Effect of the Nuclear Medium on the Proton Investigated with the Reaction $^{12}C(e,e'p)^{11}B$

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A longitudinal-transverse separation has been carried out for the coincident quasifree proton knockout reaction on ^{12}C in the range of three-momentum transfer 0.27–0.46 GeV/c. The deduced ratio of longitudinal and transverse response functions indicates a significant effect of the nuclear medium on the coupling of the virtual photon with the proton. The observed modification of this coupling implies a breakdown of the impulse approximation.

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The usual description of the quasifree scattering process assumes the validity of the impulse approximation; i.e., the free-nucleon current is used.[1] This is reasonable since, within the nucleus, the nucleons are relatively loosely bound. However, there are indications that the intrinsic properties of the nucleon change in the nuclear environment,[2] which implies a breakdown of the impulse-approximation. The influence of the nuclear medium is a subject of growing interest, inspired by the current picture of nucleons as composed of quarks. Because the confinement scale for quarks in a nucleon is only slightly smaller than the average nucleon-nucleon distance in nuclei, the quark structure of a nucleon—and thus its properties—may be modified inside the nucleus.[3] For example, it has been suggested[4] that the confinement volume for quarks may be enlarged in the nucleus in order to explain the European Muon Collaboration effect.[5] Recent relativistic formulations of the mean nuclear potential also suggest that the intrinsic nucleon properties may be affected by a modification of the Dirac spinors arising from a combination of strong scalar and vector fields inside the nucleus.[6] We note that many of the above-mentioned effects could, instead, be expressed as mesonic effects.

Quasifree electron scattering, i.e., "elastic" scattering from bound nucleons which are almost on shell, is especially suited for obtaining information on modified nucleon properties. Since the coupling of the virtual photon to a free nucleon is accurately known from experiment,[7] possible modifications of the coupling due to the nuclear medium can be identified.

Detailed studies of inclusive quasifree electron scattering (e,e') on ^3He, ^{12}C, ^{40}Ca, ^{48}Ca, and ^{56}Fe have been performed at the Centre d'Etudes Nucléaires de Saclay.[8] The deduced ratio of transverse to longitudinal strength is much larger than expected from the free photon-nucleon coupling. The coupling to meson exchange currents due to pions and nucleon isobars does not seem to explain this discrepancy. An improved description is obtained either through the introduction of an enlarged quark-bag radius[9] or by use of a relativistic spinor for the nucleon given by the σ-ω model.[10] Inclusive experiments involve an averaging over initial energies and momenta of the knocked-out nucleon(s). Thus the analysis depends on the assumed nuclear structure. An exclusive experiment has the advantage of fixing the kinematics, and—for knockout to the ground state of the residual nucleus—excluding two-nucleon emission. A detailed discussion of exclusive $(e,e'p)$ experiments can be found in the review article by Frullani and Mougey.[11] In this Letter the results of an exclusive $^{12}C(e,e'p)^{11}B$ experiment are presented along with a comparison to both the inclusive data and the models mentioned above.

The $(e,e'p)$ coincidence cross section can be expressed[12] in terms of four structure functions W_i. In parallel kinematics, when the momentum of the outgoing proton $\mathbf{p}'$ is parallel to the momentum transfer $\mathbf{q}$, only two structure functions W_L and W_T remain[13]:

$$d^6\sigma/dE_{e'}\,d\Omega_{e'}\,dE_{p'}\,d\Omega_{p'} = p'E_{p'}\sigma_{\mathrm{Mott}}Q^2(\mathbf{q}^2\epsilon)^{-1}\{\epsilon W_L(\omega,q,p') + W_T(\omega,q,p')\}, \quad (1)$$

where σ_{Mott} is the Mott cross section, $Q^2=\mathbf{q}^2-\omega^2$ the four-momentum transfer squared, ω the electron energy loss, and $\epsilon=[1+(2\mathbf{q}^2/Q^2)\tan^2(\theta_{e'}/2)]^{-1}$ the photon polarization parameter with $\theta_{e'}$ the electron scattering angle.[14] For scattering from a bound nucleon W_L and W_T depend on the separation energy and momentum inside the nucleus. In the plane-wave impulse approximation this dependence is the same for W_L and W_T and Eq. (1)

can be factorized[13]:

$$d^6\sigma/dE_{e'}\,d\Omega_{e'}\,dE_{p'}\,d\Omega_{p'}=p'E_{p'}\sigma_{ep}S(E_m,\mathbf{p}_m), \quad (2)$$

