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Relativistic effects in the electrodisintegration of deuterium

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Abstract

The structure function R_{LT} and the cross-section asymmetry A_ϕ with respect to the direction of the momentum transfer in the reaction ^{2}H$(e,e'p)$ have been measured at a four-momentum transfer squared of 0.2 (GeV/c)^2, for missing momenta between 160 and 220 MeV/c at an invariant mass of 1050 MeV. For a proper description of these data calculations that include a relativistic form of the nucleon current operator are favoured. The absolute ^{2}H$(e,e'p)$ cross-section data favour a covariant calculation over non-relativistic calculations with relativistic corrections.

1. Introduction

The simple structure of the deuteron as a two-nucleon system makes it possible to perform accurate calculations for various types of reactions, for instance electrodisintegration. Thus the deuteron may be used to gauge our knowledge of the nucleon current operator including contributions from meson-exchange currents (MEC), isobar configurations (IC), and in particular the relevance of a relativistic description of the current operator.

Cross section data [1–5] on the reaction ^{2}H$(e,e'p)$ in the quasi-free region are well described by calculations up to missing momenta (p_m) of about 200 MeV/c. However, calculations with a non-relativistic current operator fail to describe the cross section asymmetry A_ϕ with respect to the direction of momentum transfer $\boldsymbol{q}$. This was first shown in an experiment [6] performed at NIKHEF with Q^2 = 0.2 (GeV/c)^2 in the p_m range 50–170 MeV/c. Calculations using a relativistic form of the current operator [7–9] gave a significantly better description of these asymmetry data. These findings came as a surprise given the modest values of Q^2 and p_m involved. Comparable results were obtained by experiments probing a similar Q^2 range at Bonn [10] with relatively large systematic errors and p_m = 0–90 MeV/c, and at MIT [11] (p_m = 95 MeV/c), whereas data from Saclay [12] (p_m = 50–150 MeV/c) did not confirm these findings. An experiment at SLAC [5] at

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the higher Q^2 value of 1.2 $(\mathrm{GeV/c})^2$ and a p_m range of 0–160 MeV/c found clear evidence in favour of the adoption of a relativistic current operator. Since the systematic and statistical uncertainties in the existing data are relatively large, there is a need for new high-precision data at low Q^2. Moreover, as the differences between the relativistic and non-relativistic calculations are larger at higher missing momenta, such new accurate data should be collected at relatively high missing momenta. In this letter, we present the results of such an experiment performed in the range p_m = 160–220 MeV/c and at $Q^2 = 0.2$ $(\mathrm{GeV/c})^2$.

2. Definition of observables

Using the one-photon exchange approximation, and the extreme relativistic limit for the electron tensor, the unpolarised $^2\mathrm{H}(e,e'p)$ cross section can be written in the laboratory frame as [7]:

$$\frac{d^5\sigma}{d\epsilon' d\Omega_{\epsilon'} d\Omega_p} = \sigma_{\mathrm{Mott}}(v_L R_L + v_T R_T + v_{TT} R_{TT} + v_{LT} R_{LT}), \quad (1)$$

where ϵ' is the energy of the scattered electron, σ_{Mott} the cross section for scattering off a point charge, v_i kinematic factors depending on the electron kinematics and R_i structure functions describing the dynamics of the deuteron system. The R_{LT} interference structure function originates from the interference between the charge and transverse components of the hadronic current, and as such is known to be especially sensitive to the structure of the current operator [8]. Since R_L and R_T do not depend on the out-of-plane angle ϕ, and since $R_{LT} \propto \cos\phi$ and $R_{TT} \propto \cos 2\phi$, R_{LT} may be determined by performing measurements at $\phi = 0$ (proton detected in-plane forward of $\boldsymbol{q}$) and $\phi = \pi$ (proton detected backward of $\boldsymbol{q}$):

$$R_{LT} = \frac{\sigma^0 - \sigma^\pi}{2\sigma_{\mathrm{Mott}} v_{LT}}. \quad (2)$$

In order to reduce the influence of experimental systematic errors with respect to R_{LT} the asymmetry A_ϕ is evaluated:

$$A_\phi = \frac{\sigma^0 - \sigma^\pi}{\sigma^0 + \sigma^\pi} = \frac{v_{LT} R_{LT}}{v_L R_L + v_T R_T + v_{TT} R_{TT}}. \quad (3)$$

The quantity A_ϕ is sensitive to the current operator, but is only slightly influenced by the choice of the deuteron wave function. The data will be presented in terms of A_ϕ, R_{LT} and the absolute cross section.

