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Observation of a large longitudinal analyzing power in a nuclear reaction

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Abstract

We have measured the longitudinal analyzing power A_z of the pp $\rightarrow$ ppπ^0 reaction at 375 MeV bombarding energy. We find that for certain angle combinations of the outgoing particles the observed A_z is as large as 0.3, demonstrating that sizeable longitudinal analyzing powers in reactions with multi-particle final states are possible. This result has implications for pp parity violation experiments above the pion threshold. The observed A_z is dominated by the interference between s and p wave pions in conjunction with nucleon-nucleon P waves in the final state. © 2000 Elsevier Science B.V. All rights reserved.

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Experience shows that measurements of polarization observables are important in studies of reaction mechanisms in nuclear and particle physics. In the simplest of such experiments one measures the analyzing power A_y by observing the change in the reaction cross section as one switches between spin up and spin down with a beam polarized perpendicular to the reaction plane.

Analogous observables obtained with the beam polarized either along the beam direction (A_z) or perpendicular to the beam direction with the polarization vector lying in the reaction plane (A_x), are not ordinarily measured since, if parity is conserved,

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these analyzing powers are assumed to be identically zero. In fact, a measurement of the longitudinal analyzing power A_z in, for example, p-p elastic scattering provides a means for detecting parity violation in nuclear interactions (see for example Ref. [1]). Observed values for the parity-violating longitudinal analyzing power are of the order of $A_z \approx 10^{-7}$, i.e., very small.

It is often not understood that the $A_z = 0$ parity constraint does not apply to reactions in which the final state contains more than two particles and at least two of them are detected in non-coplanar kinematics. In this case A_z may differ from zero. Since the allowed angular patterns for this observable are rather complex, one might expect that measurements of A_z would provide a critical test of any reaction model.

In a previous attempt to measure A_z for a three-body final state reaction in non-coplanar kinematics [2], the reaction ^{2}H(p,pp)n was studied with a longitudinally polarized 9 MeV proton beam. The reported A_z is consistent with zero at the level of 0.003. In this Letter, we present new results for A_z for the reaction $pp \to pp\pi^0$ at $T_p = 375$ MeV, and demonstrate that for this case A_z is large.

The longitudinal analyzing power A_z is measured by observing the reaction yields Y_+ and Y_- with beam polarization parallel or anti-parallel to the beam momentum (z-axis),

$$A_z = \frac{1}{P_z} \frac{Y_+ - Y_-}{Y_+ + Y_-}, \tag{1}$$

where P_z is the beam polarization. The yield from a reaction with more than two particles in the final state depends on the experimental arrangement. Consider, for instance, an experiment where two particles are detected in coincidence. We denote the direction of the two particles by (θ_1, φ_1) and (θ_2, φ_2) where θ is the polar angle with respect to the z-axis and the azimuth φ is measured relative to the x-axis. The x-axis we fix so that it points horizontally to the left of the beam and the y-axis, pointing up, completes the right-handed Cartesian coordinate frame.

The invariance of physical laws under spatial inversion is treated formally by the parity operation which reverses polar vectors (coordinates, momenta) but does not affect axial vectors (spins, cross products of polar vectors). As shown in Ref. [3], as a consequence of parity conservation, polarization observables in nuclear reactions either remain the same or change sign when the final state is reflected on the x–z-plane. In particular, for the longitudinal analyzing power, parity conservation requires that

$$A_z(\varphi_1, \varphi_2) = -A_z(-\varphi_1, -\varphi_2). \tag{2}$$

Since the initial state is invariant against a rotation around the z-axis, we can set $\varphi_1 = 0$ without loss of generality. It is then easy to see that for *coplanar* detected particles (when $\varphi_2 = 0$ or π) Eq. (2) requires that $A_z = 0$. It is also clear that A_z vanishes if only *one* particle is detected.

