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WHAT CAN BE LEARNED WITH FAST NEUTRONS?

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ABSTRACT

The DOE/NSF Nuclear Science Advisory Committee (NSAC) is preparing a new Long Range Plan for the development of nuclear science. This document, written as input to the Long Range Plan subcommittees, describes a number of ways that experiments with incident neutrons impact on outstanding problems in nuclear reactions and spectroscopy. It is argued that major extensions of present capabilities are required to carry out these experiments.

WHAT CAN BE LEARNED WITH FAST NEUTRONS?

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I. Introduction

This document is a brief outline of what can be learned about nuclear structure and reaction mechanisms from several types of reactions induced by fast neutrons (∿ 5 to 200 MeV). Such an outline is particularly timely because of the formulation of a new Long Range Plan by NSAC. Moreover, several groups throughout the world have begun to think about facilities to extend present capabilities for studying neutron-induced reactions. These projects range from reasonably modest upgrades of present facilities to entirely new facilities which could produce intense, nearby monoenergetic neutrons at energies of 100 MeV or more.

The decision to write this outline grew out of informal discussions that the author had with participants at a workshop (Microscopic Approaches to Nucleon-Nucleus Scattering, Asilomar, May 24-27, 1983) in which results of neutron-scattering experiments played an important role in clarifying the physics issues at hand. Input, ranging from helpful discussion and advice to the writing of a few paragraphs, has been provided by several scientists who have an interest in obtaining further information with neutrons. These include H. M. Blann, V. R. Brown, R. W. Finlay, V. A. Madsen, F. L. Petrovich, C. H. Poppe, and R. L. Walter. S. M. Austin emphasized the importance of communicating the material discussed herein to the Long Range Plan subcommittees. However, the author must take full responsibility for the accuracy of the present report, as well as the choice of topics and the manner in which they are presented.

The discussion includes the following topics, which in the most modern views of nuclear reaction mechanisms are highly overlapping:

- Effective interactions
- Elastic scattering
- Inelastic scattering
- (n,p) reactions
- Preequilibrium reactions
- Radiative capture

Mainly because of lack of time, this outline does not include many other topics that could be profitably studied with incident neutrons. These include transfer reactions (e.g. (n,^{3}He)), low-energy neutron studies (e.g. statistical physics), few-nucleon problems, and nucleon-nucleon scattering.

Presently available facilities producing high-quality, nearly monoenergetic neutron beams are limited to 26 MeV for unpolarized beams (Ohio) and below 20 MeV for polarized beams (TUNL). A few pioneering elastic-scattering measurements up to 40 MeV at a facility now terminated (Michigan State) showed that experiments at higher energies are practical. Discussions at the Asilomar workshop indicated that conventional time-of-flight techniques should be useful in the range up to perhaps 100 MeV (100-500 keV resolution, depending on incident energy and experimental configuration). Experiments are very difficult at much higher energies (200-800 MeV), and it is hard to think of a general-purpose facility in this energy range. Although most of the topics discussed below require neutron beams with good energy definition, certain kinds of measurements (e.g. total neutron cross sections and some types of radiative capture) can be made with "white-source" incident neutron spectra produced by electron (ORELA, LLNL) or proton (LAMPF/WNR) linacs. In fact, total cross sections measured in this way are the only reasonably extensive body of neutron data in the range above 25 MeV available for testing effective interactions.

II. Effective Interactions

A major development in understanding elastic and inelastic nucleon-scattering reactions during the last few years has been the development of complex, energy dependent effective interactions suitable for use in a one-step folding-model description of the scattering potentials and form factors. These interactions range from parametrizations of the free nucleon-nucleon scattering amplitudes (e.g. Love-Franey)[1] useful in impulse-approximation calculations which are expected to be valid well above 100 MeV, to more complicated density-dependent interactions that take into account effects of the nuclear medium, which may be useful down to much lower energies, perhaps 10 MeV. Examples of the latter category are the Brieva-Rook[2] interaction, and most recently the Hamburg-Paris interaction of von Geramb *et al.*[3] These interactions begin with a potential that describes free nucleon-nucleon scattering, and include medium corrections by calculating the two-body scattering in the presence of symmetric, infinite nuclear matter. The results are applied to finite nuclei by use of a local-density approximation (LDA).

Extensive testing over a wide energy range (10-800 MeV) is required to validate the properties of the effective interactions and the accuracy of the LDA. Neutron elastic and inelastic scattering are important for testing the isospin-dependent parts of the effective interactions. As an example, a short paper[4] is appended to this outline showing how a careful comparison of neutron and proton elastic scattering on the same target (^{208}Pb) yields information on the quality of the isospin-dependent part of a particular interaction (Brieva-Rook).

