MICHIGAN STATE UNIVERSITY

CYCLOTRON LABORATORY

NEUTRON-NUCLEUS REACTIONS

SAM M. AUSTIN

Summary Talk presented at the Conference on
"Neutron Nucleus Collisions-a Probe of Nuclear Structure"
Glouster, Ohio, September 5-8, 1984
(American Institute of Physics, New York, in press)

NOVEMBER 1984

MSUCL-493

SUMMARY AND OUTLOOK--EXPERIMENTAL

Sam M. Austin*
National Superconducting Cyclotron Laboratory
and
Department of Physics and Astronomy
Michigan State University
East Lansing, Michigan 48824

INTRODUCTION

This Conference was devoted to recent progress and future directions of research in the study with neutrons of nuclear properties and structure; it also included a Workshop in Experimental Techniques. My talk will reflect this emphasis, summarizing both past work and opportunities for the future. I will also comment briefly on the technical capabilities and facilities needed to make this research possible. These comments are my personal views, but I hope that they might serve to focus discussion of future facility development.

An unusual feature of the Conference is that there are two summarizers: Claude Mahaux and me. We have not attempted to co-ordinate our comments, except that he will emphasize theoretical topics and I experimental topics; this reflects a point of view that real coordination is impossible anyway and that something that both of us find important probably warrants double emphasis.

ELASTIC SCATTERING

Much progress in the study of elastic neutron scattering has been made in the past few years, stimulated by the availability of cross section data at higher energies from Ohio University and MSU (temporarily) and of asymmetry data from TUNL. This work was described in detail at the Conference.

Howell presented the results of measurements of cross sections and analyzing powers on ^{32}S and ^{28}Si and their phenomenological analysis in terms of spherical and deformed optical models. The results shown in Fig. 1 give an indication of the high quality of the cross section data that can be obtained with modern facilities. Asymmetry data on many other nuclei were discussed by Walter. Cross sections above 26 MeV are available only for the few nuclei, mostly with N=Z, studied with the MSU facility and this facility no longer exists. Asymmetry data are not often available above 17 MeV.

These are significant limitations which should eventually be removed. Nevertheless, sufficient information is now available to extract the global features of the phenomenological optical model