In the present experiment we studied the reaction $pp \to pp\pi^0$ at 375 MeV bombarding energy. The measurement yields the momenta of both outgoing protons, $\boldsymbol{b}_1$ and $\boldsymbol{b}_2$, over most of the available phase space. From the center-of-mass values of $\boldsymbol{b}_1$ and $\boldsymbol{b}_2$ we deduce the kinetic energy ε of the two protons in their rest frame, and the canonical momenta $\boldsymbol{p} = \frac{1}{2}(\boldsymbol{b}_1 - \boldsymbol{b}_2)$ (the relative momentum between the two protons) and $\boldsymbol{q} = -\boldsymbol{b}_1 - \boldsymbol{b}_2$ (the pion momentum), with the corresponding angles $\hat{p} = (\theta_p, \varphi_p)$ and $\hat{q} = (\theta_q, \varphi_q)$. The identity of two of the outgoing particles restricts the range of θ_p since we can always number the two protons such that θ_p is between 0° and 90°. Furthermore, the rotational symmetry around the z-axis has the effect that only one azimuthal angle, $\Delta\varphi \equiv \varphi_p - \varphi_q$, is relevant. Thus, the kinematics of the final state is described by four numbers, θ_p, θ_q, $\Delta\varphi$, ε, all of which are known *for each event*. In the following we ignore the energy parameter ε which means that the reaction amplitudes are integrated over ε. Their ε dependence is well described by phase space, an angular momentum factor and, if the outgoing nucleons are in an S-state, by the final-state interaction between them [4].

In Ref. [5] it has been shown how polarization observables in reactions with a three-body final state can be expanded into partial waves of given angular momentum quantum numbers. The angular momentum in the final state shall be denoted by ℓ_p for the pp system and ℓ_q for the pion. Using spectroscopic notation, we label the final state accordingly as $\{\ell_p, \ell_q\} = \{Ss\}, \{Ps\}, \{Pp\}$. For beam energies below

400 MeV, these are *all* the angular momentum states that contribute measurably to A_z ({Sp}is forbidden for this reaction, and the partial waves {Ds} and {Sd} can only be significant when interfering with the {Ss} wave, but such terms do not contribute to A_z). Because there are only a few angular momentum states, a partial-wave expansion yields a simple expression for A_z in terms of the four kinematics variables, $\theta_p, \theta_q, \Delta\varphi$, and ε,

$$\begin{aligned}\sigma(\theta_p,\theta_q,\Delta\varphi,\varepsilon)\cdot A_z^{b,t}(\theta_p,\theta_q,\Delta\varphi,\varepsilon)\\ = \pm B_z^{(1)}(\varepsilon)\sin\theta_p\cos\theta_p\sin\theta_q\sin\Delta\varphi\\ + B_z^{(2)}(\varepsilon)\sin\theta_p\cos\theta_p\sin\theta_q\cos\theta_q\sin\Delta\varphi\\ + B_z^{(3)}(\varepsilon)\sin^2\theta_p\sin^2\theta_q\sin 2\Delta\varphi.\end{aligned} \tag{3}$$

Here, σ is the differential cross section that would be observed with unpolarized collision partners. The $+$ and $-$ sign in the first term refers to the analyzing power measured with a polarized beam (A_z^b) or with a polarized target (A_z^t), respectively. Because in our case the colliding particles are identical, the beam and target analyzing powers are related. This can be seen by rotating the experiment by 180° around the x-axis. This exchanges beam and target and reverses the polarization. It then follows that $A_z^t(\theta_p,\theta_q,\Delta\varphi) = -A_z^b(\pi-\theta_p,\pi-\theta_q,-\Delta\varphi)$ which is consistent with Eq. (3). The coefficients $B_z^{(k)}(\varepsilon)$ in Eq. (3) are given by [5]

$$B_z^{(k)}(\varepsilon) = \sum_{\alpha,\alpha'} C_k^{\alpha,\alpha',z} U_\alpha(\varepsilon) U_{\alpha'}^*(\varepsilon) \tag{4}$$

where $U_\alpha, U_{\alpha'}$ are transition amplitudes with a given set α of initial and final quantum numbers, and the $C_k^{\alpha,\alpha',z}$ are coefficients that arise from angular momentum coupling. One finds that in $B_z^{(1)}$ products of a {Ps} and a {Pp} amplitude contribute, while $B_z^{(2,3)}$ contain only {Pp} amplitudes. Within the first 100 MeV above threshold, the dependence of the amplitudes on energy ε is well described by the phase space factor times $p^{\ell_p}\cdot q^{\ell_q}$, times a factor due to the final-state interaction between the two outgoing protons if they are in an S state [4].

We note that Eq. (3) indeed satisfies the parity conservation condition of Eq. (2), and that it is invariant against a rotation of the coordinate system around the z-axis, as expected. Eq. (3) is also invariant against the exchange of the two observed protons which is affected by replacing φ_p by $(\varphi_p+\pi)$, and θ_p by $(\pi-\theta_p)$.