3. Experimental setup

The experiment was performed at NIKHEF with the semi-continuous electron beam from the Amsterdam Pulse Stretcher (AmPS) [13], which is injected by the medium-energy accelerator MEA. The incoming electron energy was 603.8 ± 0.2 MeV, the average beam current 2.0 μA and the duty factor typically 60%. A newly developed deuterium target [14], employing natural convection for the cooling of the liquid deuterium, was used. The target thickness ranged from 200 to 220 mg/cm^2 as determined by elastic $^2\mathrm{H}(e,e)$ scattering. The scattered electron and the emitted proton were detected in the QDQ and QDD magnetic spectrometers [15], respectively.

The values of the kinematic variables were chosen such as to reach the highest p_m which simultaneously satisfied the physical constraints of the two-spectrometer setup, did not deviate strongly form quasi-free kinematics, and still allowed determination of A_ϕ and R_{LT}. The transferred four-momentum $(\omega, |\boldsymbol{q}|)$ was (225 MeV, 500 MeV/c) for the central acceptance of the electron spectrometer, corresponding to an invariant mass of 1050 MeV. This is somewhat beyond the quasi-free region, but still far from the Δ-resonance. Hence, Δ degrees of freedom are not expected to play a major role.

Two sets of measurements were performed. In the first one, the central angles of the proton spectrometer were 26.6 and 50.7 degrees, corresponding to angles between $\boldsymbol{q}$ and the emitted proton (γ_{pq}) of -12 and $+12$ degrees, respectively, and a central missing momentum of p_m = 191 MeV/c. The angle of 26.6 degrees is the most forward position of the proton spectrometer. The second data set was taken at $|\gamma_{pq}|$ = 8 degrees and p_m = 175 MeV/c.

The data have been corrected for energy losses in the target, detector efficiencies, and dead-time. The luminosity was continuously monitored by tracking the singles rate in the electron spectrometer in order to correct for target thickness fluctuations. This rate was calibrated using the known cross section of the elastic $^2H(e,e)$ reaction [16,17]. The distributions of accidental coincidences were identified using the (e',p) coincidence timing difference and subtracted from the data. After dividing out the detection volume, the data were corrected for radiative effects. The various sources of systematic errors contributing to the cross section, such as angle calibrations, luminosity monitoring, background from the aluminum walls of the target, charge integration, solid angles, incident beam energy, and determination of the detection volume add quadratically to 6%. The systematic error in A_ϕ, depending mostly on the determination of the detection volume, varies with p_m and typically amounts to 12%. The systematic error in R_{LT} amounts to 14%.

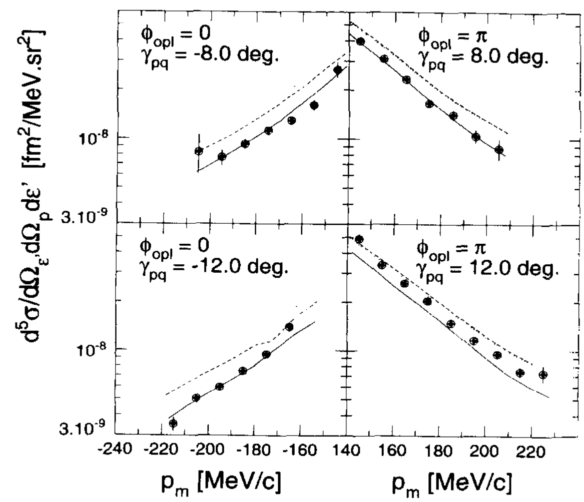

Fig. 1. Cross sections as a function of p_m at four different kinematic settings for the reaction $^2H(e,e'p)$. Negative values of p_m denote $\gamma_{pq} < 0$. Only statistical errors are shown. The systematic error is 6%. The solid curve represents the calculation by Tjon, the dotted the non-relativistic calculation by Mosconi, the dashed the calculation including relativistic corrections by Mosconi.

4. Theoretical description

The data are compared to various calculations. Hummel and Tjon [7] use a fully covariant approach within a Bethe-Salpeter framework. A consistent treatment of the electromagnetic current and the NN interaction is realised through the one-boson exchange model, including MEC contributions, final-state interactions (FSI), but without IC contributions. The nuclear current is described by the single-nucleon current with on-shell electromagnetic nucleon form-factors of Höhler [18]. The NN amplitude is constructed using the Blankenbecler-Sugar-Logunov-Tavkhelidze quasipotential approximation. In this paper negative energy states, whose effects are small, are neglected.

