CEBAF PROPOSAL COVER SHEET

This Proposal must be mailed to:

CEBAF
Scientific Director's Office
12000 Jefferson Avenue
Newport News, VA 23606

and received on or before OCTOBER 30, 1989

A. TITLE:

The Energy Dependence of Nucleon Propagation in Nuclei as Measured in the (e,e'p) Reaction

B. CONTACT PERSON:

Donald F. Geesaman

ADDRESS, PHONE AND BITNET:

Argonne National Laboratory, 9700 S. Cass Ave., PHY203,
Argonne, IL 60439-4843
(312)972-4059 or 4044 GEESAMAN@ANLPHY

(Please note that as of November 11 the area code will change from 312 to 708)

C. THIS PROPOSAL IS BASED ON A PREVIOUSLY SUBMITTED LETTER OF INTENT

- [x] YES
- [ ] NO

IF YES, TITLE OF PREVIOUSLY SUBMITTED LETTER OF INTENT

Same as above. LOI36

D. ATTACH A SEPARATE PAGE LISTING ALL COLLABORATION MEMBERS AND THEIR INSTITUTIONS

(CEBAF USE ONLY)

Letter Received 10-31-89

Log Number Assigned PR-89-022

By KES

contact: Geesaman

CEBAF Experiment Requirements

Date Submitted 10/28/8

Title & Spokesperson The Energy Dependence of Nucleon Propagation in Nuclei as Measured in the (e,e'p) Reaction. Donald F. Geesaman

Estimated total beam time (hours)	432
Electron beam energy(s) required	750, 1000, 2000, 3000, 4000
Beam current(s) (μA)	10-100
Total μA-hours required	14000
Solid target(s) material	C, Si, Ni, Pb, CH_2
Solid target(s) thickness	50-200 mg
Cryogenic target -type and length (cm)	--
Power deposition in cryogenic target (Watts)	-- watts
Polarized beam (y/n)	N
Polarized target (y/n)	N
Power deposition in polarized target	N
Effective beam spot diameter (≥100 microns)	Nominal
Scanned beam at target (y/n)	N
Dispersed beam (y/n)	N

Spectrometer Requirements	*e' Arm*	*Hadron Arm*
Solid angle acceptance (msr)	5	9
Momentum acceptance (FWHM %)	10	20
Momentum resolution (FWHM %)	0.1	0.1
Scattering angle (degrees)		
Minimum	23	19
Maximum	115	68
Scattering angle, uncertainty (mr)	1 mr	1 mr
Central orbit momenta (MeV/c)		
Minimum	350	950
Maximum	2900	1850
Spectrometer settings, reproducibility,		
Central angle (mr)	1 mr	1 mr
Central momentum (MeV/c)	2 MeV/c	2 MeV/c
Particle identification requirements		
Rejection type (e.g. π^-/e^-)	π^-/e^- π^+/p	π^-/e^- π^+/p
Required ratio (e.g. 10^{-3})	10^{-2} 10^{-3}	10^{-2} 10^{-3}
Traceback capability required (y/n)	Y	

Position accuracy along beam (mm)	----
Luminosity range (cm^{-2} sec^{-1})	Max. 6×10^{36} for ^{12}C

Remarks:

The Energy Dependence of Nucleon Propagation in Nuclei
as Measured in the (e,e'p) Reaction

A Proposal for CEBAF

October 1989

D. F. Geesaman (Spokesman), R. J. Holt, H. E. Jackson,
S. Kaufman, E. Kinney, D. Potterveld, J. P. Schiffer, B. Zeidman

Argonne National Laboratory, Argonne IL 60439

R. E. Segel

Northwestern University, Evanston Il 60201

B. W. Filippone and R. D. McKeown

California Institute of Technology, Pasadena, CA 91125

R. Milner

Massachusetts Institute of Technology, Cambridge, MA 02139

R. Gilman

Rutgers University, New Brunswick, NJ 08903

Abstract

The energy dependence of proton propagation through nuclei will be examined in measurements of the A dependence of the quasifree (e,e'p) reaction on four targets, ^{12}C, ^{28}Si, ^{58}Ni and ^{208}Pb for average emergent proton energies of 400, 700, 1000, and 2000 MeV. At T_p=400 MeV, Q^2=.76 $(GeV/c)^2$, a Rosenbluth separation will be performed to study the reaction mechanism. A consistent data set covering this large range of proton energy would be unique and provide an important survey of the reaction mechanism in the quasifree region. The experiment would be performed using the coincidence spectrometer pair in Hall C to detect the electron and proton. The A dependence of the integrated coincidence yield provides a direct measure of the proton attenuation.