where σ_{ep} describes the off-shell electron-proton scattering cross section, given by

$$\sigma_{ep}=\sigma_{\rm Mott}Q^2(\mathbf{q}^2\epsilon)^{-1}\{\epsilon|F_L(Q^2)|^2+|F_T(Q^2)|^2\},$$

and thus the longitudinal-transverse (LT) character is determined by the *nucleon* current. For elastic scattering from a free proton the F_i's are equal to the electric and magnetic proton form factors: $F_L^{\rm free}(Q^2)=G_E(Q^2)$ and $F_T^{\rm free}(Q^2)=(Q^2/4m^2)^{1/2}G_M(Q^2)$. The spectral function $S(E_m,\mathbf{p}_m)$ represents the probability to find a proton with separation energy E_m and momentum $\mathbf{p}_m=\mathbf{p}'-\mathbf{q}$ inside the nucleus. Distortion of the outgoing proton wave can be approximately taken into account by replacement of $S(E_m,\mathbf{p}_m)$ by the distorted spectral function $S(E_m,\mathbf{p}_m,\mathbf{p}')$. However, in doing so we neglect the slight difference in proton distortion for W_L and W_T. The accuracy of this approximation will be discussed later.

If the photon-proton coupling is modified inside the nucleus, σ_{ep} will be different. Hence the influence of the nuclear environment can be investigated by our studying the behavior of σ_{ep}. Since the absolute value of $S(E_m,\mathbf{p}_m,\mathbf{p}')$ is unknown, only the ratio of σ_{ep}'s can be obtained in cases where E_m, $\mathbf{p}_m$, and $\mathbf{p}'$ are the same. This can be done by performing measurements at two values of the initial electron energy E_0 and corresponding values of $\theta_{e'}$ such that $\mathbf{q}$ and ω remain constant. This results in a different value of ϵ; hence it follows from Eq. (1) that the two measurements comprise a LT separation, which will yield the ratio W_T/W_L.

The experiment was carried out with the Nationaal Instituut voor Kernfysica en Hoge-Energiefysica, Section K, coincidence facility.[15] A 41.25-mg/cm^2 natural-carbon target was used, mounted in a rotator to smooth out target inhomogeneities. The two values of E_0 were 312.8 and 443.3 MeV. The outgoing proton momentum was kept constant at 0.37 GeV/c, corresponding to a kinetic energy 70 MeV. The kinematics was centered around four values of q covering a range between 0.27 and 0.46 GeV/c with special emphasis on the points near 0.45 GeV/c, where the most accurate LT separation can be made because of the larger differences in ϵ (see Table I). The q range chosen corresponds to a p_m range between -0.09 and $+0.10$ GeV/c. We consider the $l=1$ knockout leading to the ground state of ^{11}B, and so the measurements at $p_m=-0.09$ and $+0.10$ GeV/c are near a maximum of an $l=1$ momentum distribution, ensuring good statistics. As a stability check, the measurement at $q=0.27$ GeV/c was repeated (at both energies) after all other data taking was completed. The average ratio of these cross sections appeared to be 0.996 ± 0.012. We also measured the coincidence efficiency with the ^{1}H$(e,e'p)$ reaction at both energies. The efficiencies appeared to be constant within 1% with an average value of (98.8 ± 0.9)%. Several elastic-electron-scattering measurements were carried out—intertwined with the coincidence data taking—to monitor the effective target thickness. The target angle was calibrated separately with an accuracy of 0.4 deg. These checks confirmed the stability of our experimental apparatus to within 1.2%.

The data have been analyzed and corrected for radiative losses in the same manner as described by Lapikás and de Witt Huberts.[16] In order to ensure that the same p_m range is probed at both energies, the data are sorted in small p_m bins (5 MeV/c) and weighted by their individual detection volume, which has been obtained through a Monte Carlo simulation. Only those p_m bins are considered which have a detection-volume weight larger than 50% at the low-energy kinematics. This results in a 30-MeV/c p_m acceptance. Reduced cross sections $\sigma_{\rm red}(E_0,\theta_{e'})$ were obtained by dividing the cross sections by $p'E_{p'}\sigma_{ep}^{\rm cc1}$ as calculated by de Forest.[17] Other prescriptions for σ_{ep} within the impulse approximation differ by less than 0.5% in their ratio from $\sigma_{ep}^{\rm cc1}$ in this kinematical region.[17] In Fig. 1

TABLE I. Virtual-photon polarization parameter ϵ for all $(e,e'p)$ kinematics.

