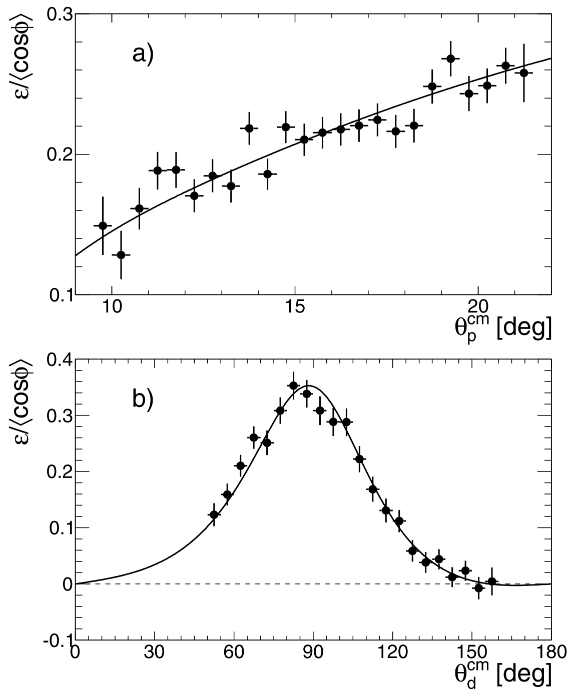

Fig. 2. Product of the beam polarisation and analysing power at a beam energy of 353 MeV for (a) elastic pp scattering and (b) the $pp \to d\pi^+$ reaction. The predictions of the SAID program [14] have been scaled to agree with the experimental data and these give average COSY proton beam polarisations of (a) $P = 0.687 \pm 0.008$ and (b) $P = 0.668 \pm 0.016$. In neither case was the uncertainty in the SAID prediction included.

The numbers of detected π^0 events were then corrected on an event-by-event basis for acceptance, dead time and relative luminosity $L_\uparrow/L_\downarrow$. The latter were important because, in the absence of data with an unpolarised beam, an average has to be evaluated.

The luminosity in the experiment was estimated from measurements of pp elastic scattering carried out in parallel. The numbers of detected events, corrected for the dead time, were compared with a simulation that used a generator which included the differential cross section obtained from the SAID analysis program [14]. Although this program does not furnish error bars, experimental data at nearby energies suggests that the associated uncertainty is about 2%, to which must be added 3% arising from acceptance and similar systematic effects. At this level the statistical error is negligible and the resulting total luminosity was estimated to be $544 \pm 22\ \text{nb}^{-1}$. At this energy the $pp \to d\pi^+$ cross section data are less precise than those of pp elastic scattering but, on the basis of the SAID predictions, one obtains the completely consistent luminosity estimate of $547\ \text{nb}^{-1}$.

The differential cross section results are presented in Fig. 3, where they are compared to those obtained at 360 MeV at CELSIUS [8]. Within the 10% luminosity uncertainty in these data, the overall agreement is very good. However, the CELSIUS data at this energy level off a little around 90°. This seems to be a feature only of the 360 MeV results since, at the other energies, linear fits in $\cos^2\theta_\pi$ all have good values of χ^2/NDF [8].

Fitting our data with a polynomial in $\cos^2\theta_\pi$, as in Eq. (1), gives parameters