This $pp \to pp\pi^0$ measurement was carried out with the Indiana Cooler storage ring. The experimental setup is described in Ref. [6]. The directions of the two outgoing protons were observed in coincidence by a set of four wire chambers, and their energies were deduced from the light from a stack of scintillators in which they were stopped. A thin scintillator just downstream of the target provided a start signal for a time-of-flight measurement from which the particles were identified as protons. From the two measured four-vectors, the center-of-mass angles $\theta_p, \varphi_p, \theta_q$ and φ_q were calculated, and the mass m_x of the third particle was deduced. Events of interest were selected by constraining m_x to a region near the pion mass peak. The background under the peak was less than 10%. The shape of the background under the peak was determined from a separate measurement with an N_2 target and used to correct the raw data. A more detailed description of the measurement can be found in Refs. [6,7].

The experiment was carried out with a polarized proton beam on a polarized hydrogen storage-cell target. This makes it possible to measure both the beam and the target analyzing power, A_z^b and A_z^t. For technical reasons, the beam polarization $\boldsymbol{P} = (P_x, P_y, P_z)$ could not be oriented completely in the beam direction, in fact the longitudinal and vertical polarization components, P_z and P_y were about of the same magnitude and there was also a small sideways component, P_x. Data were acquired with the beam polarization in the $\boldsymbol{P}$ direction, as well as opposite to it $(-\boldsymbol{P})$. The target polarization, on the other hand, could be oriented either in the x- y- or z-direction without affecting its magnitude Q. Data were acquired with both signs for each of these directions, $\pm Q_x, \pm Q_y$, and $\pm Q_z$. The value of the product of beam and target polarization, $P_z \cdot Q = 0.265 \pm 0.004$, was deduced from elastic pp scattering, using known spin correlation coefficients [8]. Elastic pp scattering near $\theta_{\rm lab} = 45°$ was measured concurrently with pion production. Since A_z^b and A_z^t are related (see Eq. (3)), only the product $P_z \cdot Q$ affects our results, however, it might be of interest that the individual values that make A_z^b and A_z^t consistent are $P_z = 0.44$ and $Q = 0.60$.

Since the statistics of the present experiment do not allow a study of a four-fold differential cross section, we have ignored the energy variable ε and the polar angles θ_p and θ_q keeping track only of $\Delta\varphi$ for each event. This is equivalent to integrating the observables over the energy ε, and over θ_p ranging from 0° to 90° and θ_q from 0° to 180°. The resulting analyzing powers as a function of $\Delta\varphi$ are displayed in Fig. 1. The upper left panel shows the beam analyzing power A_z^b, obtained by evaluating Eq. (1) with yields measured with $+\boldsymbol{P}$ and $-\boldsymbol{P}$, while averaging over the target polarization. The upper right panel shows the target analyzing power A_z^t obtained by averaging over the beam polarization. The bottom row shows the target analyzing powers A_x^t and A_y^t, measured with *transverse* target polarization. The latter two quantities, as a function of the rotationally symmetric $\Delta\varphi$ are expected to vanish; this is clearly confirmed by the data. This is an important test, since it proves that the beam analyzing power, which is measured with a mixture of transverse and longitudinal polarization components, is sensitive *only* to the longitudinal component, P_z.

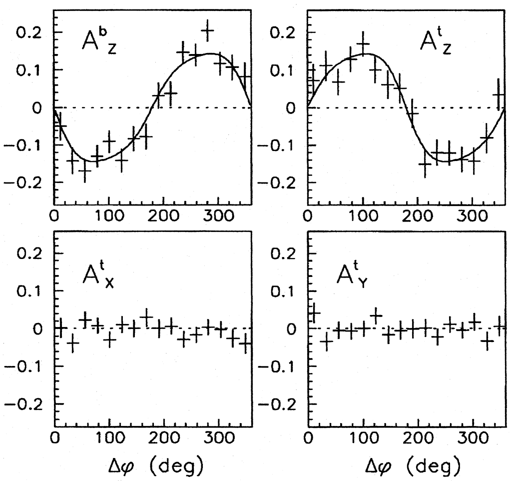

Fig. 1. Longitudinal beam and target analyzing powers A_z^b and A_z^t (top row) as a function of $\Delta\varphi$. The curves are a fit using the $\Delta\varphi$ dependence expected from a partial-wave expansion of the observables (see Eq. (5)). The bottom row shows the transverse target analyzing powers A_x^t and A_y^t. These observables vanish as expected because of the cylindrical symmetry of the initial state. This observation proves that the transverse components that are present in the beam polarization do not contribute in the measurement of A_z^b.