E_0 (MeV) \ q (GeV/c)	0.27	0.42	0.44	0.46
p_m (GeV/c)	+0.10	−0.04	−0.07	−0.09
312.8	0.60	0.27	0.21	0.17
443.3	0.80	0.58	0.53	0.50

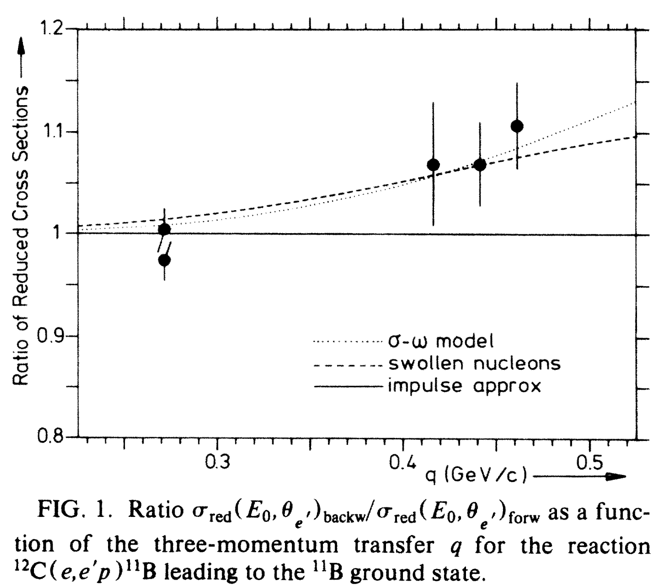

FIG. 1. Ratio $\sigma_{\rm red}(E_0,\theta_{e'})_{\rm backw}/\sigma_{\rm red}(E_0,\theta_{e'})_{\rm forw}$ as a function of the three-momentum transfer q for the reaction ^{12}C$(e,e'p)^{11}$B leading to the ^{11}B ground state.

the ratio $\sigma_{\rm red}(E_0,\theta_{e'})_{\rm backw}/\sigma_{\rm red}(E_0,\theta_{e'})_{\rm forw}$ is displayed. Only statistical errors are shown. Since the data are presented as a ratio most of the systematic errors drop out, with only those related to the target angle, energy calibration, and system stability remaining. The uncertainty in the energy calibration causes a 0.5-MeV/c error in the relative value of p_m between the two kinematics. Near the maximum of an $l=1$ momentum distribution this yields an additional error on the ratio of 1%, which becomes somewhat larger near $p_m=0$ GeV/c ($q=0.37$ GeV/c). The systematic error in the ratio totals 2%.

As mentioned before, we assumed the proton distortions to be the same for W_L and W_T. The uncertainty of this assumption has been calculated with the distorted-wave impulse-approximation code PEEP.[18] It can be expressed as a correction to the ratio of Fig. 1, and amounts to less than +0.3% at $q=0.27$ GeV/c and about −1.6% at $q=0.45$ GeV/c. These numbers change by less than 0.2% if another optical potential is used. The effect of the Coulomb distortion on the electron has been estimated with an empirical expression suggested by Knoll.[19] It changes the ratio plotted in Fig. 1 by +1% over the entire q region under consideration. These corrections have not been applied to the data.

Since the distorted spectral function is the same at both energies, the ratio shown in Fig. 1 should be equal to 1, if σ_{ep} is not affected by the nuclear medium. At $q=0.27$ GeV/c the data and the predictions of the models are indeed close to unity as expected, since the longitudinal contribution dominates in this q region. That the experiment reproduces this result provides an important check on the analysis. At large values of q, where the transverse contributions are largest, the data indicate a deviation of (8.4 ± 2.6)% from the impulse approximation.

In order to make a comparison with the inclusive data on ^{12}C,[8] a LT separation has been performed. By use of Eqs. (1) and (2) the ratio W_T/W_L was derived from the exclusive data of Fig. 1. We plot $R_G=[(4m^2/Q^2)W_T/W_L]^{1/2}$ as a function of Q^2 in Fig. 2. As can be seen from the expressions for $F_L^{\rm free}(Q^2)$ and $F_T^{\rm free}(Q^2)$, R_G is the ratio of the form factors G_M/G_E for a free proton. For a bound proton we interpret R_G as the value of G_M/G_E inside the nucleus.

