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Nuclear-Density Dependence of the Electron-Proton Coupling

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A quasielastic ($e, e'p$) experiment has been performed on ${}^6\text{Li}$ for both backward- (transverse) and forward-angle (longitudinal) electron kinematics. Cross sections for knockout of protons from two different orbits ($1s$ and $1p$) have been measured simultaneously. The densities probed by the ($e, e'p$) reaction differ by a factor of 4 between these orbits. In both cases the backward/forward cross-section ratio deviates by the same amount from the impulse approximation.

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The description of quasielastic scattering from complex nuclei is generally based on the impulse approximation (IA), i.e., the assumption that the interaction between the projectile and the bound nucleon can be described by use of the free-nucleon current. However, there exists empirical evidence, which stems from inclusive electron-scattering experiments, suggesting that the nucleon current deviates from the IA prediction. First, the experimental Coulomb sum rule is not saturated by about 40%¹ and second, the ratio of longitudinal to transverse strength in the quasielastic peak is much smaller than expected.² Theoretical investigations of the role of correlations in the longitudinal and transverse response functions have not succeeded in explaining the discrepancies so far.³ Models beyond the conventional framework have been proposed,⁴⁻⁸ in which basically the current of a nucleon is modified within the nucleus. In most models, e.g., the relativistic mean-field model⁴ and the soliton model,⁸ the change of intrinsic nucleon properties, and therefore of the electron-proton cross section σ_{ep} , depends on the density of the surrounding nuclear medium. Also the A dependence of the confinement size, as discussed by Close *et al.*,⁷ is essentially due to differences in the average density.

With the objective of investigating the nuclear-density dependence of the electron-proton coupling, a quasielastic ($e, e'p$) experiment has been carried out on ${}^6\text{Li}$. Since a high-resolution ($e, e'p$) experiment offers the possibility to study the individual proton orbits, it can be used to observe knockout from regions in the nucleus with different densities. This is in contrast with inclusive electron scattering in the quasielastic region, in which an average over all available orbits is measured. The choice

of ${}^6\text{Li}$ as target nucleus is motivated by the possibility of studying $1p$ and $1s$ knockout simultaneously as a result of the relatively small difference in binding energy (16.7 MeV) of these orbits. This allows for the observation of proton knockout from both a high-density ($1s$) and low-density ($1p$) region. Here we discuss the results of the experiment and its implications for a possible dependence of σ_{ep} on the density.

In order to study the virtual-photon-proton coupling inside the nucleus a relative ($e, e'p$) measurement is performed in which the polarization of the virtual photon is varied, while the nuclear structure part of the cross section is kept constant. The change in photon polarization ϵ is obtained by going from a low incoming electron energy and a backward electron scattering angle to a high energy and a forward angle. The nuclear structure part is the same in the two measurements, because the momentum transfer $\mathbf{q}$, the energy transfer ω , and the initial proton momentum $\mathbf{p}_m$ are held constant. Since the outgoing proton momentum $\mathbf{p}'$ and the angle between $\mathbf{p}'$ and $\mathbf{p}_m$ do not change either, as illustrated in Fig. 1, the effect of final-state interactions also cancels to a very good approximation in the ratio of cross sections. A more detailed discussion of such an experiment can be found elsewhere.⁹

The data will be expressed in terms of a ratio R , which represents the ratio of backward over forward reduced cross sections. The reduced cross sections are obtained by dividing the coincidence cross sections by $K\sigma_{ep}^{\text{cc1}}$, where K is a kinematical factor and σ_{ep}^{cc1} is the off-shell electron-proton cross section based on current conservation, as proposed by de Forest.¹⁰ The aforementioned kinematical conditions imply that R does not depend on

FIG. 1. Kinematical arrangement of a pair of measurements at two different values of the incoming electron energy and scattering angle.

nuclear-structure aspects, i.e., the momentum distribution. This statement assumes the validity of the factorized expression for the $(e, e'p)$ cross section.¹¹ Corrections for small deviations ($\leq 0.5\%$) from this approximation will be discussed later.

