Observation of inverse diproton photodisintegration at intermediate energies

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The reaction $pp \rightarrow \{pp\}_s \gamma$, where $\{pp\}_s$ is a proton pair with an excitation energy $E_{pp} < 3$ MeV, has been observed with the ANKE spectrometer at COSY–Jülich for proton beam energies of $T_p = 0.353, 0.500,$ and $0.550$ GeV. This is equivalent to photodisintegration of a free $^3S_0$ diproton for photon energies $E_\gamma \approx T_p/2$. The differential cross sections measured for c.m. angles $0^\circ < \theta_{pp} < 20^\circ$ exhibit a steep increase with angle that is consistent with $E1$ and $E2$ multipole contributions. The ratio of the measured cross sections to those of $np \rightarrow d\gamma$ is on the $10^{-3} \sim 10^{-2}$ level. The increase of the $pp \rightarrow \{pp\}_s \gamma$ cross section with $T_p$ might reflect the influence of the $\Delta(1232)$ excitation.

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Photoabsorption on two-nucleon systems in nuclei at several hundred MeV allows one to probe fundamental properties of nuclei at short distances. The photodisintegration of the simplest nucleus, the deuteron, through the $\gamma d \rightarrow pn$ reaction is widely used as a testing ground for different theoretical ideas of the nucleon-nucleon interaction, such as meson-exchange models and isobar currents [1] or, more recently, quark-gluon degrees of freedom [2]. However, much less is known, both experimentally and theoretically, on the other simplest process

$$\gamma + \{pp\}_s \rightarrow p + p + p, \quad (1)$$

where $\{pp\}_s$ is a proton pair in the $^1S_0$ state. The photodisintegration of the spin-singlet $pp$-pair differs from that of the spin-triplet ($^3S_1 - ^3D_1$) $pn$ pair, where the $M1$ magnetic dipole transition dominates $\gamma d \rightarrow pn$ at several hundred MeV through the excitation of the $\Delta(1232)$ isobar [3, 4]. In contrast, due to selection rules, there is no direct contribution to reaction (1) from $S$-wave $\Delta N$ intermediate states [3, 5] and $M$-odd multipoles are forbidden. Furthermore, since the diproton has no electric dipole moment, only the spin-flip contribution to the $E1$ operator survives [6]. Features of the underlying dynamics, which are not visible in the photodisintegration of the deuteron, may therefore reveal themselves in reaction (1).

In the absence of a free bound diproton, reaction (1) has only been investigated for a $^1S_0$ diproton bound within a nucleus, the lightest of these being $^3$He [7]. However, since the $M1$ absorption on quasi-deuteron pairs is so strong, the $^3$He$(\gamma, pp)n$ reaction has large backgrounds associated with apparent three-nucleon absorption, combined with final state interactions (FSI). The total cross section for photon absorption by two protons in $^3$He for photon energies $0.2 – 0.5$ GeV was found to be only a few percent of the total rate [1]. These contaminations are absent in the inverse reaction with the production of a free $^1S_0$ diproton

$$p + p \rightarrow \gamma + \{pp\}_s. \quad (2)$$

At excitation energies $E_{pp}$ of the final $pp$ pair less than a few MeV ($E_{pp} < 3$ MeV, for definiteness), the system is almost exclusively in the $^3S_0$ state. The known experiments on hard $pp$ bremsstrahlung at intermediate energies were not designed for the study of the quasi-two-body channel (2). In the published data [10, 11, 12, 13, 14], the selection of low $E_{pp}$ events was either impossible instrumentally or was not done if feasible. In the COSY–TOF experiment at a beam energy of $T_p = 0.293$ GeV, the $pp\gamma$ data did not exhibit any sizeable FSI enhancement at low $E_{pp}$ and no estimate of the cross section for channel (2) was made [15]. The aim of the present work was to observe the reaction in the region of the $\Delta$ and to measure its differential cross section. Here we present results at $T_p = 0.353, 0.500,$ and $0.550$ GeV.

The experiment was performed using the ANKE setup [10] installed at the internal proton beam of the synchrotron storage ring COSY–Jülich. Positively charged secondaries produced in the hydrogen cluster-jet target traversed the vertical magnetic field of the spectrometer and entered the forward detector, consisting of multiwire chambers followed by a hodoscope of vertically oriented scintillators.

