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Evidence of the Coulomb-force effects in the cross-sections of the deuteron–proton breakup at 130 MeV

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Abstract

High precision cross-section data of the deuteron–proton breakup reaction at 130 MeV deuteron energy are compared with the theoretical predictions obtained with a coupled-channel extension of the CD Bonn potential with virtual Δ-isobar excitation, without and with inclusion of the long-range Coulomb force. The Coulomb effect is studied on the basis of the cross-section data set, extended in this work to about 1500 data points by including breakup geometries characterized by small polar angles of the two protons. The experimental data clearly prefer predictions obtained with the Coulomb interaction included. The strongest effects are observed in regions in which the relative energy of the two protons is the smallest.

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The successes of meson-exchange theories in the description of two-nucleon observables directed the research towards systems composed of three nucleons (3N), where nucleon–nucleon (NN) interaction models can be tested in a non-trivial environment and, moreover, additional dynamics related to the presence of the third nucleon can be investigated. The deuteron–nucleon breakup process, with its variety of final states and rich information contained in the observables of the 3N continuum, is ideally suited for such tests. Although studies of this process are very challenging, both in the sense of theoretical calculations as well as of precise measurements, an important progress has taken place in this field over last years. At present, breakup observables can be predicted rigorously via exact solutions of the Faddeev equations with realistic NN potentials, combined with model 3N forces [1] or with the two- and three-nucleon interactions obtained by an explicit treatment of the Δ-isobar excitation [2–5] within the coupled-channel framework. Alternatively, the dynamics is generated by the chiral perturbation theory approach at the next-to-next-to-leading order [6–11] with all relevant NN and 3N contributions taken into account. In parallel, the data base, rather poor until recently in the region of medium energies, has been significantly enriched

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by our measurement of the $^1\mathrm{H}(\vec{\mathrm{d}}, pp)n$ reaction at the beam energy of 130 MeV. Precision of the obtained experimental data and coverage of a large fraction of the phase space for cross-sections [12,13] and for analyzing powers [14,15] allows one to reliably test predictions of various theoretical approaches. In this Letter we supplement the cross-section results with additional configurations, characterized by small polar angles of the two breakup protons.

The theoretical achievements in the 3N system have been shadowed by (but also stimulated) a persistent discussion about a possible bias of the obtained conclusions induced by neglecting potentially important pieces of the interaction dynamics. In all the above mentioned approaches the calculations are performed in a non-relativistic regime. Moreover, they ignore the long-range Coulomb interaction, thus can properly describe the neutron–deuteron (nd) system, while the data used in their verifications are precise (and numerous) enough only for the proton–deuteron (pd) system. Very recently the situation started to change. An important progress took place in both, the fully relativistic treatment of the breakup process as well as with respect to the inclusion of the Coulomb interaction. It is worthwhile to comment that—contrary to the long-trusted expectations—in both aspects the conclusions from the sector of elastic scattering proved not to be directly applicable for the breakup process, for the whole variety of its kinematical configurations. Pioneering study on incorporating relativity in the calculation of the elastic scattering observables [16] indicated that those effects are indeed expected to be very small. However, the very recent study on implementing boost and relativistic kinematics to the breakup process [17] revealed quite large (several percent) effects for some specific geometries. When regarding the long-range electromagnetic force influence, again the calculations for the elastic scattering cross-section at 65 MeV [18,19] showed an essentially negligible difference between nd and pd predictions, even in the cross-section minimum, the most sensitive region to study the 3N force effects (significant Coulomb effects are visible only at very small scattering angles). However, the very first set of calculations, in which the Coulomb effect in the breakup reaction is taken into account [20,21], indicates that they can lead to a dramatic change of the cross-section magnitude in certain regions of phase space. In this Letter the influence of the Coulomb interaction on the differential cross-sections of the breakup reaction is further studied, using the extensive data set at 130 MeV deuteron energy. The aim is a quantitative check of the theoretical predictions which include the effect of the Coulomb interaction and the analysis of the dependence of this effect on kinematical variables.

