(n,p) and (n,d) Reactions at 152 MeV*

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The (n,p) reaction on the nuclei ^{6}Li, ^{7}Li, ^{9}Be, ^{12}C, ^{27}Al, ^{40}Ca, and ^{51}V has been studied at 152 MeV. The ground-state transition is clearly detected for ^{6}Li, but is not resolved for the other nuclei. In all nuclei, a strong excitation with a Q value of about -25 MeV is reported. This is interpreted as an excitation of giant collective multipole resonances. In the lightest elements there is also strong evidence for quasielastic scattering for angles around 20°. Comparisons are made with the medium-energy (p,n) and (p,p') reactions. Some results are also reported for the (n,d) reaction on ^{6}Li, ^{7}Li, and ^{12}C.

I. INTRODUCTION

MANY proton-induced reactions have been investigated in the intermediate energy region because of the availability of intense monochromatic proton beams. Reactions of this nature include (p,p'), (p,n), (p,d), and $(p,2p)$. These have given us much valuable information on nuclear structure as well as providing sufficient data so that the reaction mechanisms are quite well understood.

The complementary neutron-induced reactions have not previously been studied in detail because the neutron beams which have been available have had poor energy resolution,[1] e.g., a full width of 40 MeV at a peak energy of 140 MeV. The recent completion of the Harvard monokinetic neutron beam[2] has enabled us to undertake an investigation of some (n,p) and (n,d) reactions. A preliminary report of the (n,d) work has already been published.[3] The energy spectrum of the neutron beam is still quite broad (6 MeV); thus we can not detect individual energy levels in these reactions although shell structure is quite clearly observed. The beam intensity (4×10^4 neutrons per sec) is an order of magnitude smaller than the earlier poor-resolution beams. Because of this low intensity, we have been forced to conduct a survey rather than an exhaustive investigation.

At low energies the (n,p) reaction has been studied in good resolution in counter experiments up to 22 MeV,[4] while other investigations have been made using the techniques of nuclear chemistry[5]; a comprehensive review of low-energy experiments is given by Cindro.[6] At higher energies the poor resolution of the neutron beams has permitted only the most cursory investigations at 90 [7] and 300 MeV.[8] However, from the results of proton-induced reactions such as (p,n) and (p,p'), one is able to outline three expected features of (n,p) reactions: Firstly, one expects a weak excitation of the ground state of the resulting nucleus; secondly, there should be clear excitation in the resulting nucleus of the isobaric analog states of the giant multipole resonance of the target nucleus; thirdly, one expects to see features of quasielastic scattering. All these effects have been detected in the present work.

For the (n,d) reaction, a similar situation holds. At low energies the reaction has been well studied,[4,9,10] but extrapolation of the results to higher energies is not very useful; on the other hand, at the higher energies the data are few and limited by the energy spread of the neutron beams.[7,8] However, one can make comparisons with the excellent (p,d) results available.

II. EXPERIMENTAL METHOD

The elements studied were chosen to cover a fair range of atomic weight. It soon became clear that more information could be obtained with light elements, and so we concentrated on these. Each target was weighed and its thickness determined. The targets were all approximately 0.6 g/cm² thick, i.e., 3 MeV thick for 140-MeV protons and 5 MeV thick for 140-MeV deuterons. The ^{6}Li target was in the form of the metal and was enriched to 96%. It was kept under mineral oil which had been purified by placing it in a vacuum for an hour. Before use, the target was wiped dry and a thin layer of plastic was sprayed on it. In this way we were able to keep it several hours in air without serious deterioration of the surface. For ^{7}Li we also used an

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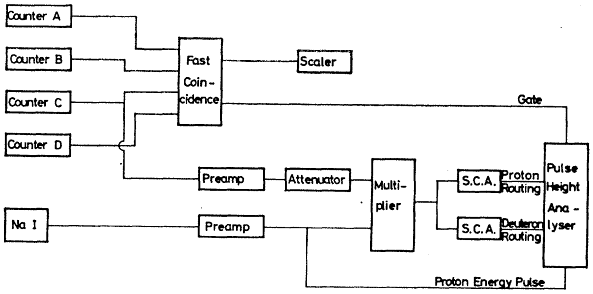

FIG. 1. Simplified flow diagram of the logic circuits used.

enriched target (99% ^{7}Li) and it was similarly treated. The natural calcium target (97% ^{40}Ca) was kept under kerosene and was sprayed with plastic before use. For the other targets (^{9}Be, ^{12}C, ^{27}Al, and ^{51}V) no special precautions were necessary. A polyethylene target was used for calibration purposes.

For particle detection we used a combination of a three-counter plastic scintillator telescope and a sodium iodide crystal. A coincidence in the telescope signaled the passage of a charged particle. This particle was identified as a deuteron or proton from a knowledge of its rate of energy loss (dE/dx) in counter C (see below) and the energy (E) it deposited as it stopped in the sodium iodide crystal. The energy of this partidle was then stored in the appropriate half of the memory of a pulse-height analyzer (PHA). Figure 1 gives a simplified diagram of the logic circuits used.