The acceptance of the system is shown in Fig. 1a in
the laboratory energy of the photon in the inverse reaction (1).

the missing c.m. energy for the events from the $\gamma\gamma$ events in the

The number of protons stored in the ring was typically a few times $10^{10}$ and the target density was $10^{14}$ protons/cm$^2$. The errors in the integrated luminosities in Table I include both systematic and normalization effects. More detailed descriptions of the setup and data-processing procedure can be found elsewhere [18, 19, 20].

Single protons from elastic $pp$ scattering, identified by their momenta and ionization losses, were recorded for luminosity purposes. Differential cross sections from Ref. [17] were used to establish the absolute normalization. The number of protons stored in the ring was typically a few times $10^{10}$ and the target density was $10^{14}$ protons/cm$^2$. The errors in the integrated luminosities in Table I include both systematic and normalization effects. More detailed descriptions of the setup and data-processing procedure can be found elsewhere [18, 19, 20].

When proton pairs hit different counters, the difference $\Delta t_{\text{meas}}$ of the arrival times can be measured and compared with the time-of-flight difference $\Delta t(\vec{p}_1, \vec{p}_2)$ calculated using the measured momenta, assuming that both particles are protons. The $\Delta t_{\text{meas}} - \Delta t(\vec{p}_1, \vec{p}_2)$ distribution has a FWHM of $0.6 - 1.1$ ns, so that genuine proton coincidences can be identified unambiguously (Fig. 1b).

The tracking system led to a precision in the determination of the momentum $\sigma(p)/p \approx 1\%$ and polar angle $\sigma(\theta) \approx 0.2^\circ$ for protons around 0.6 GeV/c and these gave a resolution $\sigma(E_{pp}) = 0.1 - 0.5$ MeV for $E_{pp} < 3$ MeV.

The determination of the four-momenta of the two final protons allows a full kinematical reconstruction of $pp \rightarrow ppX$ events and the derivation of the missing-mass spectra for the pairs with $E_{pp} < 3$ MeV. In our previous work at $T_p = 0.625$ and 0.8 GeV [19, 20], only a hint of reaction (2) could be seen. For the present energies, a clear peak is revealed around $M_x^2 \approx 0$ (Fig. 2). This is well separated from the $\pi^0$ signal at 0.353 GeV whereas, at 0.5 and 0.55 GeV, the two structures partially overlap because of broadening of the pion peak away from the production threshold. Fits of the $M_x^2$ distributions as the sum of modeled $\gamma$ and $\pi^0$ contributions and a straight line background lead to the parameters listed in Table II. The missing-energy distributions for the $\gamma$-peak events in the overall c.m. frame, which are reflections of the resolution of the setup and the $E_{pp}$ range, have widths $\approx 1$ MeV. The mean $E_x^m$ in Table II agree with the expected kinematic values to within $\approx 0.2$ MeV. The energy $E_x$ of the inverse reaction is averaged over the $E_{pp}$ range 0–3 MeV and distributed with an rms of 0.5 MeV.

The $E_{pp}$ spectrum of events from the $\gamma$-peak is shown in Fig. 3a before correcting for acceptance. The solid curve represents the Monte-Carlo simulation, with events being generated according to phase space, modified by a Migdal-Watson $pp$ FSI factor taken from the square of the low-energy $pp$ elastic amplitude in the $S_0$ wave [19]. These events were traced through the experimental setup, with due allowance for all its known features. The

![FIG. 1: Performance of the setup at 0.5 GeV. a) The polar angle projection $\theta_{XZ}$ onto the median plane of the spectrometer plotted versus the particle momentum. The experimental points show the acceptance for detection of single particles. The curves depict the kinematical loci for $p$ and $d$ from the indicated processes. The symbol (pp) denotes a $pp$ pair with the invariant mass equal to $2m_p$. The acceptance $A(pp)_\gamma$ for reaction (2) is shown in the inset as a function of the c.m. polar angle $\theta_{pp}$ of the proton pair. b) Identification of the proton pairs, as described in the text.](image)