---

* Research supported by the U.S. National Science Foundation

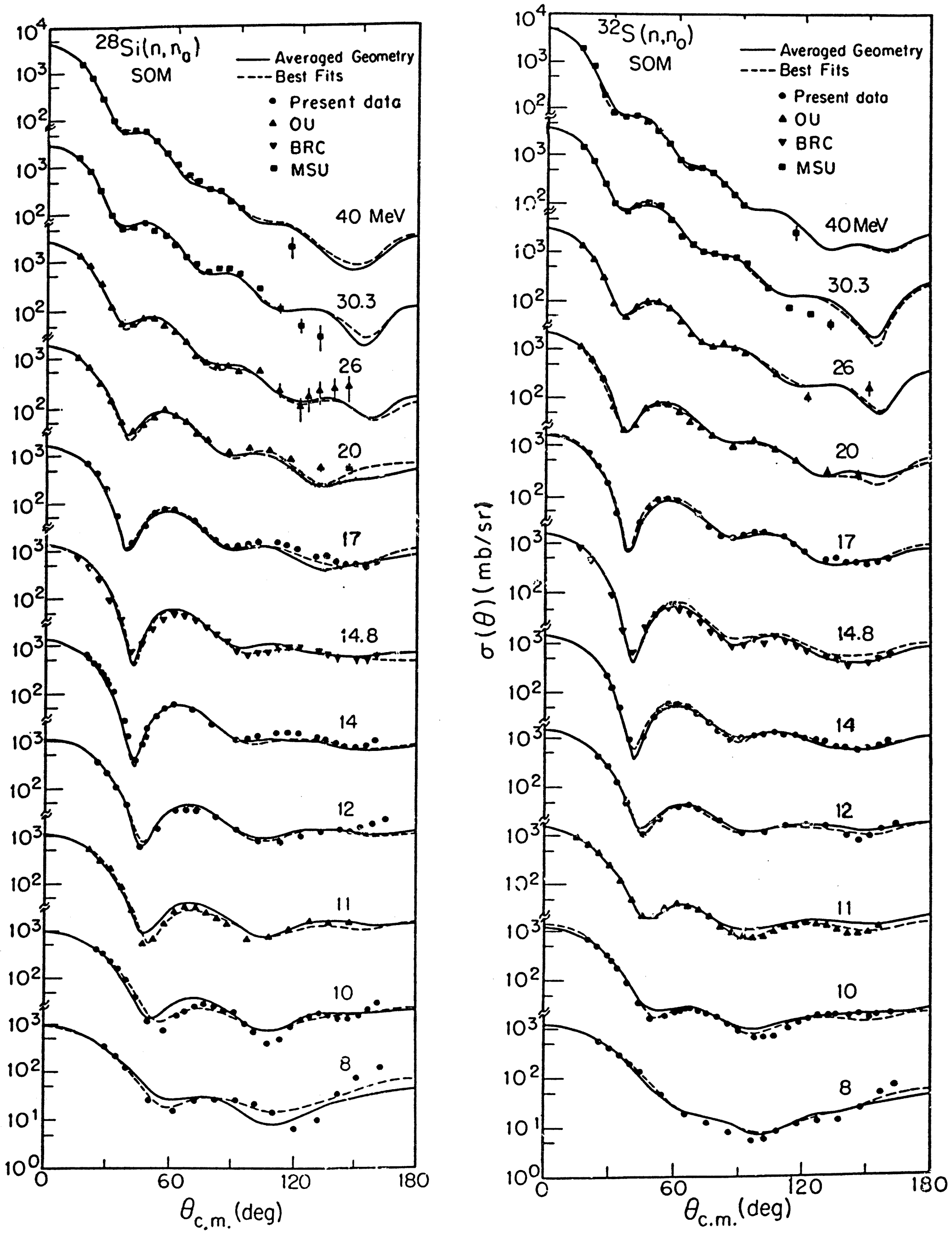

Fig. 1. Cross sections for the elastic scattering of neutrons from ^{28}Si and ^{32}S. Data are from TUNL, Ohio University, MSU and Bruyeres-le-Châtel. (From the paper by C. Howell).

potential(OMP) for neutrons: the transition from surface to volume absorption is clear and there is evidence that the spin-orbit potential must contain an imaginary part of about 0.7 MeV(see paper DB6 by Walter, et al.). Global potentials have been obtained by Rapaport; more recent work was reported by Howell, Walter and Delaroche, et al. at this Conference. Dietrich, Von Geramb, Haouat, et al. and Lagrange, et al. showed that the data test microscopic or semi-microscopic descriptions of scattering and of the effective interaction.

A long term interest in nucleon scattering has been to determine the isovector or symmetry potential which describes the difference between nuclear(non-Coulomb) scattering of neutrons and protons from the same nucleus. The strength of this potential affects our understanding of all nuclear excitations in which neutrons and protons move differently(the best known of such excitations are the giant-dipole and Gamow-Teller resonances). In the Lane Model, the isovector potential U_1 is given by

$$U_1 = (U_p - U_n)/2\varepsilon \tag{1}$$

where the U's are the optical potentials for protons and neutrons and $\varepsilon = (N-Z)/A$. The isovector potential $U_1 = V_1 + iW_1$, and the OMP $U = V + iW$, both have real and imaginary parts as noted. Thus it would appear to be straightforward to obtain U_1 given such neutron and proton potentials. However, an important problem remains: how to correct for the effect of the Coulomb interaction felt by the protons. While much progress has been made in understanding the Coulomb Correction(CC), much remains to be done. For this reason, our knowledge of the isovector potential is far from complete; since much future work will address this problem I will discuss it in some detail.

THE ISOVECTOR POTENTIAL AND THE COULOMB CORRECTION

If one assumes that nuclear forces are charge symmetric, then the Coulomb Correction for an N=Z nucleus is given by

$$\Delta U_{cc} = U_p(E) - U_n(E) \tag{2}$$

The real part of the CC arises from the fact that the incoming proton is slowed by the Coulomb field and feels the (larger) attraction characteristic of lower energy particles in the local OMP. Reasonable estimates of dV/dE and of the average slowing down of the proton yield the usual real CC of $\Delta V_{cc} \approx 0.4Z/A^{1/3}$. Comparisons of real potentials for neutron and proton scattering verify this prediction with the experimental values of the coefficient generally lying between 0.4 and 0.5.