The scintillators were made from Pilot B plastic.[11] The counter dimensions were: counter A, $15\times19\times0.08$ cm; counter B, $10\times6.5\times0.16$ cm; counter C, $10\times6.5\times0.16$ cm; counter D, $5\times2.5\times0.16$ cm. The sodium iodide crystal[12] was 7.5 cm in diam and 7.5 cm long. Counter A was placed before the target and was used in anticoincidence. This eliminated any charged particles in the beam from being counted, an extremely important consideration at small angles. The other counters were placed on a movable scattering arm. Counter D was the defining counter and was located 80 cm from the target. The beam size at the target was 6×3 cm. Thus the angular resolution of the system was $\pm3°$ at 0° but improved to $\pm2°$ at larger angles.

Counter C provided the dE/dx pulse as well as being included in the fast-coincidence requirement. The scintillator was chosen, from several available, for its pulse-height resolution, which was 22% full width at half-height (FWHH) for 160-MeV protons passing through its thickness of 0.16 cm. This resolution is limited by the Landau effect. The phototube (an EMI 6097) was chosen because it combined the qualities of good resolution, stability, and high gain, with a reasonably fast response. For the other plastic counters, faster phototubes (RCA 7850) were used. For the sodium iodide crystal we used an RCA 8054 phototube because of its good resolution and stability; 2% resolution for 160-MeV protons was achieved.

For the particle identification, a simple multiplier circuit[13] was used. The product $(dE/dx)E$ is approximately constant over the energy region of interest. For protons between 100 and 140 MeV, the product varies from 6.5 to 7.2 (arbitrary units) while for deuterons between 100 and 140 MeV it varies from 11.1 to 11.9 (in the same units). The pulses from the sodium iodide were amplified and used as one input for the multiplier. The pulses from the plastic dE/dx counter were stertched, amplified, and then passed into a precision attenuator. The attenuator was normally set for a pulse-height reduction of a factor 1.7. This meant that when we were calibrating the system in the proton beam, we could simulate deuterons by switching out this attenuation. From the attenuator the dE/dx pulses went to the multiplying circuit. The output of this circuit was sent to two single-channel analyzers (model RIDL 33-10B) which were set so that one responded to deuterons, the other to protons. The outputs of these single-channel analyzers were used as routing pulses for the PHA (model RIDL 34-12B), and fast coincidences ($\bar{A}BCD$) of the plastic telescope were used as gates for the PHA. The sodium iodide pulse was then analyzed and stored in the memory.

The neutron beam was not monitored directly. Instead, we used an ionization chamber to measure the intensity of the external proton beam before it reached the deuterium target in which the neutrons were produced. The proton-beam intensity has been shown to be proportional to the neutron-beam intensity.[2] (In earlier experiments great care had been taken to measure the flux of only those protons which struck the deuterium target and thus could produce beam neutrons. This was done by designing special plates for the ionization chamber. Unfortunately, these plates tend to deteriorate because of radiation damage, and as a result the ionization current decreases with time. We found that plain plates in the ionization chamber were sufficiently accurate for this experiment, and they were not as susceptible to radiation damage.) We calibrated the ionization chamber by placing a polyethylene target in the neutron beam and observing free neutron-proton scattering. The neutron beam intensity was then determined from the known n-p cross sections.[14]

When the sodium iodide detector was placed at 0°, the crystal was in the neutron beam and therefore registered many pulses from neutron interactions in the crystal. This had two adverse effects: It reduced the energy resolution and it caused gain shifts in the phototube. These shifts altered the energy pulse which was

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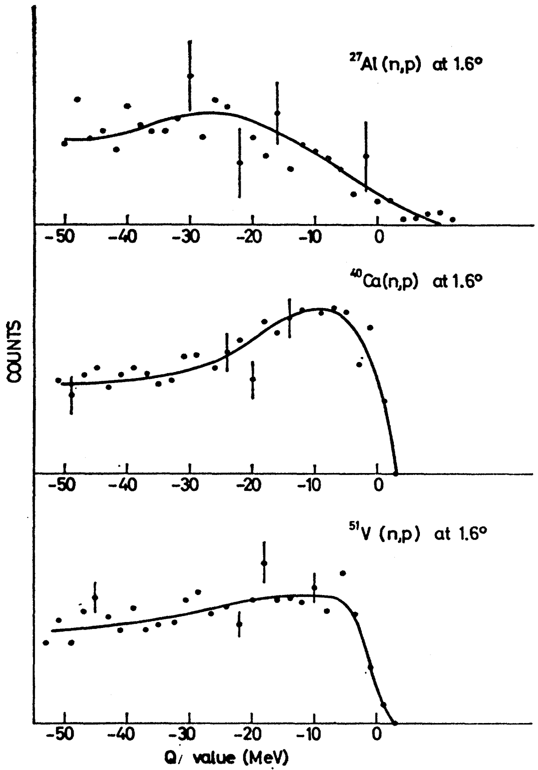

FIG. 2. Spectra of the (n,p) reaction at 1.6° for the nuclei ^{27}Al, ^{40}Ca, and ^{51}V.

used in the multiplier circuit, and therefore changed the calibration of the output of this circuit. The gain change in the sodium iodide was, fortunately, slow and not too large, so that we were able to correct it by recalibrating every 8 h or so with protons from the external beam of the synchrocyclotron. The calibrations were made at several proton energies, so that we were able to check the linearity of the energy response of the sodium iodide crystal.

The separation of protons and deuterons was not perfect. We were limited primarily by the dE/dx counter. During calibration runs with protons and pseudodeuterons, we achieved 95% separation but during the data-taking runs it sometimes deteriorated to as low as 90%. Runs which were found to be worse than this were rejected.