It is important to note that the (p,n) analogue-state reaction evidently does not supply exactly the same information as neutron-proton scattering comparisons. For example, Brieva and Lovas[5] have shown that the Brieva-Rook isovector interaction underestimates the magnitude of the (p,n) reaction in the energy range of E_p = 25-45 MeV by a factor of two to four (Fig. 1). This result appears to be at variance with the proton-neutron comparison on ^{208}Pb (Ref. 4) and a similar study[6] on ^{54}Fe and ^{56}Fe, which indicate that the magnitude of the isovector terms is reasonable. Part of the difficulty may be that the large, negative Q-value in the (p,n) reaction leads to a significant energy mismatch in the initial and final states, with a consequent ambiguity in the energy at which the effective interaction is to be evaluated. Direct comparison of neutron and proton scattering at the same incident energy removes this ambiguity. The influence of the Coulomb potential on proton scattering, which also must be understood to isolate the isospin effects, is discussed below in connection with elastic scattering.

The problems found in reconciling elastic proton and neutron scattering with (p,n) have involved neutrons only up to 26 MeV, plus the few (but important) data[7] measured at 30 and 40 MeV. In addition to further data for systematic studies in the energy range currently available, it would be very desirable to have neutron elastic angular distribution data as high in energy as practicable (∿ 100 MeV), both for testing the isospin content of effective interactions and to find out whether the problems in reconciling (p,p), (n,n) and (p,n) become less severe with increasing energy.

Analyzing-power measurements for both elastic and inelastic scattering with polarized neutron beams, in comparison with proton scattering, shed light on the isospin-dependent part of the two-body spin-orbit force. Comparison of analyzing powers in ($\vec{n}$,n), ($\vec{p}$,p), and ($\vec{p}$,n) reactions would be interesting; to date there have been very few $(\vec{n},n)$ and $(\vec{p},n)$ measurements in an overlapping energy range. It would also be interesting to trace the development with energy of the imaginary part of the spin-orbit interaction; it is predicted[2] to be weak at low energies (10-50 MeV) and to be significant at medium energies (80-200 MeV).

In principle, comparison of neutron and proton inelastic scattering to non-normal parity states can give information on the isospin mixture of the spin-dependent part of the central effective interaction, since the proton and neutron interaction strengths are proportional to $v_\sigma + v_{\sigma\tau}$ and $v_\sigma - v_{\sigma\tau}$ respectively. However, v_σ is known[8] to be weak compared to $v_{\sigma\tau}$ over the entire energy range (up to 800 MeV), and this makes the expected differences between proton and neutron scattering small. Neutrons above 100 MeV would probably be required, to minimize the effects of multistep processes.

Improved knowledge of the isospin-dependent parts of the effective interaction, which can partly be obtained by the studies proposed here, should have an impact on other areas of nuclear physics and nuclear astrophysics. As an example, the properties of very neutron rich nuclei, which are not accessible in the laboratory, are important for r-process nucleosynthesis. Estimates of these properties (e.g. masses, sizes, neutron-proton density differences, optical-model transmission coefficients) come from extrapolations of shell-model and optical-model physics well beyond known nuclei. Better knowledge of the effective interaction which can come from scattering, such as the density dependence of v_τ, should improve the reliability of these extrapolations.

III. Elastic Scattering

The importance of neutron elastic-scattering measurements in the context of a microscopic folding-model description of the optical potential has largely been dealt with in the previous section. Here we comment mainly on Coulomb corrections and neutron-proton ground-state density differences.

Except for incident energies that are very high compared to the Coulomb barrier (which is roughly 14 MeV in Pb), the Coulomb potential is expected to induce significant modifications in the nuclear part of the optical potential seen by incident protons. These Coulomb corrections affect both real and imaginary parts of the potential, and comparison of neutron and proton elastic scattering has been the essential means of establishing the effects experimentally. Whereas the main features of the Coulomb correction in the real potential have been known for a long time[9] and are reasonably well understood in terms of nonlocality effects, strong evidence for a Coulomb correction in the imaginary potential has only recently been presented,[10] largely as a result of one case (^{40}Ca) for which a body of neutron angular-distribution data extends up to 40 MeV. Understanding the physical origin of the imaginary Coulomb correction is a topic of considerable recent theoretical effort. The approaches include a shell-model based picture of the imaginary potential,[11] in which several different contributions to the Coulomb correction can be identified; approaches based on nuclear-matter calculations[4,12] of the optical potential or effective interaction, together with the local-density approximation; and most recently (and perhaps surprisingly) a phenomenological treatment based on the Dirac equation.[13] Coulomb effects are most easily isolated by comparing neutron and proton scattering on self-conjugate nuclei, since neutron-excess ((N-Z)/A) terms are absent. However, Coulomb effects should be even more pronounced for heavy nuclei; the attached reference[4] shows that the correct choice of the method for including Coulomb effects must be made in the folding-model approach to achieve consistency between proton and neutron scattering on ^{208}Pb.