The origin of the imaginary part of the CC is more complex. Since the imaginary potential arises from second order processes, different excitation of levels in the intermediate system has important effects. These excitations are affected, for example, by different Q values for the (n,p) and (p,n) reactions, the inaccessibility of high-lying collective states because of the Coulomb repulsion, and the longer time the proton spends in the neighborhood of the nucleus. Osterfeld presented estimates of these effects for the case of ^{40}Ca and showed that the individual effects are large, but are energy dependent and almost cancel near 30 MeV. A comparison of available imaginary potentials for neutron and proton scattering by Rapaport verified this prediction for ^{40}Ca. However, it does not appear to apply generally. More recent work by the MSU group and work reported by Howell at this Conference indicates that the imaginary CC remains large at 30 MeV for ^{28}Si and ^{32}S. There is thus no general phenomenological picture that allows us to determine the imaginary CC from the available measurements on the N=Z nuclei. Theoretical calculations are seldom available and may not yet be reliable for such detailed predictions; Osterfeld's results underestimate the imaginary potential by roughly a factor of two. This situation greatly complicates the extraction of the imaginary isovector potential.

We have noted that U_1 can be obtained by comparing the OMP's describing neutron and proton scattering from the same nucleus. However, until recently neutron scattering data have been insufficient to follow this procedure. Instead values of V for proton scattering on a series of nuclei are plotted as a function of ε and, following Eq. 1, the slope of the curve yields V_1. Hodgson pointed out at this Conference that in fact the potentials are often not a smooth function of ε; they may break into families characterized by the isospin T or the nuclear charge Z. The reason for this behavior is not understood but might be related to the usual assumption that the geometrical parameters have a simple dependence on A. It may be possible to remove this fine structure by introducing shell effects and experimental information on nuclear radii and it will be interesting to find out if such procedures are possible. But it appears to me that comparison of neutron and proton potentials is a more reliable procedure and should be used whenever data are available.

The situation is still less clear for W_1 because the imaginary CC is not known independently. It may be possible to fix V_1 using Eq. 1 and then to determine W_1 and the imaginary CC simultaneously by requiring a fit to both scattering and the Lane-Potential-related (p,n) cross section. Sufficient data to carry out these procedures over a substantial energy range are available in only a few cases. It seems that direct inclusion of coupled channel effects may reduce the importance of the imaginary CC. (Hansen, et al.)

I note here that the much used potential of Patterson, Doering and Galonsky was obtained using CC's which in light of our present knowledge are inaccurate.

MODEL INDEPENDENT ANALYSES

At this conference microscopic theories of scattering were often compared directly to experimental data, a procedure that seems to have substantial disadvantages. A theory might predict a cross section which is statistically very improbable, but one is often unable to determine what is wrong: whether the imaginary potential is too weak or the real potential is too strong or the geometry is incorrect or what. It would seem more informative to make the comparison in terms of potentials: theoretical vs. phenomenological.

Another difficulty then arises: when one fits the scattering data to obtain an OMP, one assumes a potential shape, which might not bear a detailed resemblance to nature, and which might bias the result of the analysis in an unphysical and uncertain fashion. This problem can be avoided by adopting a model independent procedure, similar to that used for electron scattering. In this approach, the potential shape is expanded in an appropriate basis and the coefficients of the expansion terms are fixed by fitting the data. This yields an estimate of the potential and its uncertainty at each radius without assuming a specific radial form. I.e., one has an unfiltered report of the implications of an experiment.

An immediate question is whether the procedure will work as well for nucleons as it does for electrons. After all, three separate potentials, real, imaginary and spin orbit, must be fixed by the data, rather than a single charge density. However, the measurements span a similar range of momentum transfer, are of comparable accuracy and more types of data are available: $\sigma(\theta)$, $A(\theta)$ and eventually the spin rotation function. All in all, in seems likely that this approach will work. It has already been used for alpha scattering and by Tornow, et al. for neutron scattering near 11 MeV on ^{40}Ca. The resulting real potentials for this case differ significantly from a Woods-Saxon shape.

INELASTIC SCATTERING

During the past few years it has become clear that comparisons of scattering with different probes can yield information about the isospin structure of nuclear states if these probes interact differently with the protons and neutrons of the target nucleus. While these differences are well known for pions, the nucleons can serve a similar role and with comparable sensitivity. This sensitivity occurs because the central isovector part(v_T) of the two nucleon interaction is large for energies in the 40 MeV range yielding an interaction between unlike nucleons 3-4 times bigger than that between like nucleons. Thus neutron(proton) projectiles are sensitive mainly to protons(neutrons) in the target.