$$a_0 = 4.05 \pm 0.08\ \mu\text{b/sr},$$

$$a_2 = -2.31 \pm 0.14\ \mu\text{b/sr}, \tag{5}$$

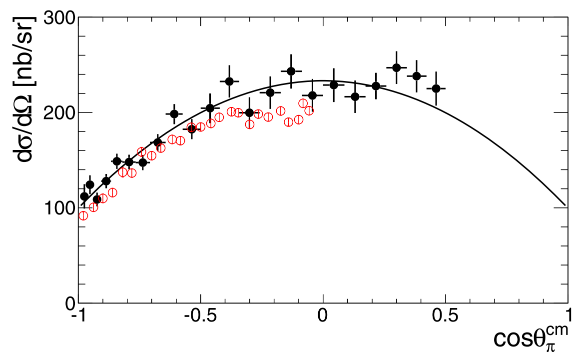

Fig. 3. Differential cross section for the $pp \to \{pp\}_s\pi^0$ reaction at 353 MeV as a function of the cosine of the pion c.m. angle. The solid (black) circles represent the ANKE measurements. The errors shown here are statistical together with a 4% systematic contribution in the $80° < \theta_\pi < 100°$ region coming from the acceptance ambiguity discussed in the text. The overall systematic uncertainty is about 4%. Open (red) circles are CELSIUS data obtained at 360 MeV [8]. It should be noted that the latter data represent averages of measurements taken in both hemispheres. The curve is a linear fit in $\cos^2\theta_\pi$ to our data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

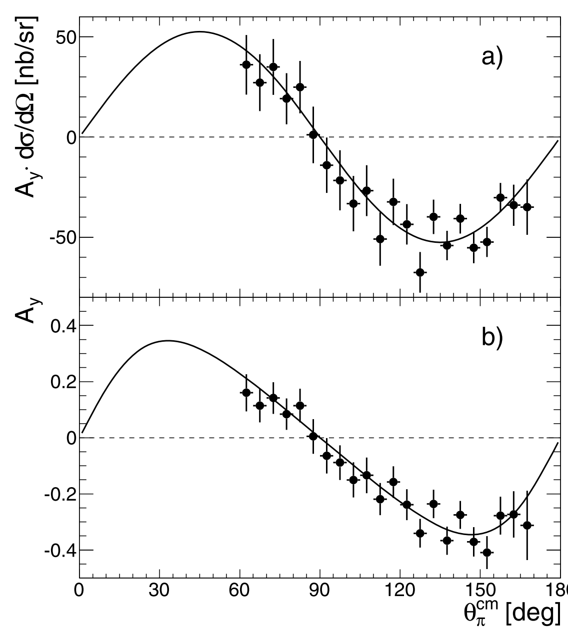

Fig. 4. a) The product of the measured analysing power and differential cross section for the $\vec{p}p \to \{pp\}_s\pi^0$ reaction, with cross section errors as in Fig. 3. The curve represents the best fit of Eq. (2), with $b_2 = 1.82\ \mu\text{b/sr}$ and all higher terms eliminated. b) Measured values of A_y for the $\vec{p}p \to \{pp\}_s\pi^0$ reaction. The errors shown are purely statistical; the overall systematic uncertainty is about 5%. The line represents the quotient of the best fit in panel a) and the fit to the cross section in Fig. 3.

Apart from the acceptance uncertainties at the larger angles, the error bars quoted here are purely statistical; the ±4% systematic uncertainty from the luminosity and acceptance largely cancels in the ratio a_2/a_0. Since $\chi^2/\text{NDF} = 23/20$, there is clearly no compelling evidence for any $\cos^4\theta_\pi$ dependence and a direct fit gives $a_4 = 0.19 \pm 0.55\ \mu\text{b/sr}$. This contribution has been omitted from the curve in Fig. 3.

The results for the analysing power of the $\vec{p}p \to \{pp\}_s\pi^0$ reaction are displayed in Fig. 4, with $A_y(d\sigma/d\Omega)$ being shown in panel a) and A_y in panel b). These observables must be antisymmetric about 90° and the crossing of the data through zero around this angle is some confirmation of our estimation of $L_\uparrow/L_\downarrow$. These data are subject to the overall uncertainties associated with the luminosity and acceptance evaluation, though these are not relevant for the A_y in Fig. 4b). There remains, however, the $\pm 3\%$ arising from the uncertainty in the value of $L_\uparrow/L_\downarrow$.