The theoretical predictions are based on a realistic coupled-channel potential CD Bonn + Δ [5], allowing for a single virtual Δ-isobar excitation and thereby yielding an effective 3N force consistent with the NN force, and including exchanges of π, ρ, ω, and σ mesons. The Coulomb interaction between charged baryons is fully included using screening and the renormalization approach [21,22]. The special choice of the screened Coulomb potential $w_R = we^{-(r/R)^n}$, with $n = 4$ being optimal, approximates well the true Coulomb interaction w for distances r smaller than the screening radius R. Simultaneously, this potential vanishes rapidly for $r > R$, yielding relatively fast convergence of the results with respect to R and included partial waves. Because of screening, standard scattering theory is applicable and the three-particle transition matrices for elastic and breakup scattering, $U^{(R)}(Z)$ and $U_0^{(R)}(Z)$, referring to hadronic plus screened Coulomb interaction, are obtained by solving the symmetrized Alt–Grassberger–Sandhas equations [24] in momentum-space

$$U^{(R)}(Z) = PG_0^{-1}(Z) + PT^{(R)}(Z)G_0(Z)U^{(R)}(Z), \tag{1}$$

$$U_0^{(R)}(Z) = (1+P)G_0^{-1}(Z) + (1+P)T^{(R)}(Z)G_0(Z)U^{(R)}(Z), \tag{2}$$

using standard partial-wave basis. In Eqs. (1) and (2) $G_0(Z)$ is the free resolvent, P is the sum of the two cyclic permutation operators, and $T^{(R)}(Z)$ is the two-particle transition matrix derived from nuclear plus screened Coulomb potentials; the dependence of operators on the screening radius R is notationally indicated. Finally, the renormalization procedure [25,26] is applied to obtain the scattering amplitudes in the unscreened limit. Further details are given in Refs. [21–23].

The experimental data were acquired in measurements performed at the Kernfysisch Versneller Instituut (KVI), Groningen, The Netherlands. The deuteron beam with energy of 130 MeV was focused to a spot of approximately 2 mm diameter on a liquid hydrogen target of 4 mm thickness. The experimental setup consisted of a three-plane multi-wire proportional chamber (MWPC) and of two layers of a segmented scintillator hodoscope: transmission ΔE and stopping E detectors. Position information from the MWPC was used for precise reconstruction of the particle emission angles, while the hodoscope allowed to identify the particles, to determine their energies and to define trigger conditions. The ΔE–E wall covered a substantial fraction of the phase-space: from about 10° to 35° for polar angles θ and the full (2π) range of the azimuthal angles ϕ. Registered were coincidences of the charged reaction products: the two protons emitted from the breakup reaction or proton and deuteron from the elastic scattering. More details on the experimental setup and procedures, as well as on the data analysis are given in Refs. [12,13].

In Ref. [13] high precision cross-section data of the deuteron–proton breakup reaction, obtained for 72 kinematically complete configurations, are presented for a regular grid of polar and azimuthal angles with a constant step in the arc-length variable S. Polar angles of the two outgoing protons, θ_1 and θ_2, were selected between 15° and 30° with a step of 5°, and their relative azimuthal angle ϕ_{12} was taken in the range from 40° to 180°, with a step of 20°. For each combination of the central values θ_1, θ_2 and ϕ_{12} the experimental data were integrated within the limits of ±1° for the polar angles and of ±5° for the relative azimuthal angle. The bin along the kinematical curve S was 4 MeV. Various theoretical predictions, valid for the nd system, well reproduce the experimental dp data in several configurations. However, large discrepancies have been observed in geometries characterized by the smallest analyzed polar angles, $\theta_1 = \theta_2 = 15°$. For small ϕ_{12} values the theories overestimate the data while at large ϕ_{12} the experimental results are under-