Introduction

The propagation of nucleons through the nuclear medium is a fundamental characteristic of the nuclear many-body problem. There remains considerable uncertainty in how to evaluate the propagation of nucleons participating in nuclear reactions. For medium energy, 100-500 MeV, protons, there are substantial variations between the "proton mean free paths" extracted from various parameterizations of the proton optical potential and from calculations based on the free nucleon-nucleon cross sections. Furthermore, especially in experiments at higher energies, it is often not possible to resolve protons which are coherently diffracted by the nucleus from those which undergo small angle or small energy loss interactions. For these experiments, a more macroscopic examination of nucleon propagation in nuclei is necessary.

The theoretical description of proton propagation also changes considerably with energy. At lower energies, non-relativistic optical potentials describe the self energy of a particle in the nuclear medium. At higher energies, relativistic optical potentials are used, and at still higher energies most descriptions of proton propagation use variants of the Glauber model.

Quasifree electron-proton scattering provides an excellent tool to study nucleon propagation effects. The electron-nucleon vertex is well understood on shell, so that these reactions can be viewed as tagging a source of protons emerging from throughout the nuclear volume, allowing true volume effects to be more succinctly studied. The study of discrete final states in the Distorted Wave Impulse Approximation (DWIA) is directly analogous to the study of proton elastic scattering. Here we fix the electron kinematics to restrict the scattered electron energies to be close to the quasifree peak at which the reaction mechanism has a large single-nucleon component. The integrated quasifree coincidence yield (integrated over missing mass and recoil momentum) provides a measure to the macroscopic attenuation, averaged over the binding energies of single-particle states and the angular range of the quasifree angular correlation ($p_f/|q|$ where $p_f \sim 250$ MeV is the Fermi momentum of the nucleus and $|q|$ is the three momentum transfer).

We have recently published the first results[1] of an experiment at the MIT Bates Laboratory with similar goals for proton kinetic energies, $T_p \sim 180$ MeV. A copy of the letter is attached as an appendix to this proposal. These results support this simple interpretation of the (e,e'p) reaction at this low four-momentum transfer squared, Q^2, ($T_p \sim Q^2/2M_p$) where the reaction mechanism has a large longitudinal component. We propose to extend these measurements from T_p=400 MeV to 2000 MeV (Q^2 of 0.76, 1.3, 1.9 and 3.8 $[\mathrm{GeV}/c]^2$). At the larger momentum transfers considered here, the transverse contribution always dominates ($\sigma_T/\sigma_L = Q^2 * \mu_p{}^2/4M_p{}^2$ where μ_p is the proton magnetic moment).

To validate this interpretation of the (e,e'p) reaction in terms of single-nucleon knockout, at one energy a Rosenbluth separation will be performed to separately study the A dependence of the longitudinal and transverse yield. While the longitudinal response is expected to be determined by the single-nucleon spectral function, the transverse response will certainly contain some contributions from meson exchange currents or other multi-nucleon mechanisms. However, the cross sections in the quasifree region are still known to scale approximately with A, even when the transverse response dominates. The single-particle knockout mechanism is further supported by the phenomenology of y scaling at these momentum transfers[2]. If multi-nucleon currents complicate the reaction mechanism, then one would expect the missing mass spectra to be rather different and the A dependence of the transverse yield to differ from that of the longitudinal yield. At BATES energies, the kinematics could be chosen to emphasize the longitudinal contribution, and relatively little yield is observed for missing masses greater than 80 MeV except at initial proton momenta larger than the Fermi momentum (Figure 1). There, we were able to interpret the double ratio of experimental coincidence/singles yields to PWIA calculated coincidence/singles yields as the proton transmission and extract an average attenuation length of 5 fm (Figure 2). This same technique should be effective for the longitudinal data at T_p=400 MeV. For the higher proton energies (T_p>400 MeV/c), a Rosenbluth separation would consume excessive beam time. However, if the A dependence of the transverse yield is observed to follow that of the longitudinal yield at T_p=400 MeV, it is reasonable to use the total cross section to measure the attenuation. An appropriate region of single-particle response can be determined for the T_p=400 MeV longitudinal missing mass spectra. With the quality of data expected from CEBAF, the A dependence of the absolute coincidence yield may provide the best measure of proton propagation and the ratio of coincidence to singles yields will provide important information on the reaction mechanism.

