Spin-triplet final-state dominance in the $pp \to pn\,\pi^+$ reaction at 492 MeV

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Abstract

The near-forward cross section for the $pp \to pn\pi^+$ reaction has been measured at 492 MeV by using the large acceptance ANKE magnetic spectrometer placed at an internal target position of the storage ring COSY-Jülich. Protons and pions emitted near zero degrees were detected in coincidence, and those with $\theta_\pi \leq 2^\circ$ and $\theta_p \leq 2.5^\circ$ were subjected to detailed analysis. Under these conditions, the excitation energy in the np system was below 3 MeV over the measured momentum range. This is the region of the np final-state-interaction peak, which was measured with a resolution of a fraction of an MeV. The shape of the peak allows one to conclude that the fraction of final spin-singlet np pairs is below about 10%. By using the results of scattering theory, this limit is confirmed through a comparison with the cross section for $pp \to d\pi^+$. The smallness of the singlet contribution is consistent with trends seen in lower energy data.

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The two-body $pp \to d\pi^+$ reaction has long been used as a test bed for both experimental measurements and theoretical models of intermediate energy pion production [1]. Unfortunately, there is no ${}^1S_0$ bound state in the S-wave spin-0 np system, analogous to the ${}^3S_1$ deuteron bound state in the spin-1 system, that would enable a similar study of the other isospin channel. On the other hand, there is a virtual (antibound) ${}^1S_0$ state very close to threshold at an np excitation energy $E_{np} \approx -0.07$ MeV. Both this and the deuteron pole at -2.22 MeV induce strong S-wave final-state-interaction (fsi) peaks in the $pp \to pn\pi^+$ reaction leading to spin-singlet and triplet np channels. To simulate a two-body reaction, the excitation energy in the np system should be confined to within a few MeV. Furthermore, the singlet and triplet contributions should be cleanly separated. This should in fact be possible with good energy resolution because the fsi peak widths are proportional to the (real or virtual) binding energies. The width of the singlet peak would therefore be a fraction of an MeV as compared to the 2-3 MeV of the triplet.

Inclusive $pp \to \pi^+X$ reactions at intermediate energies show an np enhancement at the edge of phase space, but the energy resolution achieved and the contamination from the much stronger $pp \to d\pi^+$ channel makes it very difficult to study the fsi region at low E_{np} [2]. The data nevertheless suggest that the triplet fsi provides the major signal [3]. To avoid feed-through from the $d\pi^+$ final state, it is useful to measure the proton and pion of the $pn\pi^+$ channel in coincidence and this can also lead to better determination of E_{np}. Such an experiment was carried out at LAMPF at 800 MeV [4]. Although fsi peaks were observed, the number of E_{np} points in the very low energy region was limited, as was the resolution, and so it was not possible to isolate a narrow singlet fsi peak from a broader triplet one. Nevertheless their model-dependent analysis suggested that the singlet fsi represented a very large fraction of the total strength at all angles measured. We report here on the results of an exclusive $pp \to pn\pi^+$ measurement at $T_p = 492$ MeV, where both the proton and pion were detected close to the forward direction. The resolution of a fraction of an MeV in E_{np} allows us to separate contributions from the singlet and triplet fsi peaks and our results suggest that the singlet fraction is below 10%. This upper bound is confirmed by comparing the magnitude of our cross section with that for $pp \to d\pi^+$ using general scattering theory results [5].

The experiment was carried out at the ANKE spectrometer placed inside the storage ring of the proton synchrotron COSY-Jülich. The main ANKE components are shown in Fig. 1, but see Ref. [6] for a detailed description. Foil targets made of CH_2 (polyethylene) were used in the experiment and the background from carbon was measured using a polycrystalline diamond target. The spectrometer dipole D2 separates positively charged ejectiles from the circulating COSY beam and allows one to determine their momenta at the target over a wide momentum range. The horizontal angular acceptance of $|\vartheta_{\rm H}| \leq 12^\circ$ is mainly fixed by the allowed start-stop combinations of the on-line TOF-trigger system. The vertical angular acceptance is in the range $|\vartheta_{\rm V}| \leq 7^\circ(3.5^\circ)$ for the lowest (highest) detectable ejectile momenta.