The $A_y d\sigma/d\Omega$ data are consistent with a $\sin\theta_\pi \cos\theta_\pi$ behaviour and a fit using the general form of Eq. (2) yields

$$b_2 = 1.82 \pm 0.10\ \mu\text{b/sr} \tag{6}$$

with $\chi^2/\text{NDF} = 15/21$. There is therefore no evidence for any $\sin\theta_\pi \cos^3\theta_\pi$ dependence and a direct fit gives $b_4 = 0.11 \pm 0.42$ μb/sr. The resulting curves without this contribution are shown in Fig. 4.

In order to understand the significance of the results reported here, we must attempt a partial wave description of the data. The most general form of the reaction amplitude is

$$\mathcal{M} = A\boldsymbol{S}\cdot\hat{\boldsymbol{p}} + B\boldsymbol{S}\cdot\hat{\boldsymbol{k}}, \tag{7}$$

where $\boldsymbol{S}$ is the polarisation vector of the initial pp spin-triplet state. $\hat{\boldsymbol{p}}$ and $\hat{\boldsymbol{k}}$ are unit vectors in the c.m. frame along the directions of the incident proton and final pion, respectively.

The observables studied here are expressed in terms of the two scalar amplitudes A and B through [4]

$$\begin{aligned}\left(\frac{d\sigma}{d\Omega}\right)_0 &= \frac{k}{4p}\left(|A|^2 + |B|^2 + 2\,\text{Re}\left[AB^*\right]\cos\theta_\pi\right),\\ A_y\left(\frac{d\sigma}{d\Omega}\right)_0 &= \frac{k}{4p}\left(2\,\text{Im}\left[AB^*\right]\sin\theta_\pi\right).\end{aligned} \tag{8}$$

The experimental data show no evidence for high partial waves at 353 MeV and so we model these results with only $\ell = 0$ and $\ell = 2$ contributions. The latter can arise from initial $L = 1$ or $L = 3$ waves so that, in total, there are three possible transitions, ${}^3P_0 \to {}^1S_0 s$, ${}^3P_2 \to {}^1S_0 d$, and ${}^3F_2 \to {}^1S_0 d$. [See e.g. Ref. [16] for the explicit form of the spin-angular structures.] We denote the corresponding amplitudes by M_s^P, M_d^P, and M_d^F, respectively.

Expanding the scalar amplitudes in terms of these partial waves gives

$$\begin{aligned}A &= M_s^P - \frac{1}{3}M_d^P + M_d^F\left(\cos^2\theta_\pi - \frac{1}{5}\right),\\ B &= \left(M_d^P - \frac{2}{5}M_d^F\right)\cos\theta_\pi.\end{aligned} \tag{9}$$

Eqs. (8) and (9) then allow one to relate the measured observables of Eqs. (1) and (2) to the partial wave amplitudes. For consistency, since we have neglected any possible effects arising from s–g interference, we shall also drop terms that are bilinear in d-wave production amplitudes. In this approximation

$$\begin{aligned}a_0 &= \left|M_s^P\right|^2 - \frac{2}{3}\,\text{Re}\left[M_s^P\left(M_d^P + \frac{3}{5}M_d^F\right)^*\right],\\ a_2 &= 2\,\text{Re}\left[M_s^P\left(M_d^P + \frac{3}{5}M_d^F\right)^*\right],\\ b_2 &= 2\,\text{Im}\left[M_s^P\left(M_d^P - \frac{2}{5}M_d^F\right)^*\right],\end{aligned} \tag{10}$$

and so the data only provide three relations between the three complex amplitudes. The transverse spin correlation parameters contain no extra information since $A_{y,y} = 1$ and this is also true for $A_{x,x}$ up to d–d interference terms. If the longitudinal-transverse spin correlation parameter $A_{x,z}$ were measured, this would provide one further relation but this would still not be sufficient for an unambiguous partial wave decomposition. For this we need information about the phases of the production amplitudes.

The ${}^3P_0$ partial wave is uncoupled and, at the energy where the experiment was performed, its inelasticity is very small. Under these conditions the Watson theorem, which fixes the phase induced by the initial state interaction to that of the elastic proton–proton scattering, applies [17]. Thus we take $M_s^P = |M_s^P|e^{i\delta_{{}^3P_0}}$, with $\delta_{{}^3P_0} = -14.8^\circ$ [14]. Note that we do not include any phase associated with the ${}^1S_0$ final pp state because it is common for all partial waves and therefore does not affect the observables.