In a related proposal (following LOI46), it is proposed to study the A dependence of the (e,e'p) reaction at very high-momentum transfer to search for evidence of "color transparency", the concept that high-momentum transfer processes must occur on physically small objects. The methodology of that proposal is the same as the method for this proposal. The studies considered here will be an important test on this methodology. At the highest Q^2, we may indeed observe the onset of this phenomena.

The data sample proposed here would provide a single body of systematic data over most of the proton energy range important at CEBAF, TRIUMF and LAMPF. The proposed experiment places quite modest requirements on the incident beam and coincident spectrometers. However, the large solid angles, high-incident beam energies, and the need for a large, internally consistent data set make this experiment uniquely suited for CEBAF's facilities.

The wide range of proton energies involved in this experiment does present a challenge in providing a consistent theoretical interpretation. No single calculational scheme is, at present, able to deal with the entire range. We expect that the experiment proposed here will stimulate such theoretical activity. But, if a successful approach does not become evident, then this experiment becomes even more important in providing a benchmark to calibrate proton reinteraction effects for a number of CEBAF (e,e'p) experiments on heavier nuclei.

Experiment

The experimental conditions assumed in this proposal are presented in Table I. The Hall C HMS and SOS spectrometers will be used. The measurements at the highest proton energies will be made by reversing the role of the spectrometers. A representative set of measurements is given in Table II. The counting rates are estimated based on Fermi gas predictions. Beam time would be distributed between the four targets roughly as 1:1.2:1.6:2.6 (carbon, silicon, nickel, lead) as determined from the BATES results. The outgoing protons are confined to a cone with an opening angle of $p_f/|q|$. This kinematic focusing improves with increasing proton energy. At each energy the number of proton angles is chosen to span the range in recoil momentum (p_r) from $0 < p_r < 300$ MeV/c. The kinematic focusing coupled with the CW nature of the CEBAF beam and the fact that quasifree scattering remains a dominant reaction mechanism in this range of electron energy loss minimize the random coincidence rate as a problem for this experiment. The minimum time per point was assumed to be 20 minutes for 10000 coincidence events. At T_p=400 MeV, 40000 events per angle setting would be acquired. The Rosenbluth separation will use data at three energies corresponding to virtual photon polarizations of 0.14, 0.47 and 0.87. The net time involved would be 12 days of data taking and 6 days of calibration. Roughly half the time is required for the 400 MeV Rosenbluth separation.

Calibration will be performed with a CH_2 target to ensure the same source geometry as the experimental data. It will involve a careful mapping of the singles acceptence of each spectrometer and studies of the coincidence response of the pair with ^{1}H(e,ep) elastic scattering.

Resources Required

The experiment will use the standard electron (HMS) and hadron (SOS) spectrometers of the Hall C system. The momentum resolution requirements are modest. A momentum bite > 18% is required for the hadron spectrometer at T_p=400 MeV to cover the entire missing mass range. Particle identification is important: particularly pion-proton resolution in the hadron spectrometer and electron-pion resolution in the electron spectrometer. Of more concern is the angular resolution of the spectrometer detection systems which is important for the recoil momentum resolution. The targets involved are all self-supporting foils, and, with the exception of lead, relatively durable.

This experiment would also be suited for the Hall A coincidence spectrometer system. However, two momemtum bites would be required to cover the appropriate kinematic range, increasing the required beam time by 7 days. Given that resolution is not a crucial issue, Hall C would seem to be a more appropriate place for these experiments. We would like to emphasize our interest in the physics of the experiment and we will plan on carrying it out at whichever facility is available in a timely fashion.