III. (n,p) RESULTS

For some of the target nuclei, spectra were taken with the telescope at only 0° (average scattering angle of 1.6°) because of the length of time needed to obtain each spectrum. We concentrated on the lightest nuclei because these showed the most structure. In Table I we give the Q values[15,16] of the (n,p) reactions which we

TABLE I. Q values of the (n,p) reactions.

Reaction	Q value (MeV)
^{6}Li$(n,p)^{6}$He	−2.7
^{7}Li$(n,p)^{7}$He	−10.0
^{9}Be$(n,p)^{9}$Li	−12.8
^{12}C$(n,p)^{12}$B	−12.6
^{27}Al$(n,p)^{27}$Mg	−1.8
^{40}Ca$(n,p)^{40}$K	−0.5
^{51}V$(n,p)^{51}$Ti	−1.7

studied. Little is known about the nucleus ^{7}He, and therefore in order to calculate the Q value of the reaction ^{7}Li$(n,p)^{7}$He, we assumed ^{7}He to be ^{6}He with an unbound neutron.

In Fig. 2 we show the spectra of the protons at 1.6° from (n,p) reactions on ^{27}Al, ^{40}Ca, and ^{51}V. The results from aluminum are not very clear, but calcium and vanadium each show a single peak. These spectra are similar in character to the results of the (p,n) reaction at 143 MeV,[17] in which the energy resolution was 18 MeV.

It is easier to interpret the (n,p) results if we first summarize the more recent (p,n) measurements. These have been made at 18.5,[18,19] 30 and 50,[20] 93.5,[21] and 138 MeV.[22] At the lower energies, there is a clear excitation of isobaric analog states, as well as some excitation of configuration states. The reaction mechanism has been discussed by Lane and Soper.[23] The isobaric analog states are states in the resulting nucleus which correspond in configuration and isotopic spin to the ground state of the target nucleus. For nuclei with $T=\frac{1}{2}$, the isobaric analog state is the ground state of the resulting nuclei. Configuration states are states which have a similar configuration to the ground state of the target nucleus, but the isotopic spin can be different.

For nuclei such as vanadium, which have a neutron excess of two or more (i.e., $T\geqslant 1$), the (p,n) reaction leads to a nucleus in which the isotopic spin of the ground state is less than that of the target nucleus. The isobaric analog state is thus an excited state of the final nucleus. It acts as a doorway state[24] to the more numerous nuclear levels. The Q value of the reaction to

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TABLE II. Coulomb displacement energies: the Q values to the isobaric state in (p,n) reactions.

Element	Coulomb displacement energy (MeV)
^{6}Li	1.6
^{9}Be	1.9
^{12}C	2.9
^{27}Al	5.5
^{40}Ca	7.3
^{51}V	8.0

the isobaric analog state is the Coulomb displacement energy between the two nuclei. Table II gives the Coulomb displacement energy for the nuclei we have used.[16,20] For the (p,n) reactions the Q value is negative; for the (n,p) reactions the Q value is positive.

For the high-energy (p,n) reactions, the isobaric analog is still clearly excited. In counter experiments, the (p,n) reaction leading to the ground state is not detected for the medium-weight nuclei; the $\Delta T=0$ transition is much more important. In activation experiments the (p,n) reaction is observed with a cross section which is quite large even for heavy elements. A difficulty with such experiments is that one does not know the spectrum of the energy levels excited in the final nucleus; all that is certain is that one is detecting the ground-state transition plus transitions to levels which have decayed by γ-ray emission. These experiments have recently been discussed by Church.[25] We will not discuss the problems associated with such experiments, but will concentrate more on the counter experiments.

In addition to the isobaric analog state, the high-energy (p,n) spectra show a strong peak at about $Q=-25$ MeV. This peak is the most important at all angles except at 0°. Langsford *et al.*[22] suggested that this was the excitation of the isobaric analog states in the final nucleus of the giant dipole resonance states of the target nucleus. This assignment is clearly suggested by the shape and Q value of the peak. It is verified by comparison with the (p,p') reaction. In the impulse approximation the (p,p') and (p,n) reactions can be described in similar terms,[26] and the (p,p') reaction excites levels which have large radiative matrix elements to the ground state. A selection rule depresses electric dipole radiative transitions with $\Delta T=0$, but they are allowed when $\Delta T=1$. Collective states are excited by the (p,p') reaction, and excitation of the giant dipole resonance, for example, is quite pronounced.[27] A general analysis of inelastic scattering and its interpretation in terms of the shell model has recently been made by Satchler.[28] Proton inelastic scattering is similar to inelastic electron scattering, where again the giant dipole resonance is clearly excited.[29] However, it has been shown[30] that for the 180° electron scattering, levels at 20-MeV excitation energy, which are not the giant dipole resonance, become dominant, contrary to what had been thought previously.[31] A similar word of caution is also needed for (p,p') reactions in which other levels are also excited.[32] Now for (n,p) reactions, there is no isobaric analog-state transition, because only $\Delta T\geqslant 1$ transitions are allowed. Thus, we expect the giant dipole resonance transitions to dominate with the reservation that other levels must be contributing as well.