Madsen surveyed the results from comparisons of neutron and proton scattering carried out at bombarding energies below 26 MeV, mainly by the Ohio University group. In the case of single closed shell nuclei the ratio of neutron to proton matrix elements for low lying 2^+ states is found to be greater than N/Z(less than N/Z) for valence neutrons(valence protons). For open shell nuclei no definitive difference in the matrix elements is observed. These results are qualitatively understood in terms of schematic models. Alarcon, et al. presented the results of a comparison of neutron and proton scattering near 25 MeV which yields the relative sign of proton and neutron matrix elements for low lying 2^+ states in ^{34}S; the results disagree with the shell model for the second 2^+ state.

For the future, it appears likely that this technique will be extended to weaker, more complex states and to more highly excited states. A microscopic analysis based on effective charges in the shell model might yield information on the orbit dependence of effective proton and neutron polarization charges. Since reliable shell model wavefunctions are necessary, these studies might begin in the 1s0d shell as a test case and then move to heavier nuclei where they will provide unique information. When higher energy neutron sources are available, comparisons of neutron and proton scattering might be able to probe the isospin structure of the giant multipole excitations; preliminary work has been reported using pionic probes. Still more speculative would be the study of spin excitations, for example those to 1^+ states. Sensitivity to their isospin structure would depend on the relative size of the like-nucleon and unlike-nucleon interactions in the S=1 channel. While one expects the unlike nucleon interaction to be the weaker this has not yet been established experimentally.

OTHER STUDIES

Several studies somewhat outside the main line of the conference were very interesting. McEllistrem showed that scattering at low energies, a few MeV, is sensitive to the nature of the assumed coupling in deformed nuclei and may serve to determine this coupling.

Johnson described work of the ORNL group in which resonances observed in the total cross section for low energy(<1 MeV) neutrons from ORELA were analyzed to determine their spin and parity. Averages over these resonances then fix the optical model parameters in a given ℓ channel. One might not obtain a meaningful potential from a single nucleus, but systematic studies can yield interesting information. Results to date involving about eight nuclei with A = 30 to 208 yield real potentials in general agreement with those obtained from scattering data. The imaginary potential differs substantially from nucleus to nucleus; this is not understood in detail but is generally ascribed to nuclear structure effects. There is also some indication of ℓ-dependent effects; such effects have been invoked previously by Mackintosh and his collaborators to understand proton scattering data from ^{40}Ca and ^{16}O in the 25 MeV region.

Studies of elastic neutron scattering from ^{208}Pb and Bi^{209} in the few MeV region were described by Finlay. Data from Ohio University and Studsvik seem to show a significant anomaly in the real part of the OMP near the Fermi surface; the results are in good agreement with the proton data(after adjustment for the CC and the symmetry energy) where they overlap, and extend the systematics to very low energy where the proton data are dominated by Rutherford scattering.

Studies of the (n,p) reaction leading to giant resonances have been carried out over the past few years at Davis. While the available energy is low(65 MeV) and the signal to noise ratio is hence marginal, these data are our only source of information on these interesting reactions. Castaneda reported on the observation of the analog of the ^{40}Ca giant dipole resonance as observed in (n,p). Ford presented 0° data on several nuclei and apparently has observed the isovector monopole giant resonance for ^{90}Zr.

Finally, several interesting talks discussed the ways in which neutron reactions enter into astrophysical processes, particularly in the creation of the heavy elements and their use for astrophysical diagnostics. Truran, Mathews and Schramm discussed the nature of the slow and rapid neutron capture processes and their dependence on nuclear properties. Winters discussed measurements of radiative neutron capture and inelastic scattering which allow one to extract the age of the elements from the Re/Os chronometer pair. A value of 17×10^9 yrs for the age of the Universe results. This is compatible with values from the U/Th chronometer taking into account new information on the strength function for Gamow-Teller β decay obtained from (p,n) and other studies.