Commitment of Collaborators

This experiment is one of several which we anticipate for the HALL C spectrometer system. It is expected that these experiments will be a major fraction of the research effort of this collaboration once CEBAF is in operation and to that end, Argonne has agreed to build the SOS spectrometer as the required hadron arm. A substantial fraction of the collaboration have heavy commitments to other research until at least 1992.

References

[1]D. F. Geesaman et al., Phys. Rev. Lett. 63, 734 (1989).
[2]D. B. Day et al., Phys. Rev. Lett. 59, 427 (1987).

Figure Captions

Figure 1 Invariant missing energy spectra for the ^{58}Ni (e,e'p) reaction at average initial proton momenta of 60, 130, 220 and 280 MeV/c respectively (corresponding to proton angles of 50.1, 58.2, 67.9 and 72.9 degrees).

Figure 2 The transmission, defined as the experimental ratio of the coincidence to singles cross sections divided by the PWIA ratio, is plotted versus nuclear radius. The solid curves are classical attenuation calculations for three different nuclear attenuation lengths.

TABLE I

Duty Factor	100 %
Beam current	10-100 uA
Target Thickness	50-200 mg/cm^2
Targets	^{12}C, ^{28}Si, ^{58}Ni, ^{208}Pb
Beam energy spread	< 0.1%
Electron Spectrometer	
Momentum Acceptance	10%
Solid Angle	5 msr
P max	3 GeV
P resolution	0.1 %
Particle Identification	electron-pion pion-proton (for T_p=2000)
Hadron Spectrometer	
Momentum Acceptance	>20%
Solid angle	9 msr
P max	2 GeV
P resolution	0.1 %
Particle Identification	pion-proton electron-pion (for T_p=2000)

TABLE II

Proton Energy (MeV)	Beam Energy (MeV)	Coincidence* fraction	Electron angle	Proton angle	Hours per** target	Total Days
400	750	0.044	115	19,23 27,31,34	1.5	4
400	1000	0.044	69	35,39 43,47,51	0.7	2
400	2000	0.044	28	52,56 60,64,68	0.3	1
700	3000	0.084	25	47,50 53,56,59	0.3	1
1000	4000	0.134	23	43,46 49,52	0.3	1
2000	4000	0.200	40	28,31 34	3	3

*Coincidence fraction = $\frac{\text{spectrometer solid angle}}{\text{solid angle of fermi cone}}$

**For ^{12}C target. ^{181}Ta runs will require up to a factor of 3 more time.

NICKEL (e,e'p)