Even-even nuclei are particularly interesting, because one would expect the (n,p) and (p,n) reactions to be identical. The elements ^{12}C, ^{16}O, ^{28}Si, and ^{40}Ca have been studied with the (p,n) reaction.[21,22] In ^{12}C there is a clear excitation of a giant resonance; for the other elements the spectra do not continue into this region. In all these elements there are peaks which correspond to transitions to the ground state or low-lying energy levels in the resulting nucleus. For ^{12}C there is a strong transition to the ground state of ^{12}N. For the inelastic scattering of protons on the 15.11-MeV level in ^{12}C, the analog state of the ^{12}N ground state, the angular distribution is peaked forward; for 151-MeV protons the cross section drops[33] a factor of 2 between 0° and 9°. This strong forward peaking is also found in the (p,n) reaction to the ground state of ^{12}N; it indicates that the transition is either 0^+ or 1^+ (i.e., there is no change in the orbital angular momentum); in this instance it is a magnetic dipole transition. In ^{16}O the situation is uncertain in the (p,n) reaction. There are four closely spaced levels in ^{16}F and the peak found in the (p,n) reaction may be a transition to any or all of these levels. For ^{28}Si and ^{40}Ca, however, it is clear that the ground-state transitions are very weak. The (p,n) reaction on ^{28}Si excites a level at 2.5 MeV in ^{28}P, and for ^{40}Ca it excites a level at 1.4 MeV in ^{40}Sc. In addition to these strong peaks there are other weaker transitions to levels of higher excitation.

We can now compare our results of the (n,p) reaction with the results from other reactions. Since a transition with $\Delta T\geqslant 1$ is required for (n,p) reactions, one would expect the excitation of the giant dipole resonance to be important. One would also expect transitions to the ground state or low-lying levels of the resulting nucleus. In the present work we confirm the dominance of the giant dipole resonance but the existence of ground-state transitions is not clearly estab-

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lished, apart from the special case of ^{6}Li. This lack of the transitions to the ground state and low-lying levels could be partly due to poor energy and angular resolution.

For aluminum the giant dipole resonance is known to be spread from 18- to 29-MeV excitation energy.[34,35] Similarly, the (p,n) reaction gives a broader spectrum than for other elements.[21] Of course, the γ-ray transition and the (p,n) reaction can excite both the $T=\frac{1}{2}$ and $T=\frac{3}{2}$ components of the giant dipole resonance in aluminum, but the (n,p) reaction can excite only the $T=\frac{3}{2}$ component. The $T=\frac{3}{2}$ fraction probably lies in the higher part of the resonance, since this is found to be so in other nuclei.[36] Our results (Fig. 2) do not have sufficient resolution to confirm this conjecture. The transition to the ground state of ^{27}Mg is not detected; this could be because the ground state of ^{27}Al has spin and parity $\frac{5}{2}^+$, while that of ^{27}Mg is $\frac{1}{2}^+$. An electric quadrupole transition is required and this would not be very strong at 0°.

For vanadium, the giant dipole resonance is 6 MeV wide and is peaked at 19-MeV excitation energy.[37] The γ-ray transitions can reach $T=\frac{5}{2}$ and $\frac{7}{2}$ levels; the (p,n) reaction could also reach $T=\frac{3}{2}$ states, but these seem to be suppressed. The (n,p) reaction can reach only $T=\frac{7}{2}$ states. Because of the Coulomb displacement energy of 8.0 MeV, one would expect the resonance to appear at $Q=-11$ MeV; we detect a broad peak centered at $Q=-13\pm3$ MeV (Fig. 2). The apparent width of 25 MeV is partially caused by the experimental resolution, but there must be contributions from levels other than the giant dipole resonance.

For calcium the inelastic proton scattering experiments[38] have concentrated on the lower energy levels. The (p,n) data show a transition to a 1.4-MeV level in ^{40}Sc and there is a steep rise in the region of the giant dipole resonance, but the data stop at a Q value of -24 MeV. Because of our poor energy resolution, we would not expect to detect a transition equivalent to that of the 1.4-MeV level in ^{40}Sc. The giant dipole resonance should dominate. This is known to be only 4 MeV broad, centered at 20-MeV excitation energy.[35] Because of the Coulomb displacement energy of 7.3 MeV, one would expect to see a peak at a Q value of -12.7 MeV. We observe a peak at $Q=-10\pm3$ MeV; it is narrower and more pronounced than that of ^{51}V.

In Fig. 3 we present the results for ^{12}C, for various angles out to 25°. Even at the smallest angles there is no clear evidence for a transition to the ground state of

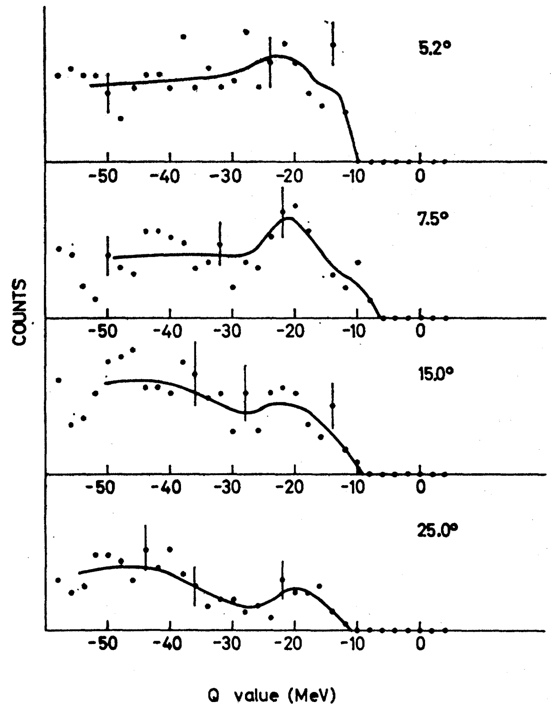

FIG. 3. Spectra of the reaction $^{12}C(n,p)^{12}B$ at several angles.