A much wider body of neutron scattering data than now exists will be necessary to isolate the role of Coulomb effects in the imaginary potential and to critically test the various theoretical approaches to understanding it. Data will be required from the light self-conjugate to the heavy nuclei. The energy range of greatest interest for this problem extends from roughly 10-60 MeV.

Further neutron angular-distribution data need to be taken in the range 5-40 MeV to map out the change in behavior of the imaginary part of the optical potential. Although the general idea of a transition between a surface-peaked to a volume form with increasing energy is well established from phenomenological analyses,[14] the details of the transition are still unclear, partly because insufficient data are available in the range 13-20 MeV where the volume component begins to be required in the analyses. Proton data are not satisfactory for such a study because the Coulomb-correction problems have not yet been fully resolved.

Since acquiring a systematic body of elastic distribution data with monoenergetic neutron beams in the range well above 100 MeV may not be practical in the near future, it would be interesting to extend white-source total cross sections up to several hundred MeV with a facility such as LAMPF/WNR. This would provide a useful constraint on the isospin terms in optical models in this energy range.

The principal ingredients in the microscopic folding model are the effective interaction and the density. For elastic scattering, the density is reasonably well known and the microscopic analysis mainly calibrates the effective interaction. However, in heavy nuclei there is evidence for slight differences between neutron and proton densities, e.g. from 800-MeV proton scattering.[15] At low energies (< 60 MeV), neutrons provide a more straightforward test of the effective interaction than protons, because they see mainly the proton density, which is well determined from electron scattering. On the other hand, incident protons are sensitive mainly to the neutrons, and the effects of assumptions concerning the neutron density can have a significant effect on the angular distributions.[4]

IV. Inelastic Scattering

Measurement of transition densities, and most particularly the separate identification of neutron and proton transition densities, is one of the principal aims of inelastic-scattering reactions. Information on neutron/proton transition density differences can be gotten by comparing results from a variety of probes, principally (e,e'), (p,p'), (n,n'), (α,α'), $(\pi^+,\pi^{+'})$, and $(\pi^-, \pi^{-'})$. The degree of sensitivity of the results to measurement with various pairs of probes has been studied by Bernstein, Brown, and Madsen.[16]

The particular advantage of comparing (n,n') and (p,p') reactions is that the reaction mechanism is the same for both probes, and thus uncertainties tend to cancel out in the comparison. At low energies (< 50 MeV), where the isovector interaction is still large, the sensitivity of the (p,p')/(n,n') comparison[16] is roughly the same as for $(\pi^+,\pi^{+'})/(\pi^-,\pi^{-'})$. Neutron/proton scattering has an obvious advantage in experimental cost. It should also be noted that nucleon scattering provides somewhat different information from pions: pions near the 3-3 resonance are strongly absorbed, and so tend to sample the tail of the nuclear surface more strongly than nucleons.

Neutron/proton scattering has been used for some time to study isospin effects in exciting low-lying 2^+ collective states.[17] The particular emphasis has been on the interplay between valence structure and core polarization. An example[18] of the state of the art is shown in Figs. 2 and 3. Both proton and neutron angular distributions were analyzed consistently with a parameter-free microscopic folding model using proton ground-state and transition densities consistent with electron scattering; simultaneous reproduction of both (p,p') and (n,n') requires a transition-density ratio $\rho_n/\rho_p \sim 0.8$, in agreement with a simple estimate of core-polarization effects in a single-closed-shell nucleus.[17]

To take full advantage of the neutron/proton technique, good-resolution neutron spectrometers at energies higher than the 26 MeV presently available are necessary. The microscopic reaction mechanism is believed to be better understood at the higher energies (> 25 MeV) than below; the Coulomb barrier places the relevant proton data in the higher energy range for high-Z targets; higher energies allow more details of the transition density to be sampled because of the greater momentum transfer; and a wider class of transitions (higher spins and higher excitation energies) becomes available. The upper energy limit that is desirable is set by a combination of resolution requirements and decreasing importance of the isospin effect (v_T weakening with energy); probably 60-90 MeV is the useful upper limit. Measurements with polarized beams should also be very interesting, as there is a large isospin-dependent term predicted in the two-body spin-orbit effective interaction, which persists[19,20] at the higher energies (e.g. 135 MeV).