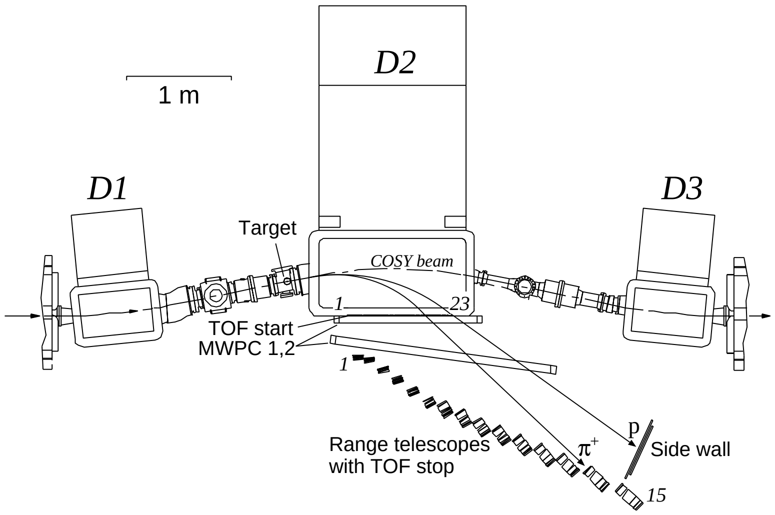

Fig. 1. Top view of the ANKE spectrometer and detectors used for the FSI studies.

The detection system [7] comprises two multi-wire proportional chambers (MWPC 1, 2 in Fig. 1) for track and momentum reconstruction, 23 scintillation counters close to the vacuum window of D2 for time-of-flight start measurements and 15 range telescopes located along the focal surface of D2. The side wall counters allow larger ejectile momenta to be measured. The identification of pions and protons is achieved *via* TOF and energy loss measurements. Background originating from the pole shoes of D2 is suppressed with the help of the track information from the MWPC's. The field strength of $B = 0.861$ T in D2 was chosen so that the pions used in the analysis were detected and identified in telescope #14 and the protons in the side-wall counters.

The spectrum of missing-mass-squared for the $p(p, p\pi^+)X$ reaction on a CH_2 target, shown in Fig. 2 for the full ANKE angular acceptance, displays a prominent neutron peak, with a standard deviation of $\sigma(m_x^2) = 0.0034\, m_n^2$, which is not present for the C target. The integrated luminosities for the two targets are different but, when the relative CH_2/C normalisation is evaluated from the spectra at high missing masses, it is found that the neutron peak sits on a carbon background of a few percent, which can easily be subtracted. Fits to the position of the deuteron and neutron peaks determined the proton beam energy to be $T_p = (492 \pm 1.7)$ MeV.

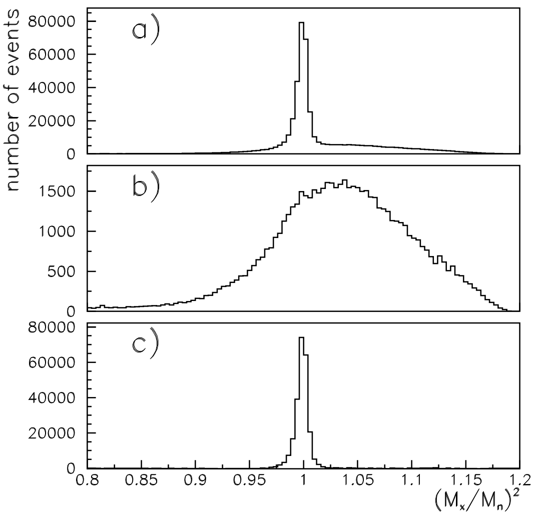

Fig. 2. Spectrum of the square of the missing mass for the $p(p, p\pi^+)X$ reaction, in units of the neutron mass, for: a) CH_2; b) C; c) CH_2-C targets, normalised to the same luminosity. By comparing the spectra at high masses, the relative luminosity $L(\mathrm{C})/L(\mathrm{CH_2})$ is deduced to be 0.264 ± 0.020.

In order to obtain clean samples of events with low np excitation energies, software cuts were imposed so as to extract two groups of events. Both of these have pion angles $\theta_\pi \leq 2.0°$, but the first group includes protons with angles $\theta_p \leq 2.0^\circ$, whereas the proton cut was extended to 2.5° for the second set. After subtracting the C background, the number of events remaining in the two cases was 1312 and 2008 respectively. The ratio follows that of the proton solid angle, the cut in the pion angle being of no importance here.

