Proton Propagation in Nuclei Studied in the *A* Dependence of the (*e*,*e*′*p*) Reaction in the Quasifree Region

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The *A* dependence of the (*e*,*e*′*p*) reaction in the quasifree region has been measured at an average Q^2 of 0.33 $(\mathrm{GeV}/c)^2$ for targets of ^{12}C, ^{27}Al, ^{58}Ni, and ^{181}Ta. The outgoing proton kinetic energy was 180 ± 30 MeV. By comparing the ratio of (*e*,*e*′*p*) coincidence to (*e*,*e*′) singles yields, average proton transmissions are obtained for each target. The resulting "mean free path" or, more precisely, the attenuation length for protons in the nucleus is significantly longer than expectations based on the free nucleon-nucleon cross section.

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The concept of nucleon propagation through nuclear matter is a deceptively simple one and describing this propagation is a central goal of nuclear many-body theory. The characteristics of nucleon propagation are likely to be dependent on many parameters, including the particle energy and momentum and the nuclear mass and isospin densities, which makes the extension of nucleon attenuation concepts to finite nuclear systems much more difficult. In addition to the fundamental nature of nucleon propagation, the interpretation of many experiments in nuclear physics requires an understanding of how nucleons propagate through nuclei. In many cases the meaning of attenuation may be experiment dependent; some experiments are not sensitive to small changes in the energy and angle of emerging nucleons that might be regarded as attenuation effects in higher-resolution experiments.

Traditionally, proton attenuation has been described in terms of the proton single-particle optical potential where *any* interaction other than elastic scattering is considered "absorption." In this context, the attenuation is traditionally discussed in terms of the average distance between collisions, the nuclear "mean free path." Many global optical-model fits have established standard potentials[1] which, in the proton kinetic-energy range from 150 to 200 MeV, imply mean free paths on the order of 6 ± 2 fm with a small dependence on the proton energy. This is much larger than the simple estimate of $1/\rho\sigma_{NN} \sim 2$ fm or the value of ~ 3 fm obtained[2] when the nucleon-nucleon cross section is corrected for Pauli blocking of occupied final states. Such short mean free paths are implicitly assumed in most intranuclear cascade calculations with the use of free nucleon-nucleon cross sections. A partial resolution of this difference can be understood by including the nonlocality of the *NN* interaction.[3-5] However, fits to data are ambiguous; some optical-model analyses for light nuclei yield considerably shorter mean free paths.[6] All such fitted optical potentials depend on assumptions concerning the potential shapes and the validity of neglecting coupling to inelastic channels.

It is desirable to attempt to find other experimental measures of proton attenuation in nuclei. In this Letter a study of the *A* dependence of the (*e*,*e*′*p*) reaction in the quasifree region is reported. In the simplest limit, the virtual photons knock out protons uniformly from throughout the nuclear volume. By comparing the integrated coincidence yield to the quasifree (*e*,*e*′) yield, one obtains a measure of the attenuation of the outgoing protons. The energy and angle resolution of the present measurement are determined by the range of single-particle momenta and binding energies. In this sense, the measurement is a "low-resolution" one and the attenuation length deduced here is not exactly comparable to the optical-model mean free path. However, given that most of the reaction cross section consists of collisions with large momentum loss, this difference is expected to be small. [High-resolution applications of the (*e*,*e*′*p*) reaction to discrete final states to study proton propagation have also been reported.[7]]

This description of the (*e*,*e*′*p*) reaction mechanism is clearly naive. A more complete treatment of proton rescattering and a comparison of (*e*,*e*′*p*) and (*p*,*p*′) results can be found in Ref. 8. However, the choice of the kinematic variables does permit the exploration of many of the features of this simple picture. The experimental distributions also provide checks on competing reaction mechanisms.