A particularly interesting example of the effects that could be studied with higher-energy beams is the structure of giant resonances. Recent

π^+/π^- comparisons[21] for the isoscalar giant quadrupole resonance (GQR) in ^{118}Sn have suggested a ρ_n/ρ_p ratio approximately 50% larger than predicted by the Brown-Madsen schematic model.[17] Some further evidence for a probe dependence of the scattering to the GQR has been presented for alphas, protons, and electrons as projectiles.[22]

It has recently been noted[23] that a comparison of <u>three</u> probes (e.g. protons, neutrons, and electrons) can determine whether a given transition is predominantly isoscalar (as is assumed for most low-lying excitations) or isovector. Since neutrons and protons vibrate in phase for isoscalar transitions and out of phase for isovector, the relative sign of neutron and proton transition densities is different for the two kinds of excitations. A third measurement is necessary to detemine the sign. Neutrons would be useful for such investigations if beams of high enough energy were available to excite the region (giant dipole resonance and above) where isovector excitations are important. Although the energy required would be large (50-80 MeV), the resolution requirements would be less restrictive than for resolving closely-spaced low-lying states.

The physics to be learned from continuing investigations of low-lying states is concerned with testing the adequacy of shell-model and collective descriptions of these states. In the latter category, the distinguishing feature of the IBA-2 is the presence of both neutron and proton bosons;[24] it would be interesting to test predictions of the model about neutron-proton density differences by proton/neutron scattering. Shell-model descriptions of low-lying states often predict large neutron/proton transition density differences.[25] Core-polarization corrections, which are usually large, are in the direction to restore the hydrodynamic limit (ρ_n/ρ_p = N/Z).[17] Neutron-proton scattering comparisons may be viewed as a way to separate the core polarization from the valence (shell model) structure. As an example, for an excitation with nearly pure neutron valence structure such as ^{54}Fe(2_1^+) illustrated in Figs. 2 and 3, the valence structure will be seen predominantly by incident protons, whereas both probes sample the core-polarization component.

V. The (n,p) Reaction

The pioneering work on the (n,p) reaction near 60 MeV at the U.C. (Davis) cyclotron[26] has stimulated a great deal of interest in the (n,p) reaction. A "Workshop on the (n,p) Reaction at Intermediate Energies" was held at IUCF on June 7-8, 1983 to discuss the physics to be learned and the experimental techniques. It is becoming apparent that a wide-ranging study of this reaction will require high-energy neutrons (> 100 MeV), to minimize effects due to distortion and the energy mismatch between entrance and exit channels.[27]

Unlike inelastic scattering and (p,n), the (n,p) reaction on a target with isospin T produces excitations in the final nucleus with a unique isospin (T + 1). These states are also favored by the isospin geometry (unity compared with 1/(T + 1) for inelastic excitation of the target); there are no isoscalar transitions to sort out from the data; and the states are shifted downward from their analogs in the target nucleus by the Coulomb energy, with consequently narrower widths expected. Investigating the three components (T+1,T,T-1) of an isovector excitation by comparing the (n,p), inelastic, and (p,n) reactions on a series of isotopes would illuminate the role of isospin in these giant resonances. For example, the symmetry energy for a given giant multipole can be obtained from the energy splitting between the three components of the giant excitation.

Excitations of the $2\hbar\omega$ type, which should be accessible by (n,p), are particularly interesting because the radial node expected in their transition densities leads to a number of distinctive structure and reaction-mechanism effects.[28] For the 1^+ excitations of this type the Δ-hole contribution is expected to be substantially enhanced in the forward direction. Experimental verification of this would help sort out the various quenching mechanisms proposed for Gamow-Teller transitions. An example of an interesting reaction-mechanism effect for these $2\hbar\omega$ transition densities that peak at higher q (because of the radial node) is the effect of the exchange force. Such a transition density samples the even and odd force components in a way that leads to quite different results for the exchange terms in the (n,p) and (p,n) reactions. The tensor force is also much more important in certain (n,p) transition densities for which $\Delta L = 2$ dominates.