FUTURE DIRECTIONS

The rapid progress of neutron physics during the past few years has been based on the development of advanced detectors and ion sources, combined with pushing the present generation of accelerators close to their ultimate capabilities. It seems clear that new experimental facilities are necessary if the field is to advance. Much of the Conference was devoted to discussions of the future directions of neutron physics, so one could reasonably judge what facilities might be most useful, and to an evaluation of anticipated technical capabilities. A summary of these discussions follows.

SOME INTERESTING PHYSICS FOR THE FUTURE

This is meant to be a sampling of research opportunities I find interesting, to give a flavor of the field. When a topic has been discussed earlier, I simply list it here. Other topics are accompanied by a brief comment.

The Nuclear Mean Field: The nuclear mean field plays a fundamental role in our understanding of nuclear structure and reactions, yet our knowledge of the field and particularly its isospin nature is at best partial. Some research opportunities:

1. Determine the global features of the OMP over a wide energy range by studies of scattering and model independent analyses.
2. Determine the values and energy dependence of real and imaginary parts of the isovector potential from neutron-proton comparisons. An idea of what should be possible can be obtained from Fig. 2, where proton and neutron OMP's for ^{208}Pb are compiled. Subtraction of these potentials, using Eq. 1, should yield the magnitude, shape and energy dependence of U_1 (assuming the CC can be made accurately).

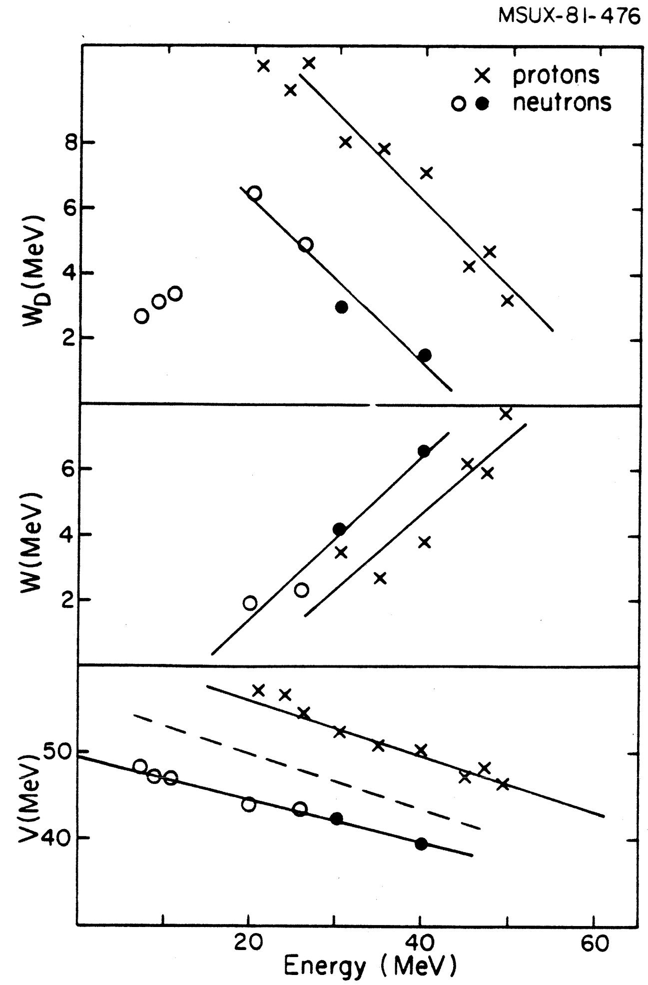

Fig. 2. Values of the OMP for proton and neutron scattering from ^{208}Pb. (R. Devito, et al.).

3. Develop a theoretical and experimental understanding of Coulomb effects and the Coulomb correction.

4. Determine or limit the amount of charge symmetry breaking(CSB) in the mean field. CSB is not ruled out by the two nucleon data at the percent level, and might be(at least partially) responsible for the Nolen-Schiffer(or Coulomb energy) anomaly. Present neutron and proton data on N=Z nuclei are marginally adequate to put limits on CSB at the requisite level; improved facilities covering a wider energy range could almost surely do so.

5. Elucidate the nature of relativistic effects in nucleon scattering, especially on the isovector and spin orbit parts of the field.

A general study of these phenomena will require a comparison of proton and neutron elastic scattering: cross sections, asymmetries and perhaps spin rotation functions in the 25 to 100 MeV range.