![TABLE I: Measurement characteristics: $L_{\text{int}}$ is the integrated luminosity; $(M^2_x)^m$ and $\sigma(M^2_x)$ in 0.01 GeV$^2$/c$^4$ units are, respectively, the mean value and the standard deviation of the missing-mass-squared distributions for $pp$ pairs with $E_{pp} < 3$ MeV at the beam energy $T_p$; $N_\gamma$ is the number of events in the $\gamma$-peak for $\theta_{pp} < 20^\circ$; $N_{bg}/N_\gamma$ is the ratio of the background to signal in the $\gamma$ peak; $E_x^m$ is the mean value of the missing c.m. energy for the events from the $\gamma$ peak; $E_x$ is the laboratory energy of the photon in the inverse reaction (1).](image)

| $T_p$ [GeV] | 0.353 | 0.500 | 0.550 |
| $E_x$ [GeV] | 0.176 | 0.249 | 0.274 |
| $L_{\text{int}}$ [nb$^{-1}$] | 573±18 | 331±10 | 318±21 |
| $(M^2_x)^m_{\gamma}$ | 0.01±0.03 | 0.02±0.04 | 0.01±0.04 |
| $\sigma(M^2_x)_{\gamma}$ | 0.28±0.04 | 0.35±0.03 | 0.41±0.02 |
| $N_\gamma$ | 180 | 335 | 525 |
| $N_{bg}/N_\gamma$ | 0.23 | 0.05 | 0.11 |
| $E_x^m$ [GeV] | 0.161 | 0.221 | 0.241 |

![FIG. 2: Missing-mass-squared distributions for the $pp \rightarrow ppX$ reaction for events with $E_{pp} < 3$ MeV. The shaded area corresponds to the predicted $\gamma$ peak, the dashed line to the $\pi^0$, and the solid to the sum of these and a straight line background.](image)
simulation satisfactorily reproduces the experiment, with
\chi^2/ndf = 11.4/11 at 0.5 GeV. If the FSI is neglected, this
figure rises to 71/11. Further evidence that P-wave con-
tamination is at most a few percent is provided by the
acceptance-corrected proton angular distribution in the
pp rest frame. As seen in Fig. 3a, this is consistent with the isotropy expected for the \(^{3}\text{He}\) final state.

In order to obtain the differential cross section \(d\sigma/d\Omega_{pp}\)
as a function of the diproton polar angle \(\theta_{pp}\), events with \(E_{pp} < 3\) MeV in the \(\gamma\)-peak of the \(M_{x}^2\) distributions were analyzed in \(\cos\theta_{pp}\) bins of 0.01 – 0.02 width. After subtraction of the background contamination, the yield of reaction (2) was found from the number of events in the missing mass intervals \(M_{x}^2 = 0 \pm 2.5\sigma(M_{x}^2)\gamma\) at 0.353 GeV and \(M_{x}^2 = 0 \pm 1.8\sigma(M_{x}^2)\gamma\) at higher energies. The background was determined at 0.353 GeV by using missing-mass intervals outside but adjacent to the \(\gamma\) peak. At 0.5 and 0.55 GeV, the contribution from the tail of the \(\pi^0\) peak was also considered, with the shape being taken from the simulation. The event numbers were corrected for detector efficiency and setup acceptance, as determined from the full Monte-Carlo simulation.

Since the two initial protons are identical, the differential cross section is a function only of \(x = \cos^2\theta_{pp}\), and the measured values given in Table I indicate a very strong dependence upon this variable. Theoretical considerations of the \(\gamma\{pp\} \rightarrow pp\) reaction [22] suggest that, in our energy range, it might be sufficient to retain transitions corresponding to only the three lowest allowed multipoles, viz \(E1, E2\) and \(M2\). Moreover, it is predicted [9] that the \(M2\) strength should vanish for \(E_{\gamma} \approx 0.25\) GeV and be rather low compared to \(E1\) and \(E2\) in the range 0.18 – 0.28 GeV. Since the \(E2\) and \(E1\) transitions do not interfere, restricting to just these two multipoles, the differential cross section is of the form

\[
\frac{d\sigma}{d\Omega_{pp}} = a[(1 + x)\kappa + 10x(1 - x)],
\]

where \(\kappa = \sigma(E1)/\sigma(E2)\) and \(a = 3\sigma(E2)/16\pi\). Here \(\sigma(E1)\) is the total cross section of reaction (2) for the \(E1\) multipole. Fitting the data with this form (see Fig. 3b) leads to the parameters \(\kappa\) and \(a\) given in Table I. For all our energies the value of \(\kappa\) shows that the \(E1\) and \(E2\) multipoles have rather similar strengths, a feature that was not evident in the \(^{3}\text{He}(\gamma, pp)n\) experiments [4, 8, 9].