The quantity R_G has also been deduced from the inclusive data,[8] which cover a large range of ω including the quasifree region. These data have been averaged over an interval of ω of about 20 MeV, corresponding to the energy acceptance of the present experiment. Assuming that the inclusive reaction proceeds mainly through single-nucleon knockout, we can apply corrections for neutron knockout and contributions of momenta perpendicular to **q**, which are not contained in the (parallel) exclusive data. The latter effect amounts

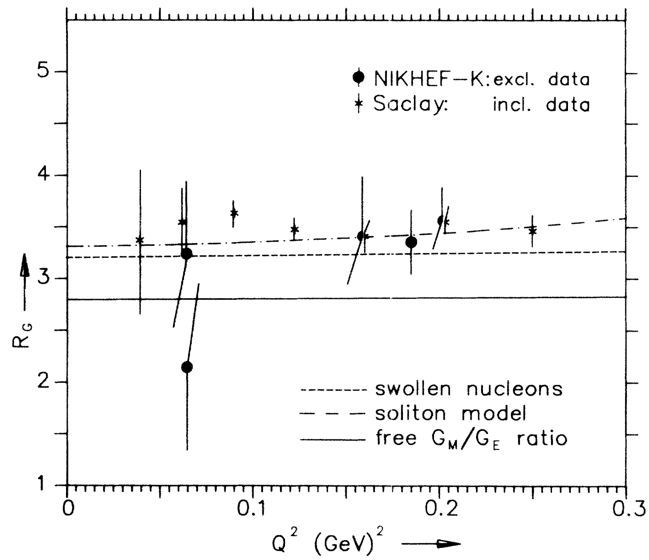

FIG. 2. $R_G=[(4m^2/Q^2)W_T/W_L]^{1/2}$ as a function of the square of the four-momentum, Q^2, for both inclusive and exclusive quasielastic scattering from ^{12}C.

to a few percent on R_G. The former correction is performed by our multiplying W_T/W_L by a factor $\mu_p^2/(\mu_p^2+\mu_n^2)=0.681$, where μ represents the magnetic moment of the nucleon. The inclusive data also contain contributions due to $l=0$ knockout, which we estimate to be less than 20% on the basis of previous measurements.[11] It is impossible to correct R_G for this contribution, since the LT character of $l=0$ knockout is unknown. However, there is no reason to expect that it is qualitatively different from that of $l=1$ knockout. As can be seen from Fig. 2, the two results are in good agreement lending support to the assumption of single-nucleon–knockout dominance. The main observation from Fig. 2 is the enhancement of the ratio G_M/G_E inside the nucleus. The "bound" ratio is 22% larger than the "free" ratio (solid curve in Fig. 2), which at small values of Q^2 corresponds to $\mu_p=2.79$.

In Figs. 1 and 2 the results of several calculations are also shown. The dotted curve represents the prediction of the σ-ω model.[6,10] Nuclear-matter estimates were used for the values of the scalar (−420 MeV) and vector (+328 MeV) potentials. In both figures the dashed curves were obtained from an enlargement of the size of the proton.[9] Since the magnetic moment is proportional to the size, e.g., the radius in a quark-bag model,[20] the enlargement factor ($\lambda=1.15$) simply multiplies μ_p. Also drawn is a curve corresponding to a calculation of Celenza, Rosenthal, and Shakin[21] based on many-body soliton dynamics in a relativistic framework. Only the effect of the nuclear medium relative to the "free" result, assuming nuclear-matter density, is incorporated in this curve. All models considered give a good description of the experimental data.

We also considered meson-exchange currents (MEC's) as a possible explanation for the observed effect. The calculation by Fabian and Arenhövel[22] for the reaction $^2H(e,e'p)n$ indicates that MEC's increase R_G by a few percent in the quasielastic region. This is contrasted by a MEC calculation[23] with the Fermi-gas model that predicts a 5%–10% reduction of R_G at $Q^2=0.15$ GeV/c^2, to be compared to the 22% enhancement that we find experimentally. It is evident that more elaborate MEC calculations are needed.

In summary, the results of the present experiment show a significant effect of the nuclear medium on the virtual-photon–proton coupling, implying a breakdown of the commonly used impulse approximation. The deduced ratio of the magnetic and electric form factors is enhanced as compared to the one for free protons. Several models succeed in describing this behavior. Therefore it would be of interest to study the relation between these models. Future exclusive experiments focusing, e.g., on the density dependence of the photon-proton coupling will be instrumental in further unraveling the effects caused by the nuclear medium.

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