For coupled channels, such as ${}^3P_2 - {}^3F_2$, the strict conditions of the Watson theorem do not apply. However, at 353 MeV the phase shift analysis of pp data show that the mixing parameter, as well as the inelasticities, are still negligibly small [14]. This means that, to a good approximation, we may neglect the coupling and use the Watson theorem also here.

Further evidence in support of the smallness of the channel coupling is to be found in two potential models [18,19]. In both models the T-matrix for the transition from the ${}^3F_2$ to the ${}^3P_2$ wave is almost real; the phase of M_d^P is driven by $\delta_{{}^3P_2} = 17.9^\circ$, whereas the phase of M_d^F can be neglected. The quality of this approximation was also checked by explicit calculations of the d-wave production amplitudes within chiral effective field theory up to order m_π/m_N (NNLO) [15]. These showed that the above phase assumptions should be valid to within $\pm 2^\circ$.

Using the phase information in this way, we find that

$$\begin{aligned}M_s^P &= (55.3 \pm 0.4) - (14.6 \pm 0.1)i\,\sqrt{\text{nb/sr}},\\ M_d^P &= -(26.8 \pm 1.2) - (8.7 \pm 0.4)i\,\sqrt{\text{nb/sr}},\\ M_d^F &= (6.0 \pm 2.4)\,\sqrt{\text{nb/sr}}.\end{aligned} \tag{11}$$

These values were obtained purely from the $pp \to \{pp\}_s\pi^0$ data presented here. It is important to note that the numbers would change only marginally if results from the $np \to \{pp\}_s\pi^-$ experiment [20] were included in a global fit. The error bars are statistical and do not include the overall systematic uncertainties. However, changing the normalisations of the differential cross section and analysing powers by 3% and 4%, respectively, leads to changes that are comparable to the quoted errors. On the other hand, we could not investigate the less tangible ones associated with the neglect of the channel coupling and the truncation in the partial wave expansion. The weakness of pion production from the initial ${}^3F_2$ waves at 353 MeV, in addition to being in agreement with theoretical prejudices, is also consistent with the low inelasticity found for this wave [14].

It is important to note that all calculations for the d-wave production amplitude, phenomenological [3] as well as within ChPT [15], give a much smaller result than that presented in Eq. (11). Systematic studies within ChPT show that the strength is very sensitive to the $NN \to N\Delta$ transition potential, which is poorly determined from elastic scattering data. Our results may therefore put strong constraints on the strength of this transition potential.

In summary, we have measured the differential cross section and analysing power of the $\vec{p}p \to \{pp\}_s\pi^0$ reaction at 353 MeV. The angular distributions of A_y and $d\sigma/d\Omega$ are both well represented by retaining only pion s and d waves in a phenomenological description. The values of $d\sigma/d\Omega$ agree well with the results obtained at CELSIUS [8] over most of the angular range. However, at this energy these data flatten off around the middle of the angular distribution and, if this effect were correct, it would signal a large contribution from ${}^3F_2$ or even higher partial waves.

By making plausible assumptions on the coupling between the nucleon–nucleon channels and invoking the Watson theorem it was possible to estimate the partial wave amplitudes with their phases. These could be checked through a future measurement of the spin correlation parameter $A_{x,z}$, though this would require the installation of a Siberian snake in COSY.

In an associated letter [20], measurements are presented of the differential cross section and analysing power of the quasi-free $\vec{p}n \to \{pp\}_s\pi^-$ reaction in this energy domain. The extraction of the isospin-0 amplitudes from these data require knowledge of the $I = 1$ s- and d-wave amplitudes of the type provided here. In addition, data have already been taken on the transverse spin correlation parameter $A_{x,x}$ for this reaction [21]. The full collection of these results will lead to very useful constraints on the parameters of the chiral effective field theory.

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