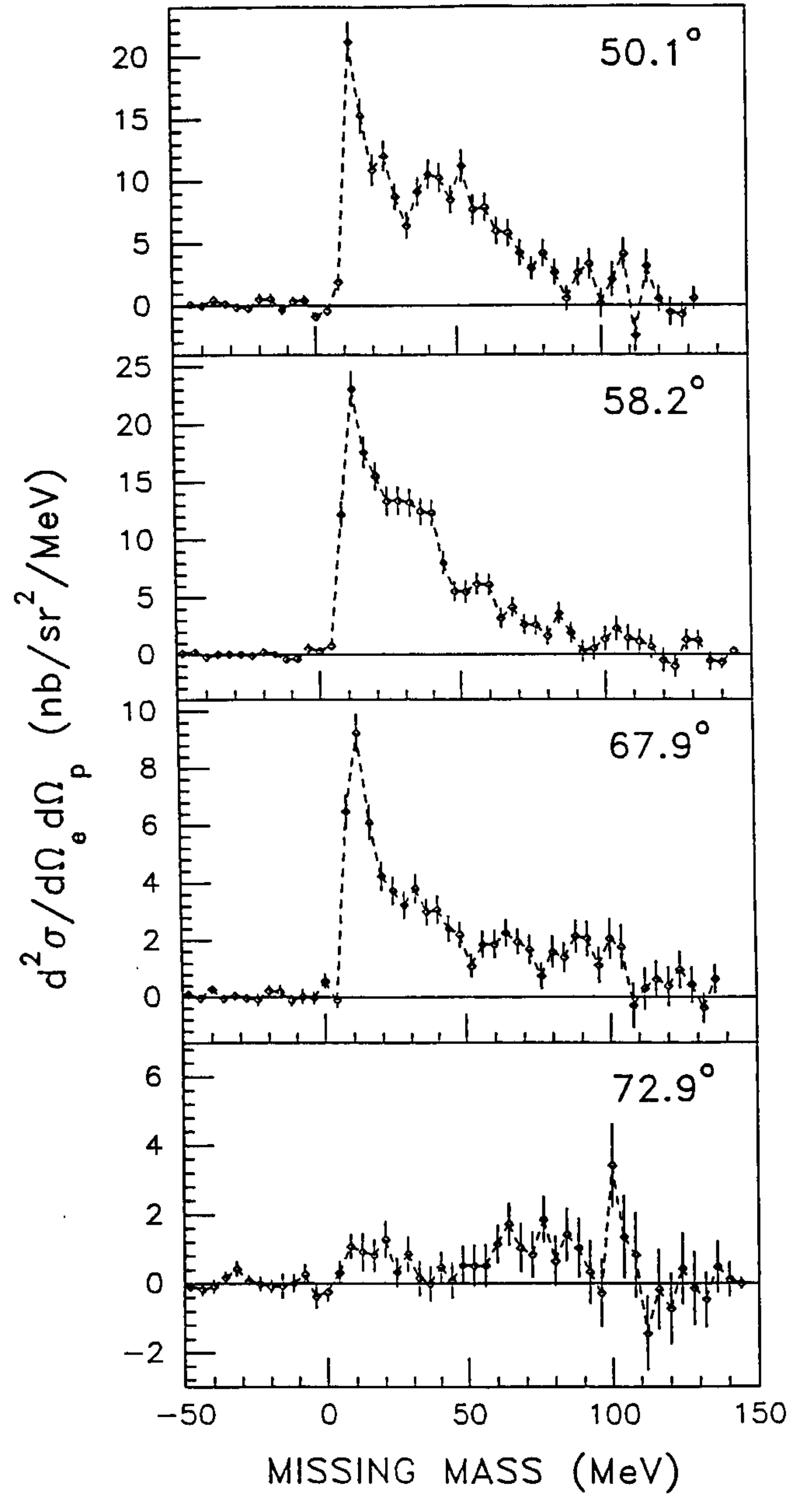
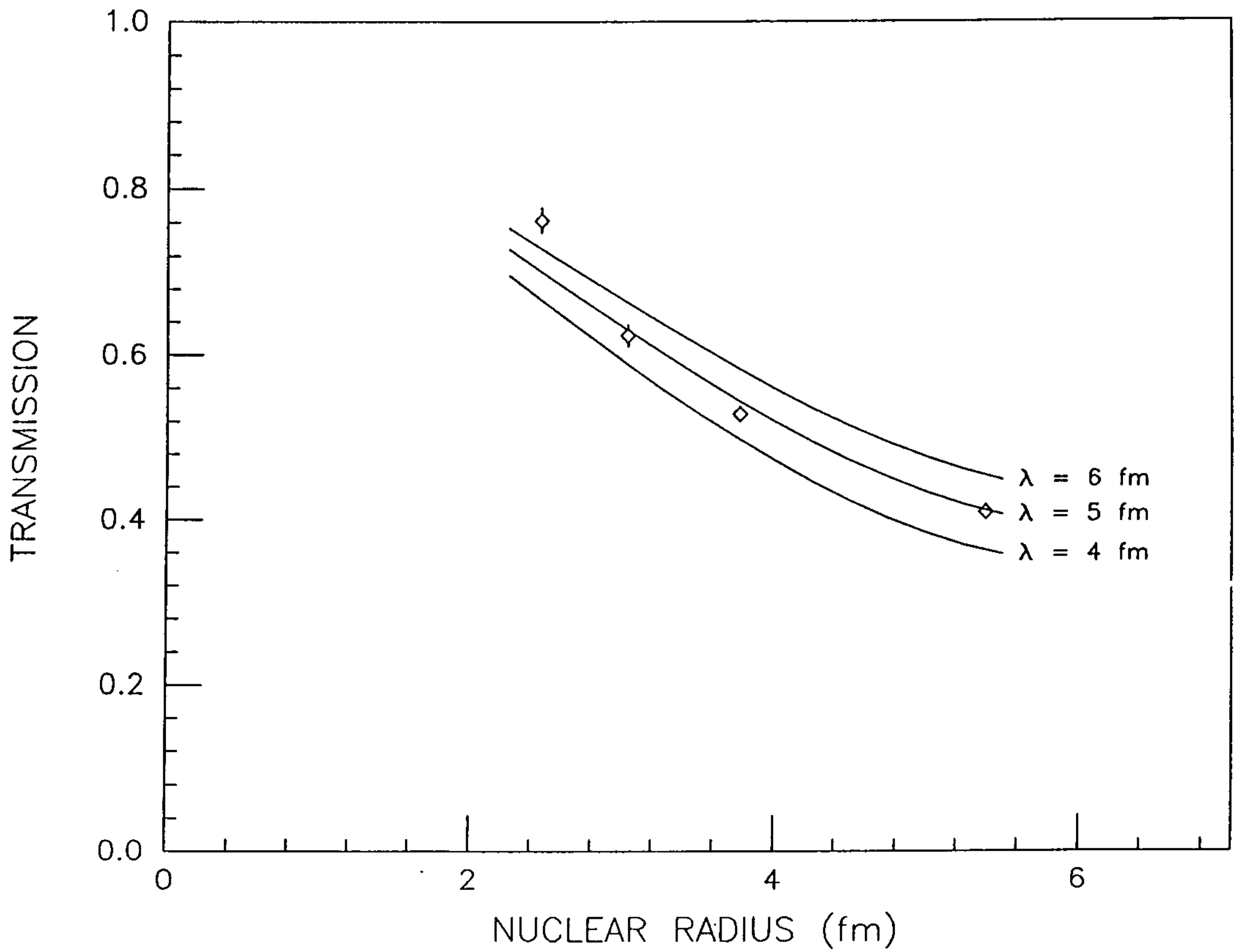