The experiment was performed using a 780-MeV electron beam from the MIT Bates linear accelerator. The targets consisted of foils (~ 100 mg/cm^2) of carbon, aluminum, ^{58}Ni, and tantalum. Electrons were detected in the OHIPS spectrometer and identified in a detector stack of two drift chambers, three plastic scintillators, and a gas Čerenkov counter for electron identification. The electron momentum resolution was 0.5% over the total momentum acceptance of 545 to 585 MeV/c. Protons were detected in the Bigbite spectrometer with a detector stack consisting of two sets of x-y multiwire proportional chambers separated by 1 m and two plastic-scintillator arrays. Protons were identified by a scintillator pulse-height cut and by time of flight with respect to the electrons. The proton momentum resolution was $\sim(0.5\text{–}2.0)\%$ over the momentum acceptance of 420 to 725 MeV/c. The integrated electron current (~ 3 μA with a macroscopic duty factor of $\sim 0.9\%$) was monitored using two toroids. The coincidence performance of the system was tested by measuring ^{1}H(e,ep) scattering from a polyethylene target.

The kinematics were chosen to detect protons in coincidence with electrons ($545 < p_{e'} < 585$ MeV/c) at the peak of the quasifree distribution (which varies from $p_{e'} \sim 550\text{–}570$ MeV/c on the four targets) at the most forward angle consistent with the constraints of backgrounds and the maximum energy available at Bates. This choice emphasized the longitudinal contribution of the e-p cross section to minimize the dominantly transverse meson exchange and neutron contributions to the reaction mechanism. Electrons were detected at 50.3° for an average four-momentum transfer Q^2 of 0.33 (GeV/c)^2. The protons were detected at average angles of 50.1°, 58.2°, 67.9°, and 72.9° to cover the range in recoil momentum (corresponding to initial proton momentum) of 0 to 320 MeV/c. Electron singles data were accumulated simultaneously thus rendering the ratio of coincidence to singles independent of uncertainties in beam normalization, target thickness, and, to a large extent, the electron-spectrometer efficiencies.

Missing-energy (ME) spectra obtained at each angle for ^{58}Ni after correcting for individual spectrometer acceptances and random coincidence are shown in Fig. 1. (ME is defined as the rest energy of the recoiling $A-1$ system plus the proton rest energy relative to the ground state of the target.) No radiative corrections have been applied. Calculations show that the radiative tail from the elastic peak within our cut is less than 1% and not strongly target dependent.

At the smaller angles, the single-particle response of the $(e,e'p)$ reaction is evident. The energy resolution of the experiment precludes the identification of specific single-particle orbitals beyond the carbon $p_{3/2}$ orbital. The yield at high missing energy, ME > 80 MeV, varies slowly with angle, is not consistent with reasonable nucleon momentum distributions for deeply bound single-particle states, and is most likely the result of two-body currents or of proton multiple scattering in the final state. Based on the missing-energy spectra at the smaller angles, calculated single-particle energies, and the multiple-scattering calculation discussed below, the region $-20 < \text{ME} < 80$ MeV was chosen as a reasonable estimate of the single-particle response. In Fig. 2, the ratio of coincidence to singles cross sections is plotted for each target, integrating over $-20 < \text{ME} < 80$ MeV, as a function of laboratory proton angle. If there were no final-state proton attenuation, then this ratio would be $\sim |q/k_F|^2/\pi$ at the two smaller proton angles where q/k_F is the ratio of the three-momentum transfer of the virtual photon to the Fermi momentum.

In order to integrate the coincidence yield over the initial momentum distribution of the protons, plane-wave impulse-approximation (PWIA) calculations[9] have been used to estimate the shape of the angular correlation.