The (n,p) reaction is also of interest for zero-$\hbar\omega$ transitions because the effect of blocking can be studied; for Gamow-Teller transitions in light and medium-weight nuclei where blocking is still incomplete, the (n,p) reaction can provide important information to evaluate the Ikeda sum rule. Also, Δ-hole components may manifest themselves more strongly in (n,p) reactions in which the purely nucleonic configurations are partially blocked, than in (p,n).

VI. Preequilibrium Reactions

During the last 10 years an increasingly sophisticated set of models has been developed to address the magnitude and angular distributions of non-equilibrium continuum spectra induced by projectiles of several tens of MeV.[29-31] These include semiclassical models (e.g. exciton models and intranuclear cascade models), which include assumptions concerning intra-nuclear nucleon-nucleon scattering. More recently, quantum-mechanical models have been proposed by Tamura, Udagawa, and Lenske,[32] and by Feshbach, Kerman, and Koonin.[33] The models and theories that have been proposed to date should be able to reproduce magnitudes and angular distributions of the non-equilibrium component of continuum spectra induced by nucleon-induced reactions over the incident energy range 15-200 MeV, if the essentials of the physics have been properly incorporated.

Neutron-induced reactions are particularly important as a test of pre-equilibrium reaction mechanisms because they avoid complications due to isospin mixing. Neutron induced reactions on targets with isospin $(T, T_z = T)$ uniquely involve $T + 1/2$ channels, whereas the spectra from proton-induced reactions depend on the degree of mixing between the $T + 1/2$ and $T - 1/2$ channels, which is at present poorly known. If the reaction mechanism is understood, comparison of spectra induced by protons and neutrons can give information on the degree of isospin mixing in pre-compound reactions. Another advantage of (n,n') reactions is that they avoid complications of Coulomb distortion on the angular distributions.

At present, (n,n') spectra are available only at 14 and 25 MeV, which is inadequate for a very thorough test of the models. Data with neutrons up to 200 MeV would be useful; requirements on resolution are obviously minimal for continuum spectra.

VII. Radiative capture

In the energy range below roughly 30 MeV, radiative capture to the ground or other resolvable states of the residual nucleus occurs principally by direct capture and by the excitation of giant resonances.[34] Electric dipole radiation is dominant, and other multipolarities (mainly E2) are readily identifiable only as interference terms with E1. Although neutron capture experiments are more difficult than proton capture, it has long been recognized that their lack of charge gives them a special advantage in studying collective E2 excitations because the direct-capture E2 component is nearly absent. This feature has been exploited by measuring excitation functions of the fore-aft asymmetry of neutron-capture angular distributions; resonance-like behavior has been observed, and associated with both isoscalar and isovector giant quadrupole resonances.[35] Proton capture measurements on the other hand, exhibit a fore-aft asymmetry that usually increases steadily with energy and is almost entirely explainable as E1 radiation interfering with E2 direct capture. A difficulty even with the neutron-capture measurements in extracting reliable parameters of the E2 giant resonances is the fact that the reaction mechanism is imperfectly understood. The main problem is the imaginary part of a form factor for excitation of the giant resonances; its origin, radial shape, energy dependence, and dependence on the nature of the various giant resonances is not well known. Extension of polarized-beam measurements to higher energies (up to 30 MeV) may help in refining the reaction models.

Well above 30 MeV, the physics is significantly different. Giant-resonance excitation is less important though still present, and meson exchange currents play a role. A particular capture model that includes such exchange currents (Gari and Hebach[36]) suggests that they may be important even as low as 60 MeV (see Fig. 4). The treatment of Gari and Hebach includes three effects: SM (shell model, related to direct capture); COR (correlation, which is the effect of giant resonances); and EXC (the exchange-current contribution). What is interesting for the present purposes is that these three coherent terms contribute differently to proton and neutron capture (Fig. 4); therefore, neutron capture measurements may be useful in untangling them. Neutron capture measurements in the range 50-100 MeV are certain to be difficult, but should be possible in selected cases; an important problem is an efficient gamma spectrometer with sufficient resolution to distinguish at least ground-state gammas. Such measurements might be made either with a monoenergetic neutron beam, or possibly with a white-source spectrum using time-of-flight for energy identification.