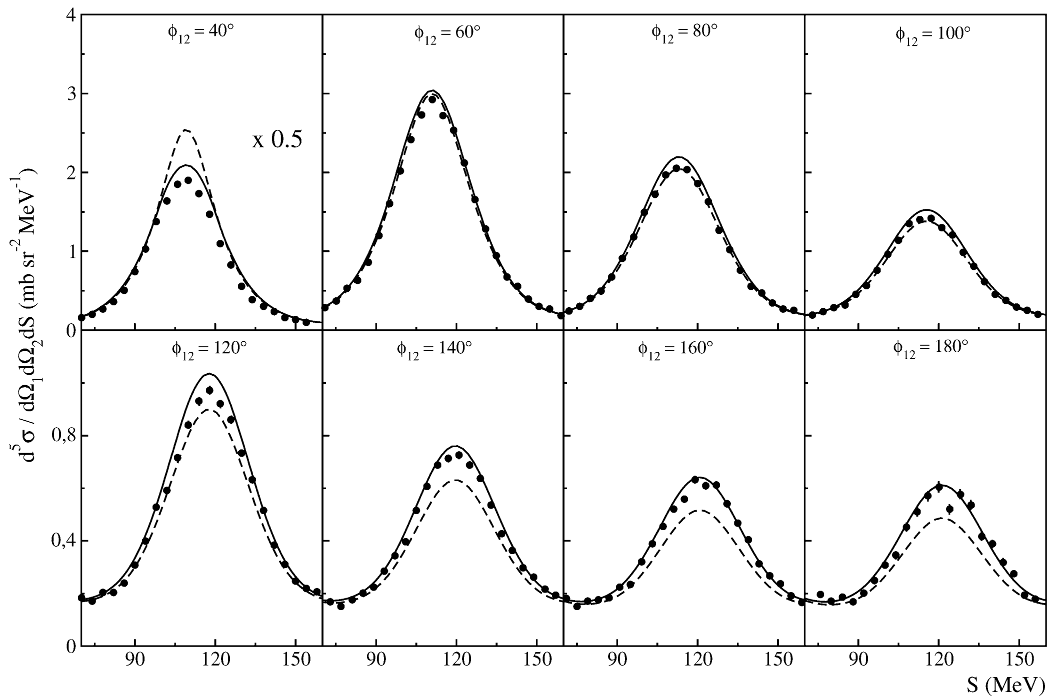

Fig. 1. Differential cross-sections of the deuteron–proton breakup at 130 MeV deuteron energy, plotted as a function of the arc length S along the kinematical curve. The data are shown for 8 kinematical configurations characterized by the proton polar angles $\theta_1 = \theta_2 = 13°$ and various relative azimuthal angles ϕ_{12}, as indicated in the individual panels. The error bars represent statistical uncertainties only. Experimental data are compared to the results of calculations with the coupled-channel CD Bonn + Δ potential, without (dashed lines) and with (solid lines) inclusion of the Coulomb interaction. The data and calculations in the first panel are normalized to the common vertical axis by the indicated factor.

estimated. Suppression of the pd data with respect to the nd theory at low relative azimuthal angles can be qualitatively understood as due to the Coulomb repulsion in the vicinity of the pp-FSI points. Recent results for the breakup cross-sections, calculated with the Coulomb interaction, confirm quantitatively these expectations. Inclusion of the long-range electromagnetic force improves significantly the agreement between the theoretical predictions and the data at $\theta_1 = \theta_2 = 15°$ for both, small and large ϕ_{12} values—see Fig. 11 of Ref. [21].

Sizable effects of the Coulomb interaction observed at $\theta_1 = \theta_2 = 15°$ motivated us to extend the study to the lowest polar angles allowed by the detector acceptance, i.e. down to 12°, where the detection efficiency is still large and well under control. Keeping the same integration limits of $\pm 1°$ for the polar angles and of $\pm 5°$ for the relative azimuthal angle, we have analyzed 8 configurations with the central values of $\theta_1 = \theta_2 = 13°$ and ϕ_{12} varied from 40° to 180° with a step of 20°. Those configurations were not particularly interesting in discussing the influences of the 3N force since the predicted effects of the 3N interaction are small in this region, but they are very well suited to study the Coulomb effect, as can bee seen in Fig. 1. The predicted influence of the Coulomb force on the differential breakup cross-sections is large—the differences between the calculations with (solid lines) and without (dashed lines) Coulomb force reach locally almost 25 percent. Due to high cross-section values the statistical errors of the data points are very small (below 3 percent). Discussion of the systematic uncertainties given in [13] is valid also in the kinematical region of the smallest polar angles, thus the systematic errors of the data points are on the level of 2–4 percent. Comparison of the data with the theoretical predictions (Fig. 1) shows that, indeed, the inclusion of the long-range Coulomb force in the calculations significantly improves the agreement with the data. Only for the configurations with ϕ_{12} equal to 80° and 100° the calculations with the Coulomb interaction included give somewhat worse description of the data, while the improvement observed at the extreme values of ϕ_{12} is striking. In terms of the global χ^2 comparison (as discussed in Refs. [12,13]) of the experimental cross-section values, the inclusion of the Coulomb interaction for the configurations presented here (nearly 200 data points) leads to a decrease of the χ^2 value by 38%. When all our cross-section data (nearly 1500 data points in 80 configurations) are used in the comparison, the χ^2 decrease due to the inclusion of the Coulomb force amounts to 20%. These results prove how important it is to include all aspects of the interaction dynamics in the theoretical description.