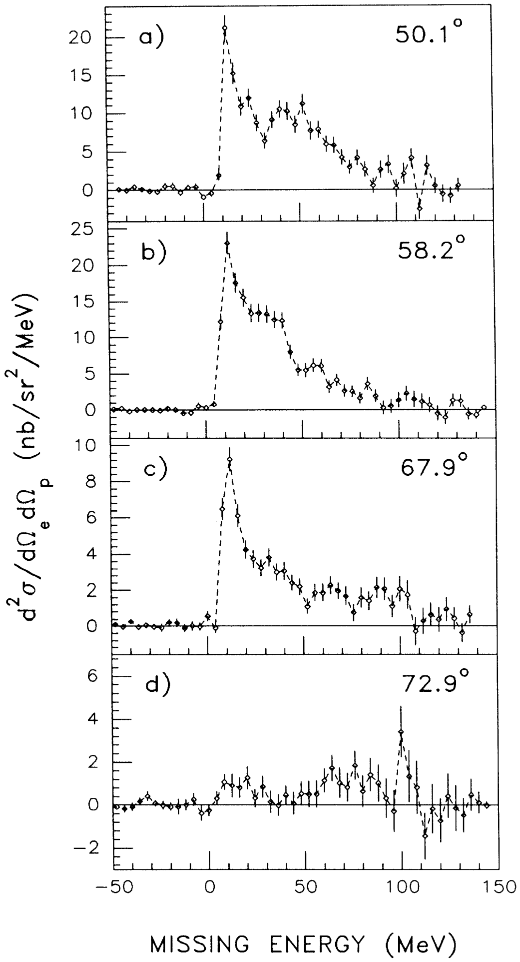

FIG. 1. Missing-energy spectra for the ^{58}Ni$(e,e'p)$ reaction at proton angles of 50.1°, 58.2°, 67.9°, and 72.9°. The average initial proton momenta are 60, 130, 220, and 280 MeV/c, respectively.

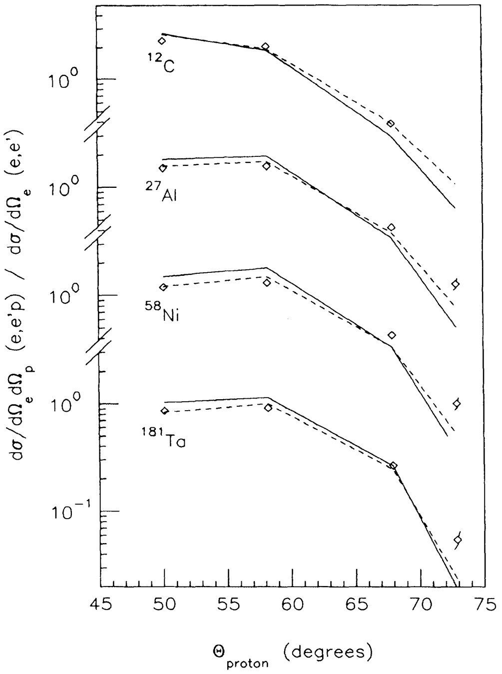

FIG. 2. Ratio of coincidence to singles cross sections for $545 < p_{e'} < 585$ MeV/c. The diamonds correspond to a missing-energy range of $-20 < \mathrm{ME} < 80$ MeV. The dashed curves are plane-wave impulse-approximation calculations normalized to the data. The normalization factors are ^{12}C, 0.77; ^{27}Al, 0.64; ^{58}Ni, 0.53; ^{181}Ta, 0.40. The solid curves are distorted-wave impulse-approximation calculations with no renormalization.

These calculations were averaged over the finite angular acceptance of the spectrometers. The results were not sensitive to the detailed choice of the single-particle potential used to calculate the spectral function. The dashed curves in Fig. 2 are calculated with energy-dependent Woods-Saxon potentials, adjusted to reproduce the rms radii of the nuclei and the binding energies of the last orbitals. The ratios were also not sensitive to the choice of off-shell electron-proton interactions (though the inclusive or exclusive cross sections are).

The shapes of the experimental angular correlations are quite similar to the PWIA predictions. The normalization factors of the PWIA calculations to the angular correlations, plotted in Fig. 3, are identified with the transmission of the nucleus for protons in this energy range, 150 to 210 MeV, and represent the central results of this experiment. It is clear that more than $1/e$ of the protons emerge from tantalum, setting the scale of the attenuation length at the tantalum radius, ~6 fm, not ~2 fm.

Two simple models of nuclear attenuation serve to illustrate the attenuation length implied by these data. First, factorized distorted-wave impulse-approximation (DWIA) calculations[9] with the volume potentials of Nadasen *et al.*[1] are shown as the solid lines in Fig. 2 for each target. (This comparison is only meant to be representative since the Nadasen *et al.* potentials were fit with additional spin-orbit terms which cannot be calculated in the factorized DWIA calculation.) These calculations for a potential with a central imaginary depth of 9.0 MeV corresponding to an attenuation length of 6.3 fm are similar to the data for C but overpredict the Al, Ni, and Ta results suggesting 4–6 fm attenuation lengths.