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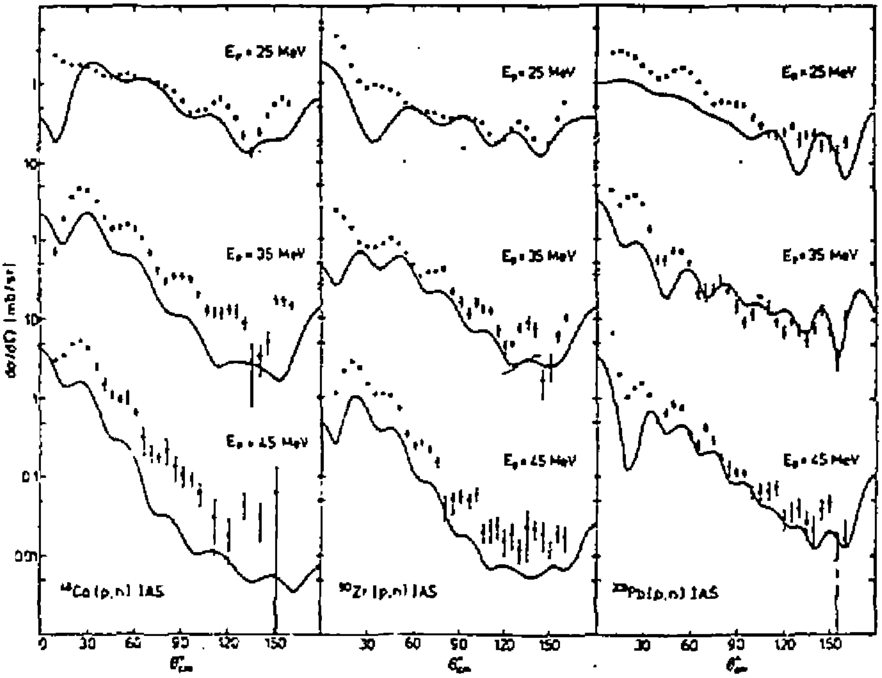


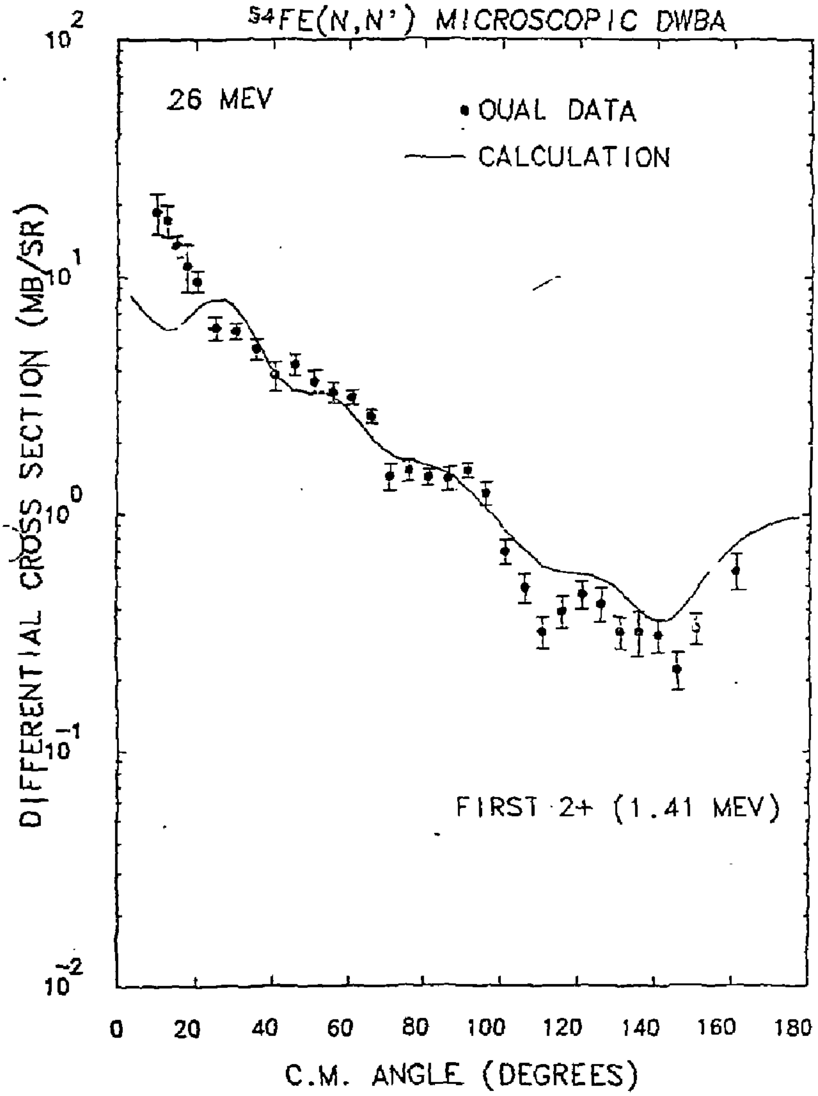
Fig. 2. Comparison of the prediction of the theoretical Lane potential with the experimental cross section [22].

all the disagreement could be attributed to $\rho_n - \rho_p$. It is even less likely that the diagonal terms of the optical potential could be blamed.