The cross sections for the \(pp \rightarrow \{pp\}\gamma\) reaction are compared in Fig. 3b with those of \(np \rightarrow d\gamma\) [3]. The diproton-to-deuteron ratio is small and varies with angle and energy between about \(4 \times 10^{-3}\) and \(3 \times 10^{-2}\). In part, this low value is due to the smaller phase space volume for the unbound \(pp\) system and this gives a suppression factor \(\approx 0.1\) [19]. The residual suppression must be related to the different dynamics in the two reactions. The crucial point here are the absence in the diproton photodisintegration of the spin-non-flip \(E1\) term [8] and the \(M1\) transition [8], which dominates the \(\gamma d \rightarrow pn\) reaction in the \(\Delta\) energy range. Intermediate \(\Delta\) states are allowed in \(P\) and higher partial waves [6], though their strength will be reduced by the centrifugal barrier.

As a consequence, the contribution of the \(\Delta\) isobar in the \(\gamma\{pp\}\rightarrow pp\) absorption should be greatly diminished compared to the \(\gamma d \rightarrow pn\) case. This logic has also been advanced to explain the relatively small cross section of diproton photodisintegration in the \(^{3}\text{He}(\gamma, pp)n\) reaction [7, 8, 10].

\[
\gamma_{d} \rightarrow pn\]

The most prominent feature in the energy dependence of the \(\gamma d \rightarrow pn\) total and small-angle differential cross sections is the bump at \(E_{\gamma} \approx 150 - 300\) MeV [8], caused by the excitation of the \(\Delta\)-isobar. In contrast, the total cross section for photon absorption by two bound protons in the \(^{3}\text{He}(\gamma, pp)n\) reaction [7] falls steadily as \(E_{\gamma}\) increases from 0.2 to 0.5 GeV, in qualitative agreement with the arguments for the \(\Delta\)-isobar suppression. It is also in line with the results of the model calculation that indicates a monotonic decrease in the \(E2\) contribution through the \(\Delta\) region [8]. Our results are in clear disagreement with these findings. It is important
to note that, if the $M2$ amplitude is neglected, the parameter $a$ would reflect directly the $E2$ contribution to the $pp \rightarrow \{pp\} \gamma$ total cross section. The values of $a$ reported in Table II rise strongly with energy and the most plausible explanation for this behavior is the influence of $D$-wave $\Delta N$ intermediate states.

A rapid rise with angle was also noted in the differential cross section for single pion production in the $pp \rightarrow \{pp\} \pi^0$ reaction near the forward direction $^{20}$. The $S$-wave $\Delta N$ contribution is also suppressed here by parity and angular momentum conservation, though a broad maximum was observed in the forward direction at 0.5 – 1.0 GeV, which might also be a reflection of higher partial waves in the $\Delta N$ intermediate states.

The $pp \rightarrow \{pp\} \gamma$ analyzing power will also be measured together with $pp \rightarrow \{pp\} \pi^0$ over an extended angular range at ANKE by using a polarized proton beam $^{22}$. This is of interest because any signal should then arise from the interference of the $E2$ with the $E1$ and $M2$ multipoles $^{21}$. Even more revealing would be a measurement of spin correlation with the polarized beam and target that are available at ANKE $^{22}$.

An extended study of reaction $^{2}$, involving also the use of $\gamma$-detectors, might be feasible at COSY, where the maximum beam energy is $T_p = 2.9$ GeV. An investigation at energies well above the $\Delta$ region would allow one to compare with other $^3\text{He}(\gamma, pp)n$ data $^{8}$. The onset of dimensional scaling, observed at large transverse momenta in $\gamma d \rightarrow pn$ for $E_\gamma > 1$ GeV $^{24}$ and suggested for $^3\text{He}(\gamma, pp)n$ $^{25}$, might also be studied in reaction $^{2}$.

In summary, the reaction $pp \rightarrow \{pp\} \gamma$ with production of the final $^3S_0$ proton pair has been observed at beam energies of 0.353, 0.50, and 0.55 GeV. The differential cross sections measured for c.m. angles in the interval $0^\circ$ – $20^\circ$ are orders of magnitude lower than those for $np \rightarrow d\gamma$. The rapid change of the $pp \rightarrow \{pp\} \gamma$ cross section with angle allows one to estimate the ratio of the $E1$ and $E2$ multipole intensities. The rise in the differential cross section with energy may be related to the $\Delta$ excitation in higher partial waves. There is no sign of such a behavior in the data on the photoabsorption on $^3\text{He}$, though the interpretation there is complicated by multinucleon absorption. The $pp \rightarrow \{pp\} \gamma$ reaction does not suffer from this drawback and further study of the process, including the measurement of polarization observables, which is possible at ANKE, might open up a new way to investigate the properties of the $pp$ system at high momentum transfers.

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