^{12}B (Q value: -12.6 MeV) although there is a definite broadening in that part of the spectrum. The peak corresponding to the ground-state transition has probably merged with the main peak because of the experimental resolution and the finite angular acceptance of the counter telescope. The giant dipole resonance in ^{12}C is very narrow (2 to 3 MeV wide) and peaks at 23-MeV excitation energy.[34,35] The Coulomb displacement is 2.9 MeV, so that one would expect a peak in our spectra at 20 MeV. The observed peak is at $Q=-21\pm3$ MeV.

In Fig. 4 we give the angular distribution of the broad peak observed in the (n,p) reaction on ^{12}C. We define this as the region between a Q value of -13 and -33 MeV. For comparison we have plotted the angular distribution calculated by Sanderson[39] for the excitation of 1^-, $T=1$ levels in ^{12}C in inelastic proton scattering. We have corrected for the difference in beam energy between his calculation and the present work. The difference of a factor 4 in the cross sections is due to the fact that we have included more transitions; furthermore, the nucleon-nucleon scattering amplitudes which come into the calculation are quite different for n-p and p-p scattering. As can be seen, the shapes of the angular distributions agree only moderately well. We were unable to resolve the transition to the ^{12}B ground state and this is peaked forward. This must contribute to the discrepancy at forward angles. We

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conclude that the peak we observe is probably due to the excitation of 1^- levels; the excitation of levels which involve a larger change in orbital angular momentum would produce an angular distribution peaking at an angle of 20° or more. Excitation of 2^- levels, however, cannot be excluded. Although not strongly excited in inelastic proton scattering, they could be more strongly excited in the (n,p) reaction, because of the different spin dependence of the nucleon-nucleon scattering amplitudes.

In Fig. 5 we present the spectra for ^{9}Be for various angles out to 15°; again a giant resonance dominates the spectrum. From γ-ray experiments one knows that the giant dipole resonance for ^{9}Be is broad, stretching from 17- to 35-MeV excitation energy and peaking at 22 MeV.[35] The Coulomb displacement energy is only 1.9 MeV. However, as in other elements mentioned above, the γ transition and (p,n) reaction can reach $T=\frac{3}{2}$ and $T=\frac{1}{2}$ states, but the (n,p) reaction is restricted to $T=\frac{3}{2}$ levels. We observe a very broad peak centered around $Q=-30$ MeV, which indicates that the $T=\frac{3}{2}$ part of the giant dipole resonance is higher in energy than the $T=\frac{1}{2}$ component. Although the transition to the ground state of ^{9}Li (Q value: -12.8 MeV) is not apparent, the spectra at 1.6° and 5.2° show a broadening of the peak in this region, while the spectra at 10° and 15° show few counts in this region. The 15° spectrum also shows a slight shift of the giant resonance peak to a higher Q value. We can discuss this more easily with reference to ^{7}Li, where the effect is much more pronounced.

In Fig. 6 we give some spectra for ^{7}Li, for angles from 5° to 20°. At the smallest angles there is slight evidence of a broadening around $Q=-10$ MeV, but the main feature is a broad peak at $Q=-26$ MeV. The giant dipole resonance in ^{7}Li goes from 15 to 30 MeV and peaks at around 23 MeV.[40] Again one would expect the (n,p) reaction to excite the $T=\frac{3}{2}$ component of the resonance, and this would be higher in energy than the $T=\frac{1}{2}$ part. At 10°, however, the peak has shifted slightly to $Q=-30$ MeV, and at 15° and 20° the shift continues out to $Q=-36$ and -45 MeV, respectively. This suggests that the ejected protons are coming from individual neutron-proton collisions in the nucleus, i.e., quasielastic scattering. Let us summarize the present experimental knowledge on this.

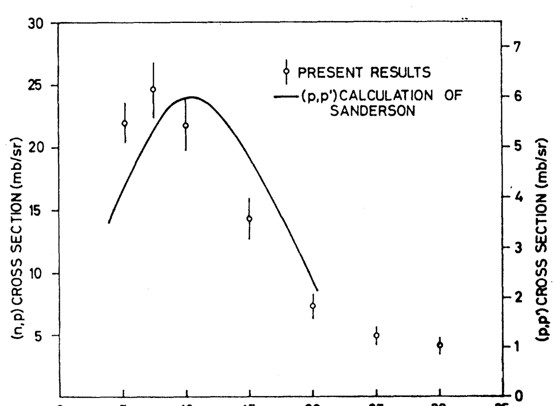

FIG. 4. Angular distribution for the transition to the isobaric analog states of the giant dipole resonance in the reaction ^{12}C$(n,p)^{12}$B.