In the raw proton momentum spectra shown in Fig. 3, the carbon background with our cuts is below 3%. The central np excitation energies are indicated and, from this scale, it is seen that our events generally correspond to $E_{np} \leq$ 3 MeV, which means that the fsi region is well covered. Because of the limited statistics, we have summed all events over the whole angular ranges and this introduces an uncertainty of $\Delta E_{np} \approx 0.55\sqrt{E_{np}}$ MeV. This is far greater than the intrinsic resolution of the system which, through kinematic fits to the $pp \to pn\pi^+$ reaction, is about $\sigma = 160$ keV. Thus the width of any spin-singlet contribution in Fig. 3 is determined by the angular integration rather than the natural width or the intrinsic energy resolution of the apparatus.

With the angular cuts we have imposed, the proton measurement efficiency is about 60% at small proton momenta (≤ 350 MeV/c), constant at about 99% for momenta between 350 MeV/c and 410 MeV/c, but falls rapidly thereafter. Taking this and other effects into account in a detailed Monte Carlo study, we show in Fig. 3 a simulation where we have assumed that the cross section is proportional to three-body phase space times essentially a pure spin-triplet fsi factor. The significance of the excellent agreement with the shape of the spectrum will be crucial for the later discussion. One of the advantages of our experimental set-up is that we also have a measurement of the corresponding pion momentum spectrum. However, within the current precisions, the singlet/triplet ratio is better determined from the proton spectrum [8].

The absolute normalisation of the $pp \to pn\pi^+$ cross section is achieved by comparing the $pp \to d\pi^+$ events, measured in parallel, to standard cross section compilations [1]. Because of the dominance of the $d\pi^+$ final state, the reaction could be identified with sufficient precision without having to detect the deuteron, thus avoiding uncertainties arising from deuteron break-up in

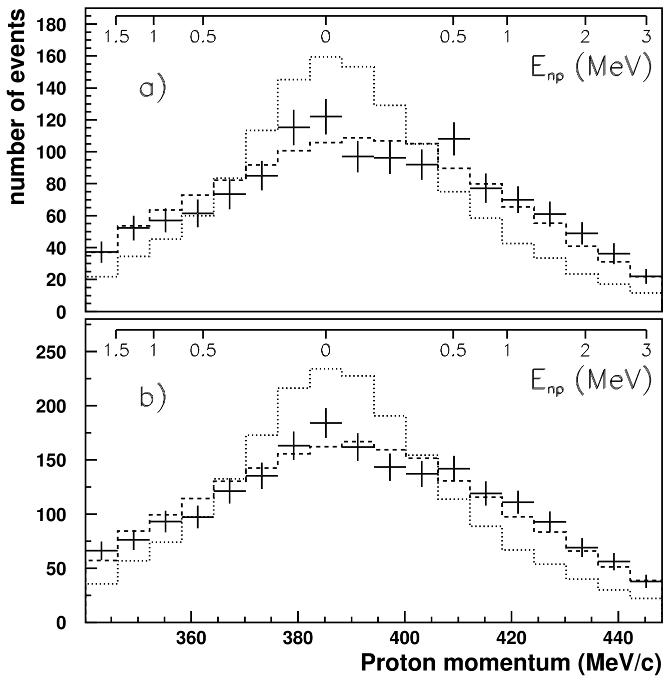

Fig. 3. Raw proton-momentum spectra of $pp \to pn\pi^+$ events (points with statistical errors), for events with $\theta_\pi \leq 2^\circ$. All the histograms are normalised to the total number of events. The relative np energy is indicated for protons and pions emitted at 0°. Figure a) is for $\theta_p \leq 2^\circ$ and b) for $\theta_p \leq 2.5^\circ$. The dashed histogram is a Monte Carlo simulation assuming pure spin-triplet final state ($\xi = 0$). Fits to the fsi formula of eq. (2) are consistent with this, giving $\xi = -.008 \pm .038$ for case a) and $\xi = -.008 \pm .036$ for b. A statistical mixture of spin states, *i.e.* $\xi = 0.25$, leads to the dotted histograms with χ^2/ndf =151.2/17 for a) and χ^2/ndf =178.2/17 for b).

the counters *etc.* The contamination from the carbon background is here larger ($\approx 23\%$) than for three-body events, but it is easy to correct for this using the normalised results from the carbon target discussed earlier. Our results are presented in Fig. 4, where only statistical errors are shown. The principal systematic effects are:

- Uncertainty in the number of $pp \to d\pi^+$ events, due to the tail of pions from the $pp \to pn\pi^+$ reaction where the proton escapes detection: $\approx 7\%$.
- Uncertainty in the ratio of C/CH_2 integrated luminosities: $\approx 2.5\%$.
- Uncertainty in the effective proton solid angle: $\approx 1.5\%$.