The Effective Interaction: Scattering provides the flexibility in choice of observables to study the effect of the nuclear medium on the interaction between two nucleons at different densities, momentum transfers and energies. Von Geramb presented evidence that the connection with theory will be particularly clean at energies near 60 MeV, since the difficult-to-treat exchange contribution is expected to be small there. A comparison of proton and neutron scattering will provide information on the isovector part of the interaction. Most of these studies will probably be done best in the 25 to 100 MeV range where the reaction mechanism is reasonably well understood and resolution will be adequate to resolve a variety of nuclear states. Studies of the spin dependent part of the effective interaction may be particularly interesting above 100 MeV where spin effects become dominant in certain reactions. Spin transfer $(\vec{p},\vec{n})$ measurements such as those described by Taddeucci may be particularly important for this purpose.

Isospin Structure of Nuclear States: This section concerns spin-independent excitations.

1. Study the isospin structure of the giant isoscalar resonances.
2. Determine the isospin structure of non-collective states.
3. Measure transition densities of excited states, and determine their isospin structure. Carr showed that neutrons at energies near 60 MeV are particularly sensitive to the nuclear interior and are generally superior to pions for probing the interior(See Fig. 3).

For these experiments resolution will often be important. In addition one must limit the energy so that differential sensitivity to neutrons and protons remains large. An energy range up to 75 MeV, reduced when resolution is important seems desirable. Energies near 60 MeV may be especially useful.

Spin Excitations: These will mostly involve isovector excitations. Then, since $V_{\sigma\tau}/V_{\tau}$ increases with energy, higher energy, at least up to 200 MeV, generally yields greater sensitivity. On the other hand some of the studies listed require good resolution, which is hard to obtain at the high end of the range.

1. Study giant Gamow-Teller(β^+) strength using (n,p) reactions. If 2p-2h excitations are responsible for a significant part of the quenching observed in (p,n) reactions, then (n,p) transitions will not be entirely Pauli blocked and (n,p) cross sections will be able to provide information on the 2p-2h excitations. For $N \approx Z$ nuclei (n,p) strength will be concentrated in low lying states; the magnitude of this strength in nuclei near Fe has important implications for supernova evolution and explosive nucleosynthesis.