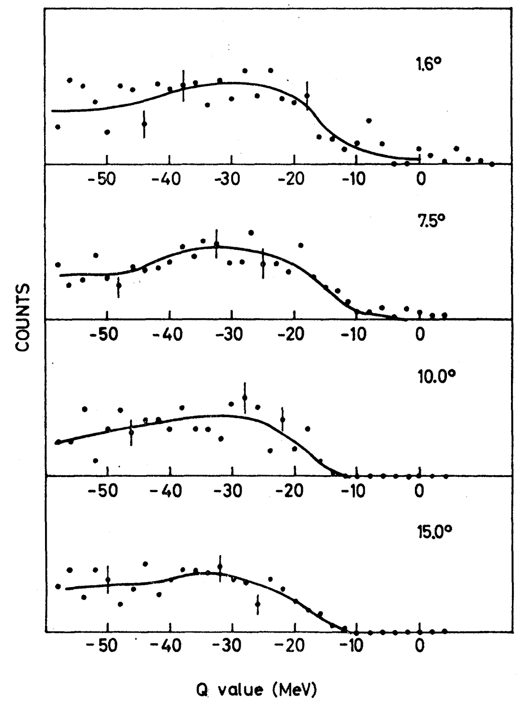

FIG. 5 Spectra of the reaction ^{9}Be$(n,p)^9$Li at several angles.

At higher energies, quasielastic scattering is well established. It was observed several years ago at 340 MeV[41] and more recently at 300[8] and at 450 MeV.[42] In these experiments only one particle was detected and a prominent peak is observed around about the energy for free nucleon-nucleon scattering. The energy of the ejected proton in the laboratory system is given approximately by

$$E=[E_0+V]R\cos^2\varphi-V\,, \quad (1a)$$

where R, the relativistic correction, is given by

$$R=[1+(\sin^2\varphi)E_0/2m_0c^2]^{-1}; \quad (1b)$$

here φ is the laboratory angle of the observed proton; E_0 is the beam energy; V is the optical-model potential well, but it can also be considered as representing the

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binding energy of the struck nucleon. For 182-MeV protons the optical-model potential is from 15 to 20 MeV deep.[43] From the $(p,2p)$ reaction one obtains the binding energy, which, for the light and medium weight nuclei investigated, is also 15 to 20 MeV.[44,45]

Quasielastic scattering around 150 MeV is well established for the $(p,2p)$ reaction. When only one particle is detected, quasielastic scattering can be swamped by interactions with the whole nucleus, especially when the recoil energy of one particle is close to its binding energy. In some experiments quasielastic scattering was not detected,[46,47] but in other apparently more accurate experiments it is clearly seen.[48,49] The extensive work of Wall and Roos shows that for all nuclei quasielastic scattering of 160-MeV protons is evident even at 20°, where for free nucleon-nucleon scattering the recoil energy is only 20 MeV. At 30° the quasielastic scattering becomes dominant; the recoil energy for free nucleon-nucleon scattering is then 40 MeV.

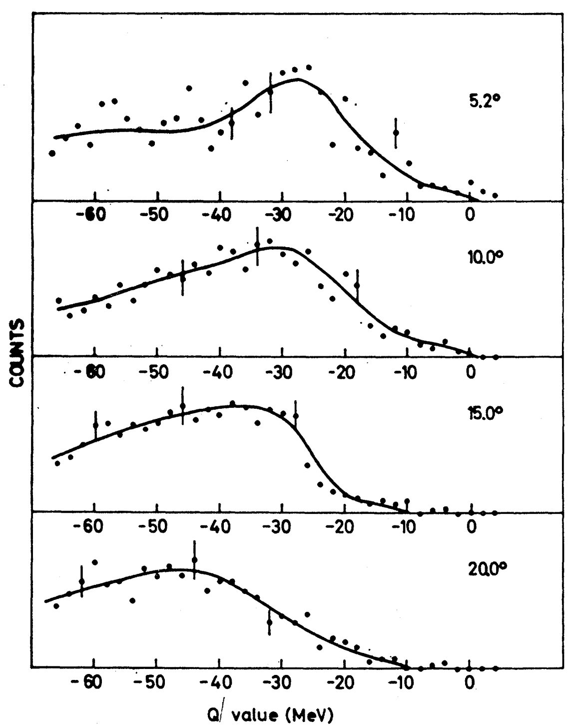

FIG. 6. Spectra of the reaction ^{7}Li$(n,p)^7$He at several angles.

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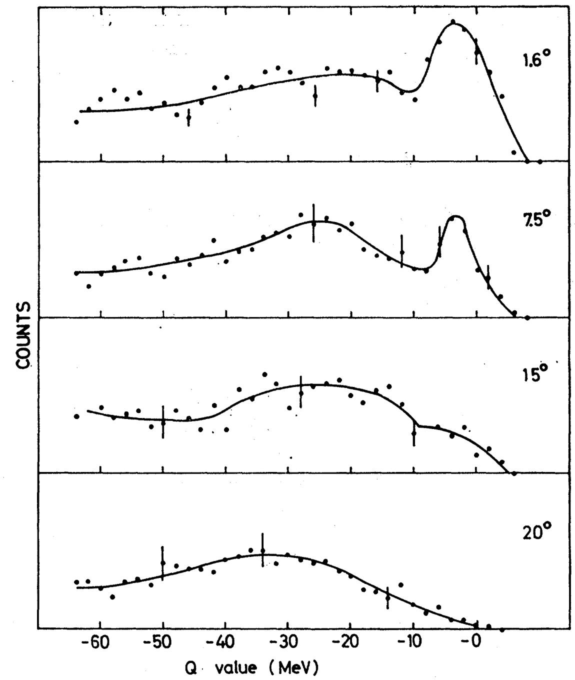

FIG. 7. Spectra of the reaction ^{6}Li$(n,p)^6$He at several angles.