Fig. 1



TRANSMISSION
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
NUCLEAR RADIUS (fm)
λ = 6 fm
λ = 5 fm
λ = 4 fm

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

D. F. Geesaman,[1] R. Gilman,[1] M. C. Green,[1,a] R. J. Holt,[1] J. P. Schiffer,[1] B. Zeidman,[1] G. Garino,[2] M. Saber,[2,b] R. E. Segel,[2] E. J. Beise,[3,c] G. W. Dodson,[3] S. Hoibraten,[3,d] L. D. Pham,[3] R. P. Redwine,[3] W. W. Sapp,[3] C. F. Williamson,[3] S. A. Wood,[3,e] N. S. Chant,[4] P. G. Roos,[4] J. D. Silk,[5] M. Deady,[6,f] and X. K. Maruyama[7,g]

[1]*Argonne National Laboratory, Argonne, Illinois 60439*
[2]*Northwestern University, Evanston, Illinois 60201*
[3]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*
[4]*University of Maryland, College Park, Maryland 20742*
[5]*University of Pennsylvania, Philadelphia, Pennsylvania 19104*
[6]*Mount Holyoke College, South Hadley, Massachusetts 01075*
[7]*National Institute for Standards and Technology, Gaithersburg, Maryland 20899*

(Received 24 April 1989)

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.

PACS numbers: 25.30.Fj, 24.10.Ht

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 unders by including the nonlocality of the *NN* interactio However, fits to data are ambiguous; some optical-m analyses for light nuclei yield considerably shorter m free paths.[6] All such fitted optical potentials depen assumptions concerning the potential shapes and the lidity of neglecting coupling to inelastic channels.

It is desirable to attempt to find other experim measures of proton attenuation in nuclei. In this L a study of the *A* dependence of the $(e,e'p)$ reactio the quasifree region is reported. In the simplest l the virtual photons knock out protons uniformly throughout the nuclear volume. By comparing th tegrated coincidence yield to the quasifree (e,e') y one obtains a measure of the attenuation of the outg protons. The energy and angle resolution of the pr measurement are determined by the range of si particle momenta and binding energies. In this s the measurement is a "low-resolution" one and th tenuation length deduced here is not exactly compa to the optical-model mean free path. However, that most of the reaction cross section consists of lisions with large momentum loss, this difference i pected to be small. [High-resolution applications o $(e,e'p)$ reaction to discrete final states to study p propagation have also been reported.[7]]