- Uncertainty in the SAID solution for $pp \to d\pi^+$, used for normalisation: $\approx 2.0\%$.

Summing these uncertainties quadratically, we arrive at an estimate of the total systematic error of $\approx 8\%$.

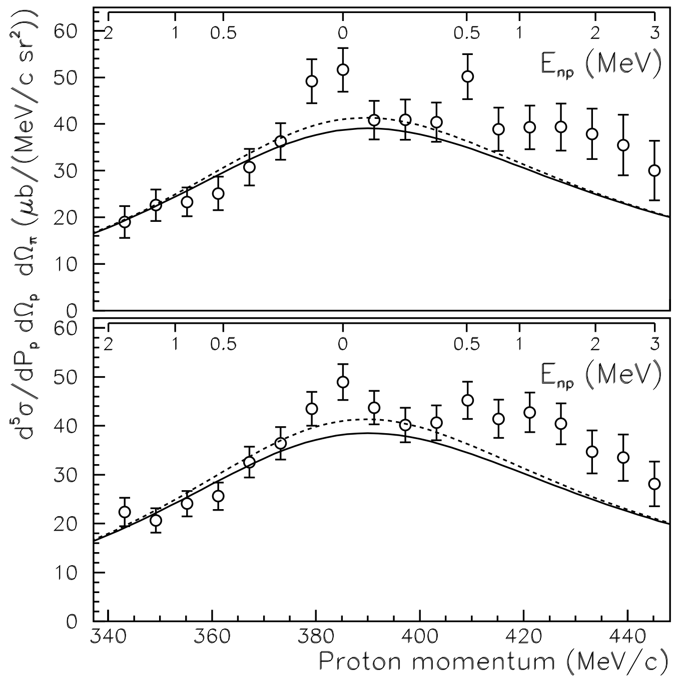

Fig. 4. Five-fold differential cross section for the $pp \to pn\pi^+$ reaction as a function of the measured proton momentum for events with $\theta_\pi \leq 2^\circ$. The np excitation energy is indicated for protons and pions emitted at 0°. The upper figure is for $\theta_p \leq 2^\circ$ and the lower for $\theta_p \leq 2.5^\circ$. The solid curves correspond to predictions for the spin-triplet contribution to the fsi peak, obtained from eq. (3) using $pp \to d\pi^+$ input data from the SAID SP96 solution [1], after averaging over the angular acceptance. The dashed curves are raw predictions without averaging. The estimates are expected to be only weakly model-dependent [5].

Since the $pp \to pn\pi^+$ events of Fig. 3 and Fig. 4 are all concentrated in the region $E_{np} \leq 3$ MeV, we can make an estimate of the relative amounts of spin-singlet and -triplet final states using the fact that any singlet fsi peak should be so much narrower than the triplet. We assume a variant of the

Goldberger-Watson fsi formula [9]

$$\mathrm{FSI}_i(k) = N_i \, \frac{(k^2+\beta_i^2)}{(k^2+\alpha_i^2)} \;, \tag{1}$$

where the α_i and β_i are determined from low energy np scattering data [13]. The triplet and singlet parameters are $\alpha_t = 0.232~\mathrm{fm}^{-1}$, $\alpha_s = -0.040~\mathrm{fm}^{-1}$, $\beta_t = 0.91~\mathrm{fm}^{-1}$, and $\beta_s = 0.79~\mathrm{fm}^{-1}$. It should be noted that the numerators in eq. (1) vary very little over our restricted E_{np} range, so that the fits are weakly dependent upon the values of the β_i. The overall constant N_i is determined by the condition that the integral of $\mathrm{FSI}_i(k)$ over k for $E_{np} \leq 3$ MeV is unity, which requires that $N_t = 0.104$ fm and $N_s = 0.0297$ fm. We then fit our data with the form

$$\frac{\mathrm{d}^5\sigma_t(pp \to pn\pi^+)}{\mathrm{d}p_p\,\mathrm{d}\Omega_p\,\mathrm{d}\Omega_\pi} \propto (\text{Kinematic factor}) \times [\xi\,\mathrm{FSI}_s(k) + (1-\xi)\,\mathrm{FSI}_t(k)] \;, \tag{2}$$

so that ξ has the physical significance of being the fraction of the cross section leading to singlet np states for $E_{np} \leq 3$ MeV.