Our results on the ^{7}Li$(n,p)^7$He reaction show a resemblance to the quasifree proton results. Unfortunately, we have not continued our investigation out to larger angles, where the process would be unencumbered by other effects. At the angles of 15° and 20°, there must still be a fairly strong final-state interaction. In addition, there is another problem. We detect the proton which has been ejected from the nucleus and so it is certain that at least the Q value has been lost in the reaction, and even more if the proton was knocked out of a tightly bound shell. To reproduce this aspect mathematically one can consider the following relation for the energy of the ejected proton (omitting the relativistic correction which is very small at our energy):

$$E=(E_0-E_B)\cos^2\varphi\,, \qquad (2)$$

where E_B is the binding energy of the proton. One can thus calculate that the apparent Q value for the reaction is

$$Q=-(E\sin^2\varphi+E_B\cos^2\varphi)\,. \qquad (3)$$

Using the rather extreme value of a binding energy of 25 MeV, we calculate the following apparent Q values: -29, -33, and -40 MeV at 10°, 15°, and 20°. For ^{7}Li we find peaks at -30, -36, and -45 MeV. Expression (1), used by other authors, gives the Q values -5, -11, and -20 MeV. It seems that the quasielastic peak is lower in energy than would reasonably be expected. We therefore suggest that the peak in the ^{7}Li spectra is due to an interference between quasielastic scattering and an excitation of giant resonance states.

The reaction ^{6}Li$(n,p)^6$He is of great interest because it is the only nucleus where the ground-state transition is dominant. We give in Fig. 7 various spectra out to 20°. At 1.6° the ground-state transition is very strong, but its cross section falls off rapidly with angle (see Fig. 8). In addition to the statistical errors as shown, there is an over-all uncertainty in the absolute normalization of 20%. The ground state of ^{6}Li has spin and parity 1^+ and that of ^{6}He is 0^+. The (n,p) reaction is thus a magnetic dipole transition; this is the reason the curve is so similar to that for inelastic scattering[33,50] to the 15.11-MeV level in ^{12}C.

The giant dipole resonance in ^{6}Li is peaked at 13-MeV excitation energy and stretches from 8 to 20 MeV.[51] The secondary peak in the spectra even at 1.6° is at $Q=-19\pm3$, which is not consistent with its being the giant dipole resonance. At 10° and 15° the peak has moved down to $Q=-23$ MeV, while at 20° it is at $Q=-33$ MeV. At all these angles there are many counts around $Q=-13$ MeV, but there is never a peak. The main effect again seems to be quasielastic scattering. Using relation (2) with a binding energy of 12 MeV (an average of the s and p protons) we find that the peak should be at -16, -21, and -28 MeV at the angles 10°, 15°, and 20°. This is in reasonable agreement with the experimental values of -23, -23, and -33 MeV.

Before completing this section on the (n,p) reaction we should mention some nuclear chemistry studies of the (p,n) reaction. An early result of Hintz and Ramsey[52] for the reactions ^{11}B$(p,n)^{11}$C and ^{34}S$(p,n)^{34}$Cl is interesting because it gives an excellent idea of the energy dependence of the reaction from 10 to 100 MeV. Other work is reviewed by Grover and Caretto.[53] At 155 MeV the activation studies of Valentin *et al.*[54] show the interesting feature that the ground-state transitions for reactions such as ^{7}Li$(p,n)^7$Be and ^{11}B$(p,n)^{11}$C can be considered as charge-exchange elastic scattering, while for even nuclei such as ^{14}N the (p,n) reaction requires a nuclear rearrangement. The former reactions have a cross section of 3.5 mb, but the latter have a very small cross section of 0.075 mb. The reaction ^{10}B$(p,n)^{10}$C is not so strongly suppressed; it has a cross section of 0.65 mb. These reactions have been interpreted in terms of the impulse approximation.[55] We have integrated our cross section for the ^{6}Li(n,p) reaction to the ground state of ^{6}He, extrapolating the experimental results out to 50° using the line in Fig. 8. We assume the cross section is zero for angles greater than 50°. This procedure probably gives the total cross section to within 20%; a further error comes from the over-all normalization. We obtain the value 2.2 ± 0.9 mb for the total cross section. This indicates that the ground-state transition in the reaction ^{6}Li$(n,p)^6$He has a cross section three times that for the reaction ^{10}B$(p,n)^{10}$C. This confirms our observation that the reaction ^{6}Li$(n,p)^6$He has by far the strongest ground-state transition.

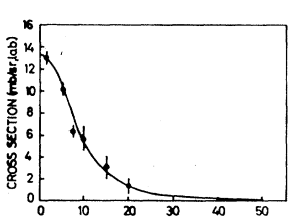

FIG. 8. Angular distribution for the ground-state transition in the reaction ^{6}Li$(n,p)^6$He. The line is drawn by eye and used to integrate the cross section (see text).