The experiment was carried out with the Nationaal Instituut voor Kernfysica en Hoge Energiefysica (NIKHEF-K) coincidence facility.¹² An enriched ${}^6\text{Li}$ foil (98.7%) with a thickness of 13.0 mg/cm^2 mounted in a rotating frame to smooth out target inhomogeneities was used. The kinematics are summarized in Table I. The outgoing proton momentum $\mathbf{p}'$ was parallel to $\mathbf{q}$ and p' was kept constant at $0.37 \text{ GeV}/c$ ($T_{p'} = 70 \text{ MeV}$). For a known separation energy all other kinematical variables can be calculated from the information supplied in Table I. At the lowest value of the momentum transfer, $q = 0.27 \text{ GeV}/c$, the measurements at both energies were carried out several times for calibration of the detection volume and for determination of the system stability. This yields a series of cross sections at each energy that should be identical. The standard deviation in the average of these cross sections is 0.9% , confirming the stability of our system. The coincidence efficiency, measured with the ${}^1\text{H}(e, e'p)$ reaction, was $(99.1 \pm 0.8)\%$ at the low incoming-electron energy and $(99.3 \pm 0.7)\%$ at the high energy.

The data have been analyzed and corrected for radiative losses in the usual manner.¹³ In representing the data by the ratio R we assumed the $\mathbf{p}_m$ vector to be well calibrated in both the backward and forward measurement, since otherwise the cancellation of the momentum distribution in R would not occur. By comparing the calculated distribution of accidental coincidences in missing momentum space with the measured distribution, it was possible to gauge the length of the $\mathbf{p}_m$ vector. This procedure yields a relative uncertainty of $0.3 \text{ MeV}/c$ in the value of the missing momentum. Together with contributions from target angle calibration, energy calibration, and system stability, this leads to an overall systematic error in the ratio of reduced cross sections R of less than 2% for all data.

FIG. 2. Ratio of reduced cross sections (backward over forward) for $1p$ knockout (crosses) and $1s$ knockout (circles) from ${}^6\text{Li}$. The impulse approximation corresponds to unity.

In Fig. 2 the experimentally determined values of R are shown for $1p$ and $1s$ knockout from ${}^6\text{Li}$. The $1p$ data have been integrated over the missing energy range $3.5\text{--}11.5 \text{ MeV}$ and the $1s$ data from 19.5 to 27.5 MeV . The data have been corrected for slight differences ($\leq 0.5\%$) in the final-state interactions between the forward- and backward-angle kinematics by means of an unfactorized distorted-wave impulse-approximation (DWIA) calculation. The parameters of the optical model¹⁴ and bound-state wave function were chosen in such a way that a fair description of the experimental momentum distributions¹⁵ was obtained. For the $1p$ bound-state wave function we used the results of an α - n - p Faddeev calculation.¹⁶ The correction due to the Coulomb distortion, which also affects the ratio slightly, consists of two parts: (i) an amplitude effect calculated by employing the high-energy approximation for the electron waves¹⁷ and (ii) an effective q shift, which has been transformed to an amplitude effect by making use of the measured momentum distribution.¹⁵ The total

TABLE I. Kinematics: Incoming electron energy E_0 , virtual-photon polarization ϵ , momentum transfer q , and missing momentum p_m for each $(e, e'p)$ measurement.

	Photon polarization ϵ				
	E_0 (MeV)	q (GeV/c)	p_m (GeV/c)	ϵ	ϵ
	322.0	0.645 ^a	0.639	0.313	0.248
	479.9	0.836 ^a	0.833	0.644	0.601
		0.264 ^a	0.267	0.412	0.442
		0.105 ^a	0.103	-0.043	-0.073

^aThis experiment was carried out at energies of 311.4 and 463.8 MeV .

correction factor for both distortion effects varies between 0.981 and 1.006 for $1p$ knockout and the difference between $1p$ and $1s$ shell knockout is smaller than 0.7%.