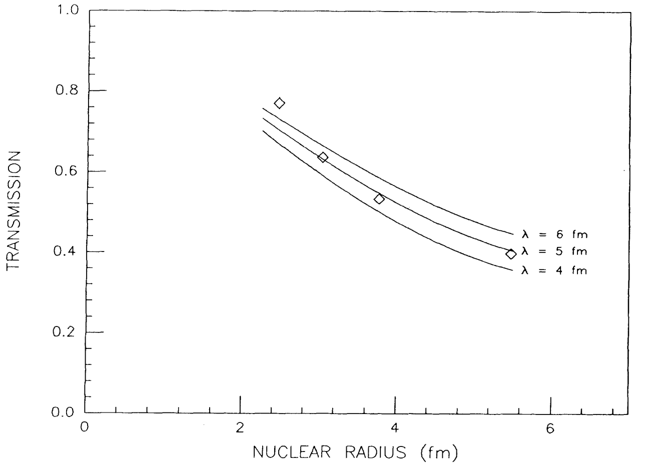

FIG. 3. The transmission, defined as the experimental ratio of the coincidence to singles cross sections divided by the PWIA ratio, is plotted vs nuclear radius. The solid curves are the classical attenuation calculations described in the text for three different nuclear-matter attenuation lengths.

Another simple model for comparison is a classical attenuation calculation of proton propagation. The probability of proton interaction along an element dz of the proton trajectory is $\sigma_{\rm eff}(\rho)\rho(r)dz$. $\sigma_{\rm eff}$ must be density dependent to account for Pauli effects and nonlocality. A reasonable choice is to take $\sigma_{\rm eff}(\rho) = \sigma_0/[1+K\rho(r)]$, with σ_0 being the appropriate isospin average of the free cross sections ($\sigma_{pp} = 22$ mb and $\sigma_{np} = 46$ mb) and K a free parameter which determines the attenuation length in nuclear matter (at $\rho_{\rm NM} = 0.17$ nucleon/fm^3). There is a significant sensitivity to the nuclear size parameters comparable to the usual optical-model ambiguities. In Fig. 3, illustrative calculations using charge distributions taken from electron scattering[10] are shown as the solid curves for three nuclear-matter attenuation lengths, $1/\rho_{\rm NM}\sigma_{\rm eff}(\rho_{\rm NM}) = 4$, 5, and 6 fm. This suggests an attenuation length of about 5 fm, large compared to the isospin-averaged value of $1/\rho_{\rm NM}\sigma = 1.8$ fm or the Pauli corrected value of ~3 fm. There is reasonable agreement between the classical local-density approximation and the DWIA estimate of an attenuation length on the order of 5 fm.

As a further check, Monte Carlo calculations of the missing-mass spectra were performed with cross sections, single-particle energies, and density distributions like those considered above. The calculated missing-mass spectra showed the same features as the data, with the multiple-scattering contributions being significant at large missing energy and relatively independent of angle. These calculations allow a thorough investigation of the sensitivity of the results to the criteria for attenuation including scattering at small angles and energy loss and will be presented in a more complete future publication.[11]

In summary, the A dependence of the $(e,e'p)$ reaction in the quasifree region has been studied to understand the attenuation of 150–200-MeV protons in the nuclear medium. This is the first attempt to perform such a broad integration of the quasifree scattering process in this proton energy regime. The bulk of the cross section is reasonably described as single-particle knockout, followed by proton attenuation through final-state interactions with the nucleus. Both classical and quantum-mechanical model analyses yield attenuation lengths of ~ 5 fm.

For penetrating probes the transmissions shown in Fig. 3 provide a direct answer to questions of how to interpret reaction yields with final-state protons in this energy region. For other reactions these data provide an easily calculable benchmark to compare models of proton propagation in nuclei.

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