To seek for the explanation systematically, we now enumerate the approximations that may affect (p, n̄) more than elastic scattering.

At the stage of calculating the effective interaction the first idea at hand is that the nuclear matter used to calculate t is symmetric. It is obvious that the asymmetry potential of a finite nucleus of asymmetry α can be calculated from the *optical potential* of nuclear matter as in previous works [15-17]) only if the nuclear matter has the same α. It is also clear, however, that 30–50 MeV above the Fermi level the effective *nucleon-nucleon interaction* can hardly feel a small difference in the neutron and proton occupation numbers. This assumption is supported by the fact that essentially the same phenomenological effective interaction is capable of accounting for (p, n̄) scattering from nuclei of various asymmetry parameters α [22, 23]). A counterpart of this statement can be said about our case: the discrepancy does not seem to depend upon α, albeit, including ^{58}Ni, which we have also analysed, our asymmetry parameters are in the range 0.13–0.21. In the light of the success of this effective interaction in reproducing elastic and inelastic scattering, these arguments make us conclude that the use of symmetric nuclear matter is not the main source of the disagreement.

Fig. 1



54FE(N,N') MICROSCOPIC DWBA
26 MEV
• OUAL DATA
—— CALCULATION
FIRST 2+ (1.41 MEV)
DIFFERENTIAL CROSS SECTION (MB/SR)
10^2
10^1
10^0
10^-1
10^-2
0
20
40
60
80
100
120
140
160
180
C.M. ANGLE (DEGREES)