Both, the quantitative considerations and the precise calculations indicate that the kinetic energy of the relative motion of the two protons, E_{rel}, should be an important parameter in the studies of the Coulomb-force effects. This quantity, equal to the total kinetic energy of the two protons in their center-of-mass reference frame, can be calculated on the basis of the energies and directions of the two emitted protons as

$$E_{\mathrm{rel}} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2} - 2m, \tag{3}$$

where E_i, $\vec{p}_i$ are respectively the total energy and momentum vector of the ith ($i = 1, 2$) proton with mass m, all expressed in the energy units. For each cross-section data point from the 80

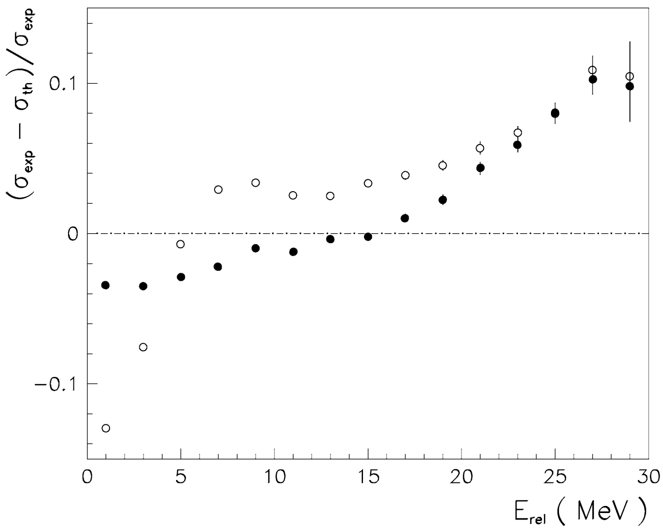

Fig. 2. Relative discrepancies between the experimental data (including the $\theta_1 = \theta_2 = 13°$ subset from this work) and the theoretical predictions of the breakup cross-sections as a function of the relative energy of the two breakup protons. The circles show the results obtained with the CD Bonn + Δ potential calculations without the Coulomb force. The full dots represent the results for the calculations with the inclusion of the Coulomb force.

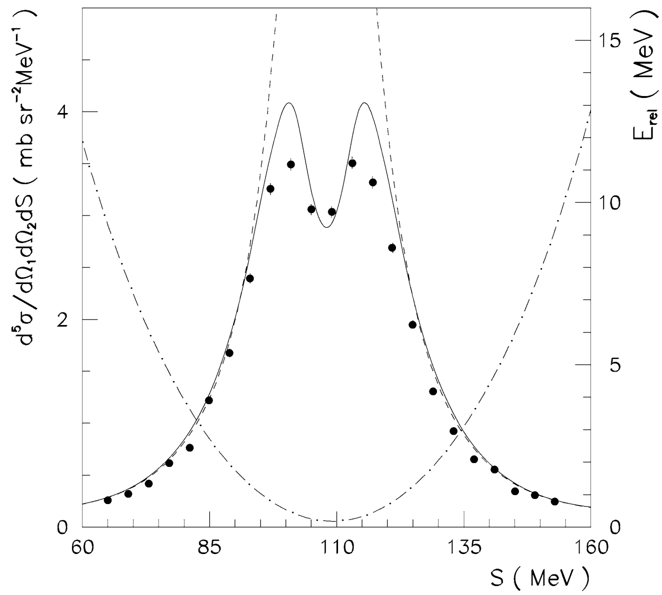

Fig. 3. Differential cross-section of the breakup reaction for the kinematical configuration characterized by the proton polar angles $\theta_1 = \theta_2 = 13°$ and their relative azimuthal angle $\phi_{12} = 20°$ (dots). The solid line represents the predictions of the CD Bonn + Δ potential including the Coulomb force. The dashed line shows the results of calculations disregarding the Coulomb force—truncated vertically for better readibility of the cross-section behavior in the central S region. The dash-dotted line and the right hand scale present the dependence of the relative energy of the two breakup protons along the S-axis.

