International Journal of Modern Physics E

DIPROTON FINAL STATES: A NEW TOOL FOR HADRON PHYSICS AT ANKE-COSY

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Received Day Month Year
Revised Day Month Year

The ANKE spectrometer at COSY-Juelich provides the possibility to select proton pairs with small excitation energy in the final state. This opens a new way to study hadron interactions at intermediate energies. The final proton pairs with small excitation energy are found presumably in the $^1S_0$ state which simplifies significantly the theoretical analysis. This approach has been successfully applied to the reactions $pd \to \{pp\}_s n$ at high and low momentum transfer kinematics, as well as to the $pp \to \{pp\}_s \pi^0$ and $pp \to \{pp\}_s \gamma$ processes.

Keywords: diproton; pion production; high momentum transfer.

PACS numbers: 25.40.Ep, 25.40.Qa, 13.60.Le

1. Introduction: diproton final states experiments at ANKE

Properties of few nucleon systems have long been a subject of intensive theoretical and experimental study. Especially important role in this study have been played by the processes with deuteron, a bound state of proton and neutron. In this respect, a particular interest arises for the investigation of the diproton, an unbound system of two protons with small excitation energy. The diproton, being the isospin partner of the deuteron, possesses different quantum numbers. Selection of the excitation energy of the proton pair $E_{pp} < 3$ MeV ensures dominance of the $^1S_0$ state of the diproton, which simplifies significantly the theoretical interpretation. The reactions with formation of a diproton involve transitions in the NN system, different from the case of the deuteron, and, in particular, the role of the Δ isobar is expected to be much suppressed because the S-wave ΔN intermediate state is forbidden.

Detection of the proton pair with $E_{pp} < 3$ MeV in an experiment requires an excellent excitation energy resolution and the ability to resolve the two spatially close trajectories of the protons. This explains the fact that so far there have been few attempts to study processes with the diproton final state. The ANKE spectometer [1] provides a resolution of $\sigma(E_{pp}) = 0.2 - 0.6$ MeV in the $E_{pp} = 0 - 3$ MeV range and is particularly well suited for this purpose.

The diproton program at ANKE involves several experiments:

- Study of mesonless deuteron break-up $pd \to \{pp\}_s n$ in collinear kinematics:
  - at high momentum transfer [2,3],
  - at low momentum transfer (charge-exchange reaction) [4].
- Study of meson production in $pN \to \{pp\}_s X$, where X is:
  - a single pion,
  - the $(\pi\pi)$ system, used to study of the ABC effect in the process $pp \to \{pp\}_s(2\pi)$ in the $T_p = 0.8 - 2.0$ GeV range.
  - a heavier meson like η and ω.
- the inverse diproton photodisintegration $pp \to \{pp\}_s\gamma$ [5].

Single pion production and the charge-exchange reaction are the key double polarization experiments in the future physics program at ANKE.

2. Deuteron break-up reactions

2.1. *High momentum transfer*

The process $pd \to \{pp\}_s n$ with a forward emitted diproton is proposed for study. The kinematics of the process is the same as in pd-backward scattering and the same mechanisms can be considered for its description. In contrast to $pd \to dp$, the amplitude of excitation of Δ in the intermediate state is expected to be suppressed by a factor of 3 due to selection of the diproton in S-wave. Thus, the one nucleon exchange mechanism, which is sensitive to the short range part of the NN-interaction potential and to the high momentum part of the deuteron wave function, is expected to dominate the cross-section.

The differential cross-section of $pd \to \{pp\}_s n$ with a forward emitted $\{pp\}$-pair has been measured in the range of $T_p = 0.5 - 2.0$ GeV [2]. Comparison of the results with a model-calculation including Δ-production, one nucleon exchange and single scattering mechanisms, shows a clear advantage in using the modern CD Bonn NN-potential over the Paris and RSC potentials in the region $0.4 - 0.6$ GeV/c of the internal deuteron momentum[2]. For further insight, additional data, in particular polarization measurements, are needed to provide a complete set of observables.

2.2. *Deuteron charge-exchange break-up reaction*

The processes $\vec{d}\vec{p} \to \{pp\}_s n$ with a forward emitted diproton and $\vec{p}\vec{d} \to \{pp\}_s n$ with the diproton going backwards proceed with low momentum transfer. One can extract the elementary charge-exchange spin amplitudes of pn-scattering from the measured polarization observables in the deuteron charge-exchange break-up process. The existing information on these amplitudes above 800 MeV is scarce. The equivalent neutron beam momentum available for COSY ranges up to 1.1 GeV in the case of deuteron beam, and up to 2.8 GeV in the case of deuteron target.