As is shown in Fig. 2 the data for both $1s$ and $1p$ knockout indicate a significant deviation from the impulse approximation. The data can be parametrized phenomenologically by a 15% enlargement of the effective proton magnetic moment in the same way as has been done for the ^{12}C data.⁹ The most important result of the present experiment is the observation that the deviation appears to be equal for $1p$ and $1s$ knockout.

If the deviation is due to a modification of the nucleon properties inside the nucleus, the electron-proton coupling depends on the nuclear density $\rho(r)$. We have calculated the effect of $\rho(r)$ on the coupling by employing a local-density approximation. The effect can be parametrized by means of $\rho_{\text{eff}}(p_m)$, which in plane-wave impulse approximation is found to be

$$\rho_{\text{eff}}(p_m) = \frac{\int j_l(p_m r) R_a(r) \rho(r) r^2 dr}{\int j_l(p_m r) R_a(r) r^2 dr},$$

where $j_l(p_m r)$ is the l th-order spherical Bessel function and $R_a(r)$ the bound-state wave function. The quantity $\rho_{\text{eff}}(p_m)$ is interpreted as the density probed in the $(e, e'p)$ reaction at a missing momentum p_m . [Note that this is not the same as the average (diagonal) density of the nucleon in its orbit.] The actual calculation of $\rho_{\text{eff}}(p_m)$ has been done in distorted-wave impulse approximation. In Fig. 3 the mean value of R in the q -range 0.4–0.5 GeV/c is shown as a function of the average of $\rho_{\text{eff}}(p_m)$ over the corresponding $\mathbf{p}_m$ volume. The error bars include in each case the systematic error. The average deviation from the IA amounts to $(6.6 \pm 1.8)\%$. It is

FIG. 3. Average ratio of reduced cross sections as a function of the density probed by the $(e, e'p)$ reaction. All data have been corrected for distortion effects.

evident that the available data do not show a density dependence in the range of ρ_{eff} covered by the present experiment and the one⁹ on ^{12}C .

The data are compared with predictions of the σ - ω model⁴ and the relativistic soliton model⁸ in Fig. 3. The vector and scalar potential in the σ - ω model¹⁸ are calculated in a local-density approximation. The nuclear-density dependence of the soliton model is taken from Celenza, Rosenthal, and Shakin.¹⁹ Their density dependence is of the form $F[q, \rho(r)]$, in which case deviations in R start linear in $\rho_{\text{eff}}(p_m)$. For the form factors we have used the recent parametrization by Simon *et al.*²⁰ Both models show a weak dependence on the nuclear density and predict a deviation from the IA which is much smaller than the measured effect. The data do not rule out mechanisms as proposed by either the σ - ω model or the soliton model, though the major effect must have another origin.

The interpretation of the present experiment could be affected by a nonnegligible contribution of the $(e, e'n)(n, p)$ two-step process, since the (transverse) photon coupling to the neutron becomes comparable to that to the proton in the backward-angle kinematics and the charge-exchange (n, p) channel is relatively strong. However, Boffi *et al.*²¹ using an isospin-dependent (Lane-type) optical potential,²² have shown that the inclusion of charge exchange does not alter the cross section for the (γ, p) reaction. An explicit distorted-wave calculation for the $(e, e'p)$ reaction along similar lines²³ yields an increase of about 2% of the reduced cross section ratio R .

The possible role of meson-exchange currents has not yet been mentioned. Actually, the modification of the nucleon current in the σ - ω model is equivalent to the exchange current due to the σ meson.⁵ Pion exchange currents give a significant contribution in case of the deuteron electrodisintegration.²⁴ Qualitatively their effect is similar to that of the models considered here, i.e., mainly an increase in the transverse cross section. However, since the range of the pion interaction is relatively long, the pion exchange currents might have a different effect. Whether such exchange currents could explain the measured deviation from the IA awaits explicit calculations of the role of meson-exchange currents in the quasielastic region. Beforehand it is not clear if the meson-exchange currents can be expected to show a similar dependence on the density as observed in the presently investigated range of ρ_{eff} . In addition more $(e, e'p)$ experiments, especially on heavier nuclei and for more deeply bound states, are required to further map the nuclear-density dependence of the electron-proton coupling.

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