This description of the $(e,e'p)$ reaction mechanis clearly naive. A more complete treatment of proto scattering and a comparison of $(e,e'p)$ and (p,p') re can be found in Ref. 8. However, the choice of the matic variables does permit the exploration of ma the features of this simple picture. The experim distributions also provide checks on competing rea 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, $\mathrm{ME} > 80$ MeV, varies slowly with angle, is not consistent with reasonable nucleon momentum distributions for deeply bound single-

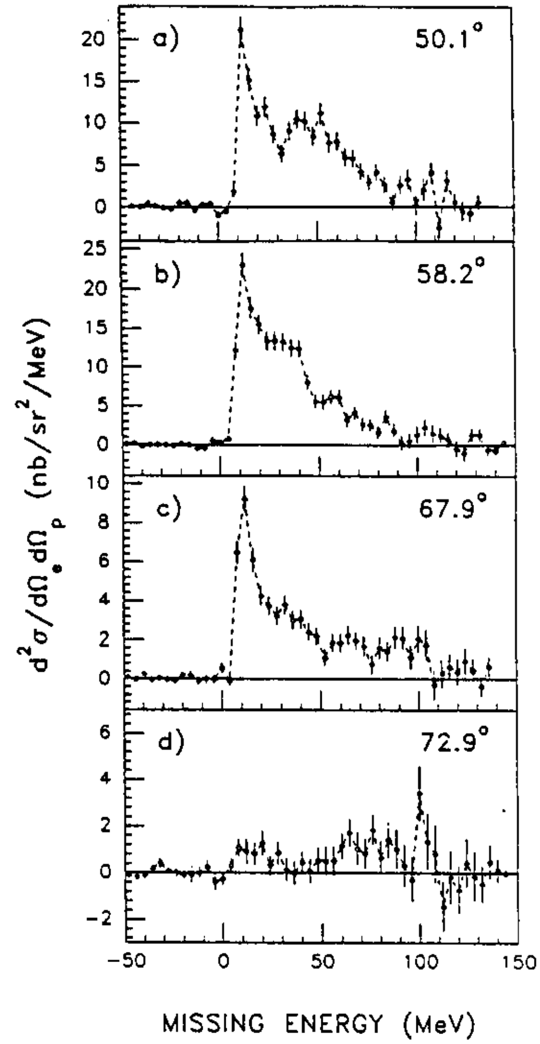


FIG. 1. Missing-energy spectra for the ^{58}Ni$(e,e'p)$ reaction at proton angles of 50.1°, 58.2°, 67.9°, and 72.9°. The average initial proton momenta are 60, 130, 220, and 280 MeV/c, respectively.

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 $-20 < \mathrm{ME} < 80$ 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 $-20 < \mathrm{ME} < 80$ 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.

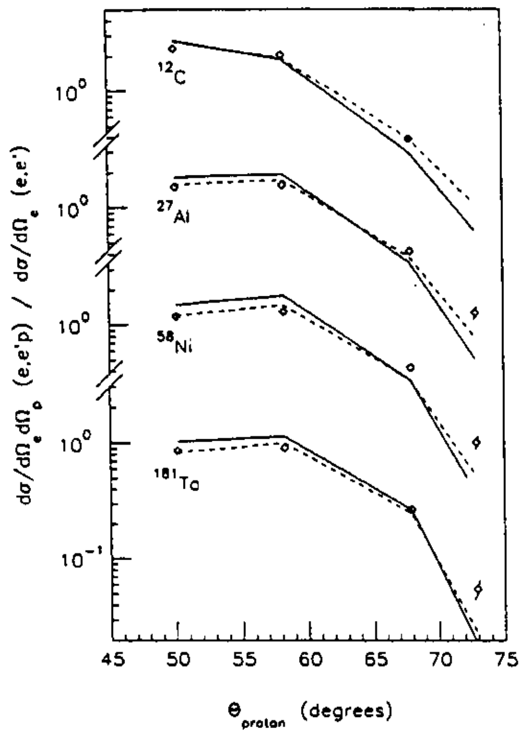


FIG. 2. Ratio of coincidence to singles cross sections for $545 < p_{e'} < 585$ MeV/c. The diamonds correspond to a missing-energy range of $-20 < \mathrm{ME} < 80$ MeV. The dashed curves are plane-wave impulse-approximation calculations normalized to the data. The normalization factors are ^{12}C, 0.77;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