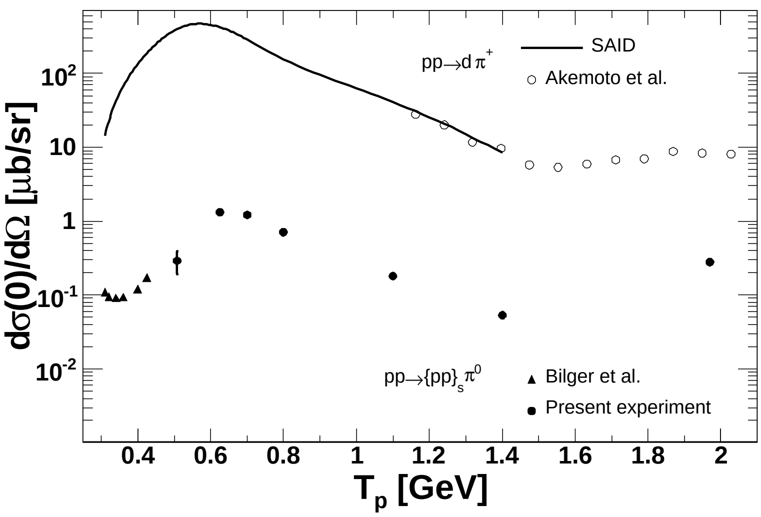

Fig. 1. Energy dependence of the forward differential cross-section for the $pp \to \{pp\}_s\pi^0$ reaction with $E_{pp} < 3$ MeV. The closed circles represent the results from the present experiment while the triangles show the low energy CELSIUS data. For comparison we show also the corresponding cross section for the $pp \to d\pi^+$ reaction. For energies up to 1.4 GeV this is represented by the dashed line taken from the SAID parametrisation whereas at higher energies the Akemoto *et al.* data are shown as open circles.

As a first step of the study, a measurement at $T_n = 585$ MeV was done, where information on the np spin-dependent amplitudes is available. The analysis showed excellent agreement of the extracted np amplitudes with the existing data [4]. Currently, the data obtained at $T_d = 2.3$ GeV are being analyzed. New double polarization measurements of the spin correlation coefficients $C_{y,y}, C_{x,x}$ are scheduled for the beginning of 2009.

3. Pion production in $pN \to \{pp\}_s\pi$

3.1. π^0 *production in* $0.5 - 2.0$ *GeV region*

The single pion production in nucleon-nucleon collisions, $NN \to NN\pi^0$, is one of the principial tools used in the investigation of NN dynamics at intermediate energies. Because of large momentum transfers involved, even close to threshold, such a meson production is sensitive to the short-range part of the NN-interaction. The $pp \to (pp)_s\pi^0$ differential cross section has been measured with the ANKE spectrometer at COSY-Jülich for seven proton beam energies T_p between 0.5 and 2.0 GeV [6]. The forward cross section is presented in Fig. 1 together with the CELSIUS data on $pp \to (pp)_s\pi^0$ [7] and is compared to the $pp \to d\pi^+$ data [8].

In the measured region of $\theta_{pp}^{cm} = \pm 18°$, the data reveal a forward dip for $T_p \leq 1.4$ GeV whereas a forward peaking is seen at 1.97 GeV. The energy dependence of the forward cross section shows a broad peak in the 0.6-0.8 GeV region, probably associated with $\Delta(1232)$ excitation, and a minimum at 1.4 GeV.

The ratio of $pp \to (pp)_s(0^\circ)\pi^0$ to $pp \to d(0^\circ)\pi^+$ cross sections can provide information on the relative strength of spin-singlet to spin-triplet production. The resulting ratio (Fig. 2) shows that singlet production in the forward direction remains small at energies even above the $\Delta(1232)$ excitation region. Below 1.4 GeV the ratio is typically a few per cent, which is significantly smaller than the trivial spin-statistics factor of 1/3.