kinematical configurations the corresponding value of E_{rel} was calculated and the data were sorted with respect to this parameter: The relative differences of the experimental and theoretical cross-sections, $(\sigma_{exp} - \sigma_{th})/\sigma_{th}$, were determined and plotted as a function of E_{rel} in Fig. 2. The relative differences have been calculated using theoretical prediction without (circles) and with (full dots) the long-range electromagnetic force. As expected, the strongest influence of the Coulomb interaction can be observed at the smallest values of E_{rel}. In that region inclusion of the Coulomb force strongly improves the agreement between the data and the theoretical description, though the discrepancies are not completely removed. In the medium E_{rel} range, 8–18 MeV, a perfect consistency between the data and the results of the calculations with the Coulomb force included is reached. At higher relative energies the theoretical calculations tend to underestimate the data, though it is worthwhile to note that for E_{rel} above 20 MeV the influence of the Coulomb force becomes practically negligible. This observation can be used to argue that the *nd* calculations can be safely applied to the *pd* breakup data in the regions of sufficiently large E_{rel} values.

Theoretical calculations using the coupled-channel CD Bonn + Δ potential predict dramatic changes of the breakup cross-section distributions due to Coulomb in configurations characterized by very small polar and relative azimuthal angles between the two outgoing protons. This statement is partially supported already by inspecting the first panel in Fig. 1. To demonstrate a still stronger action of the Coulomb force we analyzed in addition a kinematical configuration lying at the very edge of the experimental acceptance, with the central angular values of $\theta_1 = \theta_2 = 13°$ and $\phi_{12} = 20°$. The event integration ranges have been kept as in the previous cross-section analysis. It should be pointed out that at so small relative azimuthal angle between the two protons the detector acceptance is significantly reduced due to its granularity. Events in which both breakup protons hit the same detector (ΔE or E) are lost due to uncertain energy information. The cross-section results have to be corrected for these losses. The correction factors are determined on the basis of a GEANT simulation (more details can be found in [13]), however, when the effects are large, the acceptance losses are sensitive to even small geometrical inaccuracies of the setup, what can affect the cross-section normalization. Therefore, the overall systematic uncertainty of the cross-section data for the configuration discussed here is estimated to be at a level of about 6–8 percent. The result is presented in Fig. 3. In this spectacular case the Coulomb interaction leads not only to a strong suppression of the cross-section (predictions disregarding the Coulomb force reach a value of 12 mb sr^{-2} MeV^{-1}), but also to a distortion of the distribution, causing a dip at the minimal relative energy of the two breakup protons. This behavior is very well seen in the data as well.

All the performed comparisons, local and global, show that our cross-section data are much better described by the predictions in which the long-range Coulomb force is taken into account. It can be also seen that across the breakup phase space there are regions in which the sensitivity to the Coulomb force is practically negligible. In these regions one may use *nd* calculations to compare with *pd* data, but elsewhere the *pd* calculations with the full treatment of the long-range Coulomb force are paramount to the proper interpretation of the experimental *pd* results and conclusions on the underlying force models. Inclusion of the Coulomb interaction allows for a cleaner theoretical insight at possible shortcommings of the models of the hadronic dynamics.

This study makes an important step towards a precise and complete description of the breakup observables, which should eventually include all aspects of the medium-energy reaction mechanism. The theoretical predictions show that the effects of the Coulomb force, relativity and of the 3N interaction affect the breakup observables in different ways and with varying strength when inspecting the full reaction phase space. Such selectivity makes possible tracing the details of certain effects in regions where the others are proved to have relatively small influences. This is e.g. true for studies of the 3N forces—even if the Coulomb effects in the breakup cross-sections are large, there are regions in which their influence is much smaller than the expected effects of the additional nuclear dynamics. With even larger experimental coverage of the breakup phase space with respect to several observables and for various beam energies, the eventually established pattern of discrepancies between the data and the calculations might help to improve the understanding of the full dynamics of the 3N system.

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