In the calculations by Mosconi [19] the disintegration amplitude is treated in a non-relativistic framework using the Schrödinger equation with the Paris NN potential. The nuclear current is described using Sachs form factors. The Δ transition current is evaluated in the static approximation of the Δ propagator. Relativistic corrections include an expansion of the electromagnetic operators in p/M to second order. Moreover, relativistic corrections are applied to the nucleonic charge and current densities, and to the two-body currents. The effects of MEC contributions and FSI are included.

The combined acceptances of the spectrometers for a given setting define a range of electron and proton momenta around the central kinematics. Hence, they must be taken into account when comparing the data to calculations. By using the measured event sample, the average $(\omega, |\boldsymbol{q}|)$ values corresponding to each p_m bin of 10 MeV/c have been determined. These represent the so-called sub-kinematics. Under the assumption that the kinematic dependencies of the cross section are linear in each sub-kinematic, the effect of finite acceptances can be taken into account by evaluating the theoretical cross sections for each sub-kinematic. In a similar previous experiment this assumption was shown to be valid within an accuracy of one percent [16]. The calculations were subsequently averaged over the out-of-plane acceptance of the spectrometers.

5. Results

The cross section data are shown in Fig. 1. The calculations by Tjon [20], represented by the solid curve, describe the data well with the exception of the bottom-right panel where the match is not as good. Both Mosconi's [21] non-relativistic calculations (dotted) and those including relativistic corrections (dashed) overestimate the data by 30% for the forward ($\phi_{opl} = 0$) kinematics and 20% for the backward ($\phi_{opl} = \pi$) kinematics. Mosconi's inclusion of the Δ current leads to an average increase of 10%

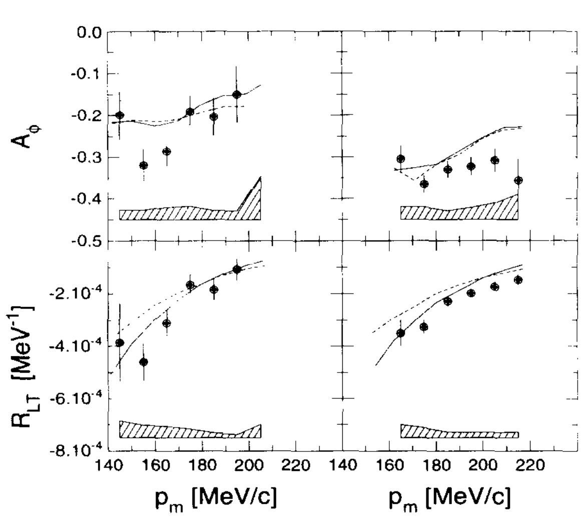

Fig. 2. The upper (lower) left panel shows A_ϕ (R_{LT}) for a central p_m = 175 MeV/c (γ_{pq} = 8 deg.), the right for p_m = 191 MeV/c (γ_{pq} = 12 deg.). The shaded areas indicate the size of the systematic error. The meaning of the curves is the same as for Fig. 1.

in the cross section, thus explaining part of the extra strength compared to Tjon's calculations.

The asymmetry A_ϕ and the interference structure function R_{LT} are displayed in Fig. 2. Both the calculations by Tjon, and those from Mosconi including relativistic corrections to the current operator, are in fair agreement with the data, whereas the calculations from Mosconi employing a non-relativistic current operator fail to describe these data. The influence of the Δ current on A_ϕ is less than 2%. A χ^2-analysis of the A_ϕ data at γ_{pq} = 12 deg., including systematic errors, rules out the non-relativistic calculation at a confidence level of 99.9%, whereas both relativistic calculations describe the data at a confidence level of 80%. Hence, we have found strong evidence for the need to use a relativistic description of the current operator in the reaction ^{2}H$(e, e'p)$ even at the relatively low values of Q^2 = 0.2 (GeV/c)^2) and p_m = 160–220 MeV/c.

6. Conclusions

We have measured the cross section asymmetry A_ϕ and the longitudinal-transverse interference structure function R_{LT} for two central values of p_m, 175 and 191 MeV/c. These data sets are reasonably described by calculations employing a relativistic form of the current operator where the non-relativistic calculations fail to do so, thus demonstrating the need for using a relativistic form of the current operator at Q^2 values as low as 0.2 (GeV/c)^2. The cross section data are in general well described by the covariant calculations from Tjon, whereas the Mosconi calculations overestimate the data significantly. The difference between these two calculations cannot simply be explained and further investigations are needed to assess the physics causing this discrepancy.

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