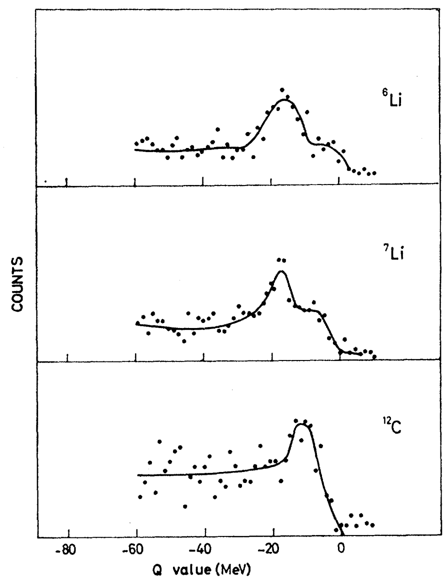

FIG. 9. Spectra of the (n,d) reaction at 1.6° for the nuclei ^{6}Li, ^{7}Li, and ^{12}C.

IV. (n,d) RESULTS

The spectra for the (n,d) reaction taken at 1.6° are shown in Fig. 9. They agree well with the more precise data on the (p,d) reaction.[56–59] The (n,d) and (p,d) reactions (see Table III) should be identical for the even-even nuclei ^{6}Li and ^{12}C, but the reactions will differ for ^{7}Li. For ^{6}Li we can distinguish two transi-

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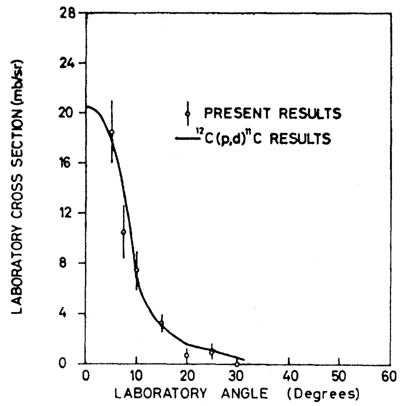

FIG. 10. Angular distribution for the reaction $^{12}C(n,d)^{11}B$, normalized to and compared with the reaction $^{12}C(p,d)^{11}C$ (see Refs. 56 and 57).

tions. The reaction $^6Li(n,d)^5He$ has a Q value of -2.4 MeV and a Q value of -3.4 MeV to reach the "ground state" of ^5He, i.e., the first resonance in neutron-helium scattering. The weaker peak is probably the ground-state transition. The stronger peak is at a Q value of -17 MeV; i.e., it is a transition to a state in ^5He at about 14-MeV excitation energy. This is in reasonable agreement with the 12° spectrum of the $^6Li(p,d)^5Li$ reaction.[58] This spectrum consists of two peaks; one is a transition to the ground state of ^5Li and the other is just resolved into two levels in ^5Li at excitations of 17.1 and 19.3 MeV. Our spectrum for ^7Li also exhibits two peaks; they have a separation of 11 MeV. The weaker peak is probably a transition to the ground state of ^6He (Q value: -7.7 MeV). The stronger peak is most probably due to the pickup of a $1s_{1/2}$ proton. The $^7Li(p,d)^6Li$ shows a similar general character,[58] but the transition to the ground state of ^6Li is split up and there are transitions to several low-lying states in ^6Li. This is due to the fact that there are several ways the remaining $1p_{3/2}$ neutron and proton can couple together.[59].

Our spectrum for ^{12}C has only one peak. From the known Q value of the $^{12}C(n,d)^{11}B$ reaction (-13.8 MeV) it is clear that the peak is predominantly a transition

TABLE III. Q values of the (n,d) reactions.

Reaction	Q value (MeV)
$^6Li(n,d)^5He$	-2.4
$^7Li(n,d)^6He$	-7.8
$^{12}C(n,d)^{11}B$	-13.7

to the ground state of ^{11}B. The ground-state transition is also the most important for the $^{12}C(p,d)^{11}C$ reaction.[56,57] In Fig. 10 we show the angular distribution for the reaction $^{12}C(n,d)^{11}B$ compared with the angular distribution of the $^{12}C(p,d)^{11}C$ reaction. We have had to normalize our results to the proton results because our absolute cross sections appear to be low, probably because of imperfect proton-deuteron separation which might cause a loss of deuterons into the proton spectra. One can see that the agreement on the shape for the (n,d) and (p,d) angular distributions is very good. The results of Détraz *et al.*[60] on the reactions $^{12}C(d,t)^{11}C$ and $^{12}C(d,^3He)^{11}B$ at 28.5 MeV show, to higher accuracy, this same effect, which indicates that neutrons and protons have the same density distribution in ^{12}C.

V. CONCLUSIONS

Because of the availability of a monokinetic neutron beam we have been able to study the reactions of neutrons on several light nuclei. We have been able to confirm effects detected in (p,n) reactions such as the excitation of the isobaric analog states of the giant dipole resonance. We have also found evidence for quasielastic scattering in the isotopes of lithium, but it was not detected in other nuclei, probably because spectra were not taken at large enough angles. The deuteron results were marred by the rather poor proton-deuteron separation. This has been rectified and experiments in progress show a considerable improvement in this respect.

The two handicaps which prevent a more thorough investigation are the neutron beam intensity and its energy spread. These parameters are correlated; the energy spread could be improved but one would have to pay a heavy price in the beam intensity. However, the method is intrinsically very good, and the advent of more intense proton cyclotrons will open up many further possibilities.

ACKNOWLEDGMENTS

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