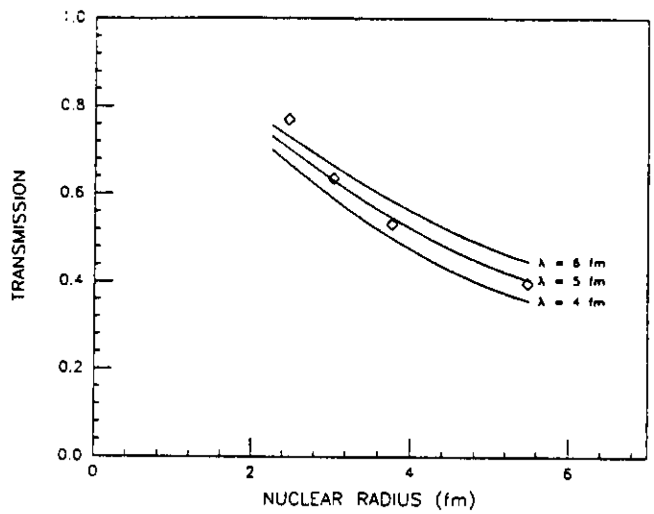


FIG. 3. The transmission, defined as the experimental ratio of the coincidence to singles cross sections divided by the PWIA ratio, is plotted vs nuclear radius. The solid curves are the classical attenuation calculations described in the text for three different nuclear-matter attenuation lengths.

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.

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 $\sigma_{\mathrm{eff}}(\rho)\rho(r)dz$. σ_{eff} must be density dependent to account for Pauli effects and nonlocality. A reasonable choice is to take $\sigma_{\mathrm{eff}}(\rho) = \sigma_0/[1+K\rho(r)]$, 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 $\rho_{\mathrm{NM}} = 0.17$ 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, $1/\rho_{\mathrm{NM}}\sigma_{\mathrm{eff}}(\rho_{\mathrm{NM}}) = 4$, 5, and 6 fm. This suggests an attenuation length of about 5 fm, large compared to the isospin-averaged value of $1/\rho_{\mathrm{NM}}\sigma = 1.8$ 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.

This work was supported by the Department of Energy, Nuclear Physics Division, under Contract No. W-31-109-ENG-38, Northwestern University by the National Science Foundation under Grant No. PHY-8608247, Massachusetts Institute of Technology by the Department of Energy under Contract No. DE-AC02-76ER03069, and the University of Maryland by the National Science Foundation under Contract No. NSFD PHY 8615512.

[a]Present address: Le Croy Research Systems, Spring Valley, NY 10977.

[b]Present address: King Faisel University, Dammam, Saudi Arabia.

[c]Present address: California Institute of Technology, Pasadena, CA 91125.

[d]Present address: University of Colorado, Boulder, CO 80309.

[e]Present address: University of Illinois, Urbana, IL 61801.

[f]Present address: Bard College, Annandale-on-Hudson, NY 12504.

[g]Present address: Naval Postgraduate School, Monterey, CA 93943.

[1]A. Nadasen *et al.*, Phys. Rev. C **23**, 1023 (1981).

[2]K. Kikuchi and M. Kawai, *Nuclear Matter and Nuclear Reactions* (North-Holland, Amsterdam, 1968), p. 33.

[3]J. P. Jeukenne, A. Lejeune, and C. Mahaux, Phys. Rep. **25**, 83 (1976).

[4]J. W. Negele and K. Yazaki, Phys. Rev. Lett. **47**, 71 (1981).

[5]S. Fantani, B. L. Friman, and V. R. Pandharipande, Phys. Lett. **104B**, 89 (1981).

[6]H. O. Meyer *et al.*, Phys. Rev. C **27**, 459 (1983).

[7]J. W. A. Den Herder *et al.*, Phys. Lett. B **184**, 11 (1987).

[8]T. Takaki, Phys. Rev. C **39**, 359 (1989).

[9]N. S. Chant and P. G. Roos, Phys. Rev. C **27**, 1060 (1983); N. S. Chant, PROGRAM THREEDEE (private communication).

[10]H. De Vries, C. W. De Jagger, and C. De Vries, At. Data Nucl. Data Tables **36**, 495 (1987).

[11]G. Garino *et al.* (to be published).