The curves in the upper part of Fig. 1 represent a fit, using an expression which is derived from Eq. (3), noting that the second term in Eq. (3) vanishes when integrating over the polar angles,

$$A_z^{b,t}(\Delta\varphi) = \frac{\pm b_1 \sin\Delta\varphi + b_3 \sin 2\Delta\varphi}{1 + b_0 \cos 2\Delta\varphi}. \qquad (5)$$

The unpolarized cross section σ depends on $\Delta\varphi$ in a way that follows from the partial-wave expansion mentioned earlier. In addition, the blind spot in the center of the detector (because of the circulating beam) causes a very similar $\Delta\varphi$ dependence of the acceptance. The denominator in Eq. (5) takes both these effects into account. The best-fit values of the three parameters with their statistical errors are $b_1 = -0.162 \pm 0.012$, $b_3 = -0.013 \pm 0.009$ and $b_0 = -0.17 \pm 0.11$. The χ^2 per degree of freedom is 0.98. The resulting value for b_0 is relatively small compared to unity. In addition, the term with b_0 peaks where the numerator of Eq. (5) vanishes and thus the values of of b_1 and b_3 are insensitive to a variation of b_0. We note that b_3 is much smaller that b_1. The same is true for the contribution by the second term in Eq. (3). This was determined by analyzing the data for pion polar angles θ_q in the forward and backward hemisphere separately. Thus, A_z in this reaction is dominated by b_1, i.e., the first term (with) $B_z^{(1)}$ in Eq. (3).

In order to be able to calculate A_z for any choice of θ_p, θ_q and $\Delta\varphi$, we must relate the parameters b_k of Eq. (5) to the coefficients $B_z^{(k)}$ in Eq. (3). Since the unpolarized cross section σ is dominated by its isotropic part, we can set $\sigma \approx \sigma_{\text{tot}}/4\pi$. The integration over θ_p and θ_q can then be carried out, and we obtain, retaining only the dominant term with $B_z^{(1)}$,

$$A_z^{b,t}(\theta_p, \theta_q, \Delta\varphi) \approx \pm(-0.619 \pm 0.046) \times \sin\theta_p \cos\theta_p \sin\theta_q \sin\Delta\varphi, \qquad (6)$$

where the largest possible value of the product of trigonometric functions equals $\frac{1}{2}$. The detector setup covers all of the phase space, except a hole, centered on the z-axis which subtends a cone of about 5° opening angle. The effect of this missing part of the acceptance was estimated, using the the dependence of the observables on angle given in Eq. (5), and found to be negligible on the level of the present statistical uncertainty.

From the present experiment we draw three main conclusions:

First, up until now, one might have assumed that the inherent symmetry of the longitudinal analyzing power would constrain the reaction dynamics such that A_z becomes small in general. By measuring a clearly identified and sizeable longitudinal analyzing power in the reaction $pp \to pp\pi^0$ we have shown that this assumption is not justified.

Second, the present result has obvious implications for studies of parity violation in pp collisions at energies above the pion production threshold. As an example, such an experiment at 450 MeV is in progress at TRIUMF [9]. At this energy, the $pp \to pp\pi^0$ reaction contributes about 1% to the total cross section, and the $pp \to pn\pi^+$ reaction (for which there is some indication [10] that it also exhibits a large A_z) contributes about 6%. If in such an experiment the detection system is sensitive to more than one of the final-state particles and is not perfectly symmetric around the beam axis there is a possibility that a parity-conserving A_z may contribute to the measured signal. Thus, at higher energies, measurements of parity violation must deal with a new source for systematic errors that is absent below the pion production threshold.

Third, it has been pointed out [11] that $A_z \neq 0$ requires that the final state description contains an axial vector (in our case, $\hat{p} \times \hat{q}$). This fact might make the observable A_z sensitive to specific terms in the transition operator. Thus, measurements of A_z constitute an important test of possible models for pion production in NN collisions. It is also noteworthy that the dominant contribution to A_z arises from an interference between {Ps} and {Pp} waves, and that any terms with {Pp} waves alone seem to be unimportant.

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