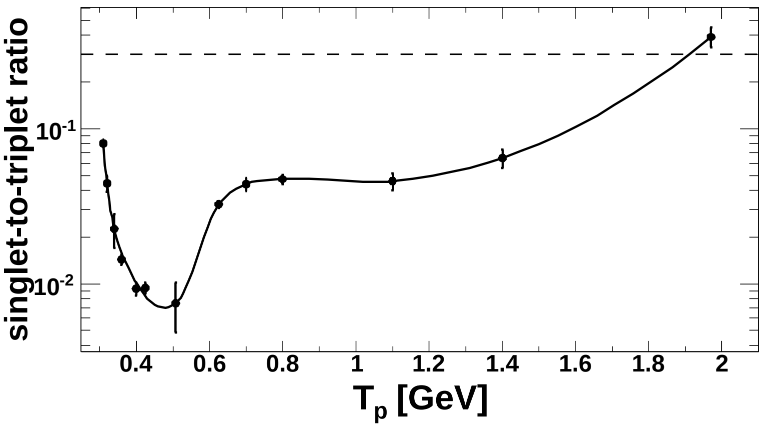

Fig. 2. Energy dependence of the ratio $R(\pi^0/\pi^+)$ of the forward $pp \to \{pp\}_s\pi^0$ and $pp \to \{pn\}_t\pi^+$ cross sections integrated up to 3 MeV excitation energy. The curve is drawn to guide the eye.

3.2. *Near threshold region*

The spin structure of the process $pn \to \{pp\}_s\pi^-$ (or $pp \to \{pp\}_s\pi^0$) with the diproton in $^1S_0$ state is $\frac{1}{2}^+\frac{1}{2}^+ \to 0^+0^+$, and there are only two spin amplitudes involved in this process. From this it follows that the measurement of the differential cross section, the analyzing power and one spin correlation coefficient is sufficient to extract magnitudes of the two amplitudes and their relative phase. A combined study of several observables in $pp \to \{pp\}_s\pi^0$ and $pn \to \{pp\}_s\pi^-$ could be used to isolate the important strength parameter d of the four-nucleon contact interaction in χPT [10].

$d\sigma/d\Omega$ in the process $pp \to \{pp\}_s\pi^0$ has been measured at 353 MeV in October 2007. Measurement of the differential cross-section and vector analysing power in $pp \to \{pp\}_s\pi^0$ and $pn \to \{pp\}_s\pi^-$ at 353 MeV is scheduled for 2009 [11]. In addition, a double-polarized experiment for obtaining of $A_{y,y}$ and $A_{x,x}$ is planned.

4. Inverse diproton photodisintegration

The fundamental reaction $pp \to \{pp\}_s\gamma$ has been observed for proton beam energies of $T_p = 0.353, 0.5$, and 0.55 GeV [5]. This is equivalent to photodisintegration of a free $^1S_0$ diproton for photon energies $E_\gamma \approx T_p/2$. The events from this process produce a peak at $M_x^2 \approx 0$ in the experimental missing-mass spectra (Fig. 3).

The differential cross sections measured for c.m. angles $\theta_{pp}^{cm} < 20^\circ$ exhibit a steep increase with angle that is compatible with E1 and E2 multipole contributions. The ratio of the measured cross sections to those of $np \to \gamma d$ is on the $10^{-3} - 10^{-2}$ level. The increase of the $pp \to \{pp\}_s\gamma$ cross section with T_p might reflect the influence of the $\Delta(1232)$ excitation. Further information on this process will be obtained within the planned measurement of $pp \to \{pp\}_s\pi^0$ and $pn \to \{pp\}_s\pi^-$ processes with the polarized proton beam at ANKE [11].

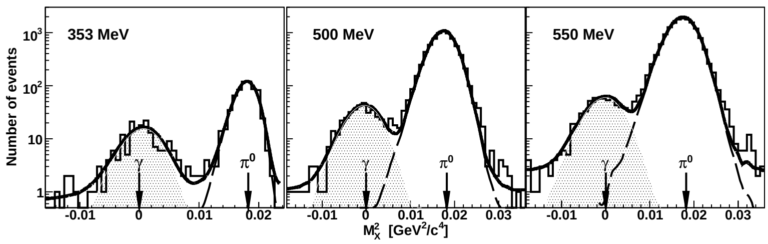

Fig. 3. Missing-mass-squared for the $pp \to ppX$ reaction with $E_{pp} < 3$ MeV. The shaded area corresponds to the predicted γ peak, the dashed line to the π^0, and the solid to the sum of these and a straight line background.

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