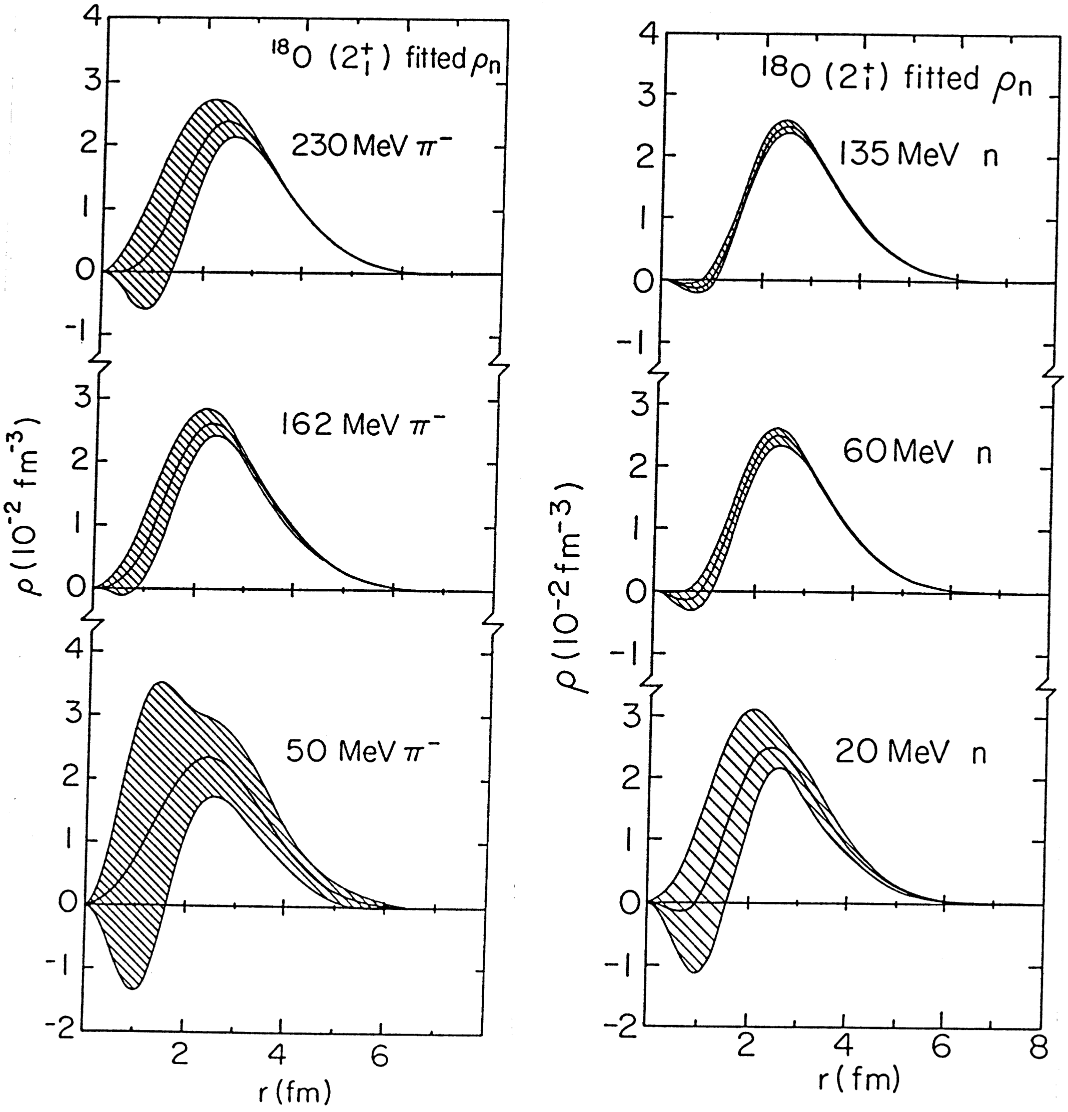

Fig. 3. Neutron densities and error envelopes for $^{18}O(2_1^+)$ determined from pion and neutron scattering pseudodata. (From the paper by J. Carr).

2. Study Gamow-Teller transitions to isolated states by (n,p) reactions--Strength to the $T_>$ states is especially sensitive to configuration mixing (see the paper by Brown) and should serve as a stringent test of shell model calculations.

3. Double beta decay--It has been pointed out that a combination of (p,n) measurements on a double beta decaying nucleus and (n,p) measurements on its daughter can yield upper limits on the rates for double beta decay. These are valuable since shell model calculations appear

to overestimate decay rates greatly. Brown applied shell model calculations to ^{48}Ca in a similar spirit.

4. $(\vec{p},\vec{n})$ measurements--Spin transfer is a specific probe of spin flip strength and Taddeucci showed it can yield otherwise unobtainable information about the reaction mechanism for charge exchange reactions and the location of spin-flip strength. Such measurements should help unravel the nature of spin transfer strength in the continuum above the giant Gamow Teller resonance.

5. High resolution (p,n) measurements--A dedicated facility would permit measurements with resolutions under 100 keV at energies up to 100 MeV. Such measurements would be useful for a variety of nuclear structure studies. For example, for the double beta decay studies mentioned earlier and for measurements of the longitudinal response function in $0^+ \rightarrow 0^-$ transitions as described by Orihara. These transitions should yield information about the importance of pion-condensate-precursor effects in nuclei.

It appears that an important program of spin-excitation studies leading to isolated states would be accessible with neutron energies in the 50-100 MeV range. Some important studies involving giant resonances require 100-200 MeV so as to increase the signal to noise ratio for these broad excitations.

EXPERIMENTAL POSSIBILITIES

During the Conference much discussion was devoted to new techniques and facilities, both at a Workshop on Experimental Techniques and in invited and contributed papers. The availability of facilities for carrying out various types of experiments was summarized by Zafiratos using the graph shown in Fig. 4; on this graph the circles are contours of energy and the solid lines indicate present capabilities. Compared to what is needed to carry out the program outlined above, present limitations are serious.

New facilities are coming on line at Studsvik and Uppsala. Olsson described improvements in the Studsvik facility which permit high resolution ($\Delta E \approx 0.5$ MeV) scattering measurements up to 22 MeV. Conde discussed the capabilities of the rebuilt cyclotron at the Gustaf Werner Institute. This facility will have intensities in the 10 μamp range up to 200 MeV and will carry out a program of (n,p) reactions with a resolution of 1 MeV at 200 MeV energies. Further details are given in the Facility Summary attached to these proceedings.