Fig. 2

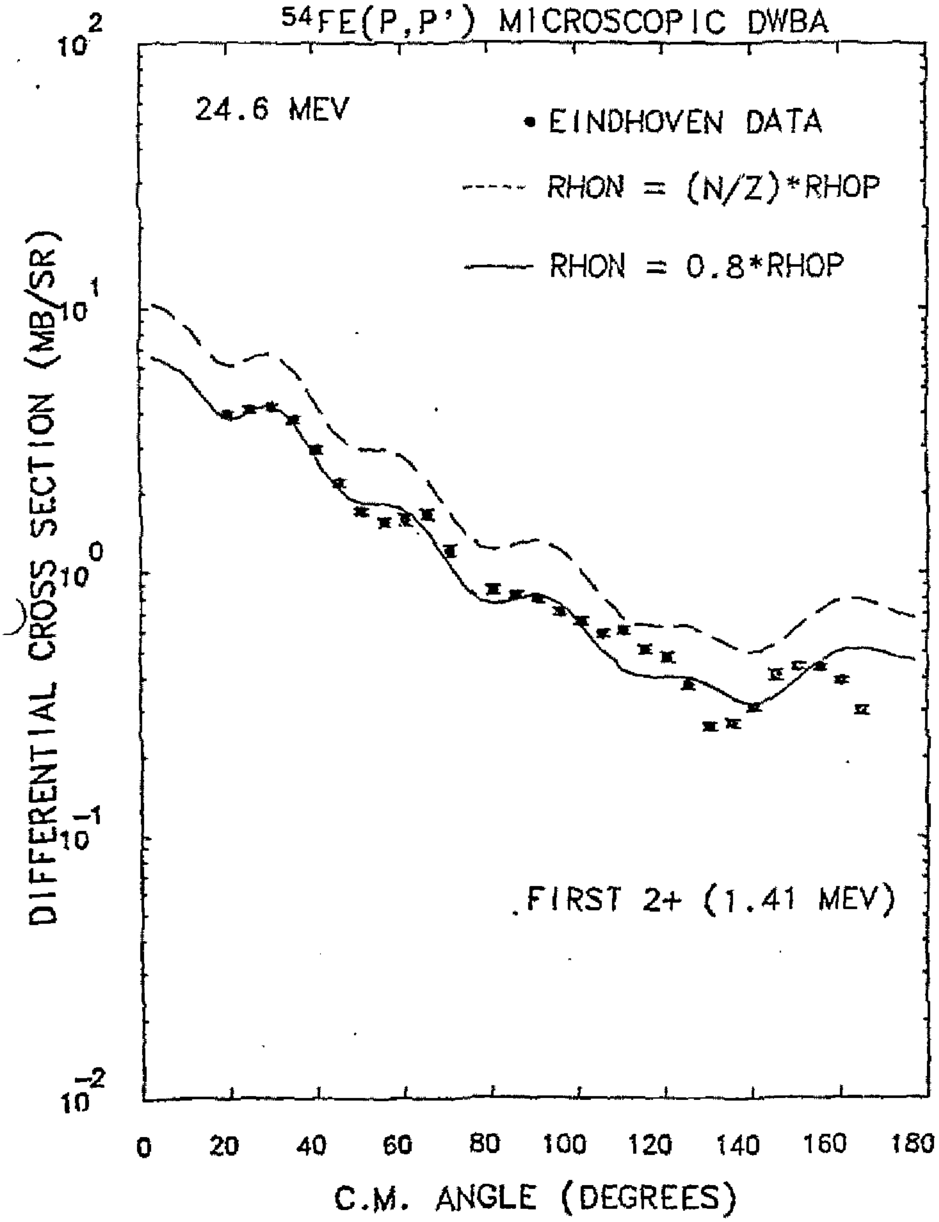

^{54}FE(P,P') MICROSCOPIC DWBA
24.6 MEV
• EINDHOVEN DATA
----- RHON = (N/Z)*RHOP
—— RHON = 0.8*RHOP
FIRST 2+ (1.41 MEV)
DIFFERENTIAL CROSS SECTION (MB/SR)
10^2
10^1
10^0
10^{-1}
10^{-2}
0
20
40
60
80
100
120
140
160
180
C.M. ANGLE (DEGREES)

Fig. 3

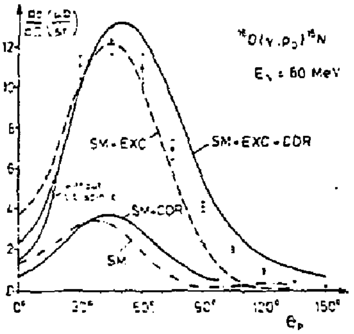


Fig. 10. Angular distribution of the reaction $^{16}O(\gamma,p_0)\,^{15}N$ for E_γ = 60 MeV. The experimental values are taken from ref. [23]. SM: shell model contribution of the one-body nucleonic-current (with and/or without the one-body spin current). EXC: meson-exchange contribution. COR: correlation-contributions of initial and final states

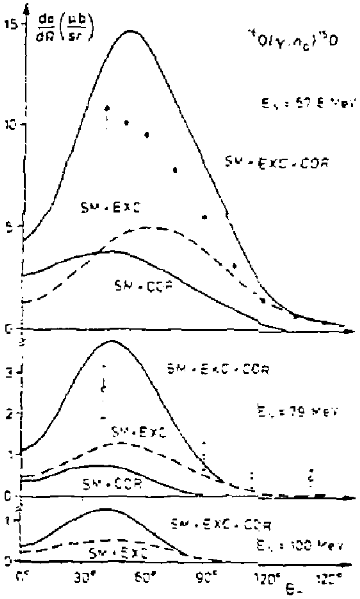


Fig. 13. Angular distributions of the reaction $^{16}O(\gamma,n_0)\,^{15}O$ for the photon energies E_γ = 57.8 MeV, 70 MeV and 100 MeV. The experimental points are from ref. [24] (○) and from ref. [26] (●)

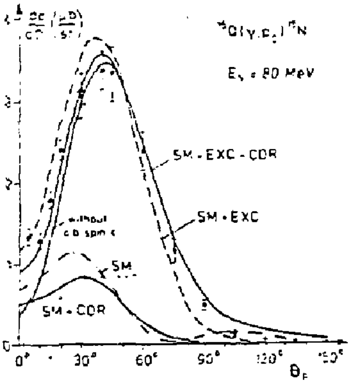


Fig. 11. Angular distribution of the reaction $^{16}O(\gamma,p_0)\,^{15}N$ for E_γ = 80 MeV. The experimental values are taken from ref. [23] (●) and from ref. [26] (▲)

neutrons

protons

Fig. 4. A selection of experimental results for neutron and proton ~~[illegible]~~ angular distributions from photodisintegration of ^{16}C, leaving the ~~[illegible]~~ residual nucleus in its ground state. Model calculations are also shown, illustrating that the neutron and proton reactions are sensitive to the various physical processes in different ways.