When this form is passed through the Monte Carlo simulation and normalised to the data in Fig. 3, an excellent fit is achieved with $\xi = -.008 \pm .038$ and $\chi^2/ndf = 18.2/17$ for group a) and $\xi = -.008 \pm .036$ and $\chi^2/ndf = 15.9/17$ for group b). Effects of smearing the predictions over the spread in E_{np} induced by the angular acceptance and momentum bite *etc.* have been taken into account. A value of $\xi = 0.25$, which would correspond to a purely statistical factor, gives excess of events in the region around zero excitation energy and shortage at the right tail of the spectrum. This increases the χ^2/ndf by about 10 units. Thus we can assert purely from the shape of the fsi peak that the singlet contribution to the cross section is likely to be below $\approx 10\%$.

A second proof that the spin-singlet fraction is small can be found from the normalisation rather than the shape of the measured differential cross section. The Fäldt-Wilkin extrapolation theorem links the np scattering wave function to the deuteron bound-state function, independently of the form of the np potential [10,3], and this allows one to predict the S-wave spin-triplet contribution to the $pp \to pn\pi^+$ cross section at low E_{np} in terms of that for $pp \to d\pi^+$ [5]. To the extent that deuteron D-state effects can be neglected,

$$\frac{\mathrm{d}^5\sigma_t(pp \to pn\pi^+)}{\mathrm{d}p_p\,\mathrm{d}\Omega_p\,\mathrm{d}\Omega_\pi} = (\text{Kinematic factor}) \times \frac{1}{(k^2+\alpha_t^2)} \times \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_\pi}(pp \to d\pi^+)\,. \quad (3)$$

This relation does not require explicit knowledge of the pion production operator, merely that it be of short range. It describes well [5] the fsi region of the LAMPF $pp \to pn\pi^+$ data taken at a variety of angular configurations [4], though it should be stressed that the number of experimental points in the fsi peaks was small.

Because eq. (3) has the same dominant fsi factor as that of the spin-triplet Goldberger-Watson factor of eq. (2), it is no surprise that the shape of the differential cross section as a function of the final proton momentum shown in Fig. 4 is largely reproduced. To within possible corrections of the order of the deuteron D-state probability ($\approx 6\%$), this approach provides a robust lower bound on the three-body cross section. Although the curves pass through the points to the left of the peak, they are slightly low compared to the data on the right. This is compatible with theoretical and experimental uncertainties, and so the normalisation of the data also shows that any singlet contribution must be below about 10%.

The inclusive TRIUMF $p(p,\pi^+)X$ data [2] indicate significant contributions from np final states other than triplet S-wave, but their excitation energies are such that P-waves cannot be neglected. The exclusive $p(p,p\pi^+)n$ measurement carried out at CELSIUS at 400 MeV [11] was analysed as for a single-arm experiment by integrating over the final proton momentum as well as over the pion angle. When this is done, there is an indication of contributions other than spin-triplet S-waves, though there is only one high point in the $E_{np} \leq 3$ MeV range.

Given that the singlet fraction is so small at intermediate energies, this suggests that one should measure its production directly by studying the $pp \to pp\pi^0$ reaction, which could be done in parallel with $pn\pi^+$ detection at ANKE.

The reaction has already been investigated at CELSIUS up to 425 MeV and values of the differential cross section quoted separately for $E_{pp} \leq 2.6$ MeV [12]. Though there is no similar detailed measurement of the $pp \to pn\pi^+$ cross section with which to compare the CELSIUS π^0 data, it is possible to estimate the spin-triplet contribution quite reliably from that of $pp \to d\pi^+$ by employing the Fäldt-Wilkin theorem [3]. If then the cross section ratio is extrapolated to 492 MeV, it indicates that the singlet fraction should be below about 1%. This very low value is due, in part, to π^+ production being maximal in the forward direction [1], whereas the π^0 are produced preferentially at 90° [12]. Thus the singlet fraction at 492 MeV would be expected to be much larger for an experiment carried out at 90°.

In summary, we have measured the exclusive $pp \to pn\pi^+$ cross section reaction near the forward direction with a resolution in E_{np} superior to that of previous works. This allows us to put an upper bound on the proportion of singlet np final states, which is confirmed independently by comparing with $pp \to d\pi^+$ results. It is hoped to continue the investigation at other energies, studying simultaneously the $pn\pi^+$ and $pp\pi^0$ channel.

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