Friesel discussed accelerators for the production of intense neutron beams with energies up to 200 MeV. He concludes that the IUCF facility could be upgraded to an

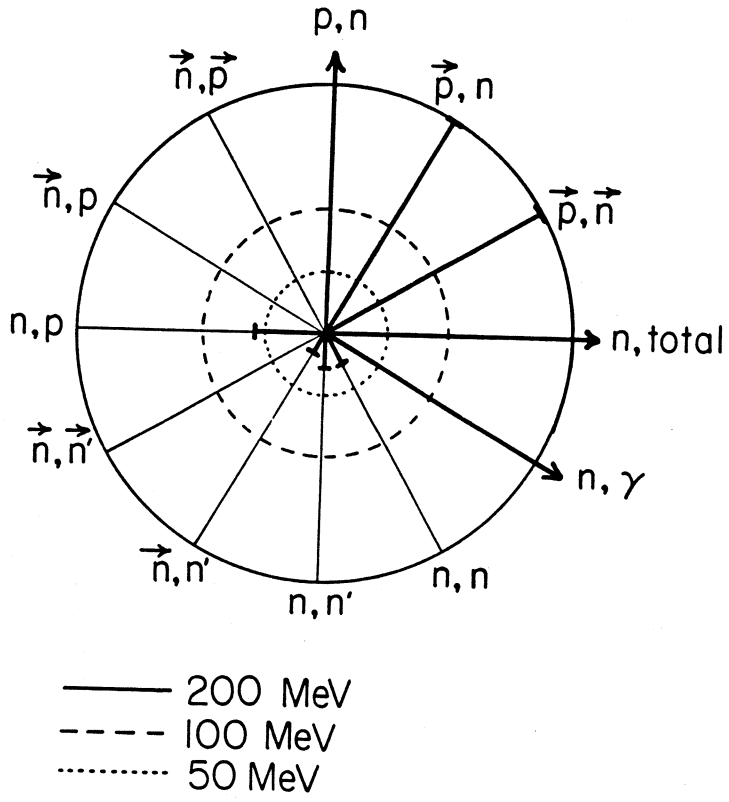

Fig. 4. Energies available for studying various reactions with present facilities. (From the paper by C. Zafiratos.)

intensity near 10 μamperes without extensive changes, but that an increase to 100 μamperes would be expensive. In general, construction of variable energy cyclotrons with milliampere beams is difficult, because of space charge effects and the requirement of high extraction efficiency to avoid radiation damage. It may be difficult to build a variable energy cyclotron for 1 milliampere beams; if this capability is required, Friesel concludes that other approaches should be examined.

Ancillary equipment was also discussed. Finlay showed that facilities employing rotating beam swingers such as that at Ohio University were well adapted to measurements at energies up to at least 75 MeV. Dietrich and Clegg pointed out that such beam swingers were consistent with the use of polarized beams. Goodman discussed beam swinger designs that would be useful at higher energies. Brady described the facility for 60 MeV $(\vec{n},\vec{p})$ studies at Davis and techniques for working at higher energies. He concludes that studies at 200 MeV are feasible with beams in the 10 μampere range, noting that technical advantages yield "nearly an order of magnitude in count rate (at a given energy resolution) in going from 60 to 200 MeV." Taddeucci discussed the feasibility of spin transfer measurements and concluded that $(\vec{n},\vec{p})$ measurements are 10^4 to 10^6 times harder than $(\vec{p},\vec{n})$ measurements which with present techniques take typically a few to 10 hours per point.

SUMMARY

In listening to talks and participating in discussions at the Conference, I came away with a strong feeling that studies of neutron interactions with nuclei have progressed greatly during the past few years and have an exciting future in store. An important question for the field is the direction of facility development which will allow one to realize this future. It seems clear that an accelerator with energy in the range of 50 to 100 MeV and beam currents of ten or tens of μamperes would support a strong physics program. A more precise specification of energy and intensity is yet to be made and could be the subject of a technical workshop. However, such a facility will not be very useful for study of giant resonance phenomena--energies of well above 100 MeV are required. It seems that an upgrade of the IUCF to yield beam currents at the 10 μampere level might be cost effective. An investment in spectrometers for (n,p) and related studies is probably desirable and useful even at present IUCF intensities.