Proton and Neutron Resonances in Nitrogen*

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Angular distributions and integrated cross sections have been measured for protons scattered elastically and inelastically from nitrogen. A broad peak, about 1 MeV wide, centered near 9 MeV, has been found in the elastic cross section without a corresponding rise in the cross section in any of the inelastic channels. The angular distribution suggests that this peak is a p-wave scattering. Broad peaks in inelastic channels (about 0.5 MeV wide) were observed near 10 MeV for protons leading to the second excited state of ^{14}N, and at 10.7 and 11.3 MeV for protons producing the fourth and sixth excited states. None of these peaks has a counterpart in the elastic scattering. They are probably caused by the production of intermediate states. Corresponding to the 9-MeV elastic proton resonance, we have found a broad resonance (0.4 MeV wide) in the elastic scattering of neutrons from nitrogen at 5.3 MeV. This resonance has a peak cross section of 0.5 b, which requires that the ratio of the neutron width to the total width be near unity. The nonelastic cross section does not show a resonance at this energy.

INTRODUCTION

RESONANCES in the elastic scattering cross sections of protons and neutrons are known to exist at energies of excitation of 20 MeV and more. For example, resonances in the elastic scattering of protons by carbon are known at 22- and 28-MeV[1,2] incident proton energies. Similarly, resonances in the elastic scattering of neutrons by carbon have been found at 15.8 and 19.5 MeV.[3] These resonances have not been detected in inelastic channels, and for some there is good evidence that the resonance appears only in the elastic channel.[2–4] This high probability of elastic reemission is a property of single-particle states.

In the present investigation, the elastic and inelastic scattering of protons from ^{14}N has been studied up to an energy of 12 MeV. Various broad resonances were observed in inelastic channels, usually specific to one or at most two or three channels, and not reflected in the elastic scattering. These are probably intermediate states in ^{15}O. In addition, a broad resonance found in the elastic scattering of protons near 8.8 MeV (excitation energy 15.5 MeV in ^{15}O) shows no similar effect in the inelastic channels and is to be interpreted as a single-particle state. The energies of excited states of the mirror nuclei ^{15}N and ^{15}O are known to be similar. One would expect, therefore, that a corresponding state in ^{15}N should be detectable in the elastic scattering of neutrons by ^{14}N at a neutron energy of about 5 MeV. The total elastic scattering cross section of neutrons in this energy range has been previously determined by direct integration of differentially measured cross sections[5,6] and by subtraction of measured nonelastic cross sections from total cross sections.[7–10] These results show the existence of a broad resonance near 3.8 MeV with sharp resonances superposed on it. Above 4.5 MeV the elastic scattering data is not clear, although the total cross section[10] has a maximum near 5.3 MeV. We have made a measurement of both elastic scattering and inelastic cross sections between 4.0 and 6.5 MeV using the spherical shell method. A broad resonance was found in the elastic scattering centered at 5.3 MeV as anticipated. Its large peak cross section shows that it is a predominantly scattering resonance. No resonance was found in the nonelastic cross section at this energy.

PROTON MEASUREMENTS

1. Experimental Method

The experimental arrangement for this investigation is described elsewhere.[11] In short, a collimated beam of protons from the Tandem EN accelerator at The University of Texas was incident on a target of adenine ($C_5H_5N_5$) evaporated on a thin carbon backing and placed at the center of a scattering chamber. The beam on passing through the target was collected in a Faraday cup, and monitored by a current integrator that had an accuracy better than $\pm 1\%$. The scattered particles were viewed by a set of four detector assemblies. Each assembly consisted of a thin transmission detector A ($50\,\mu$) in front of a thick (2.5 mm) Si detector B. These were connected in coincidence and anticoincidence such that the spectrum of particles stopped in A was separated from the spectrum of particles stopped in B. Such a coincidence-anticoincidence system also reduces the background in the low-energy

* Supported in part by the U.S. Atomic Energy Commission.
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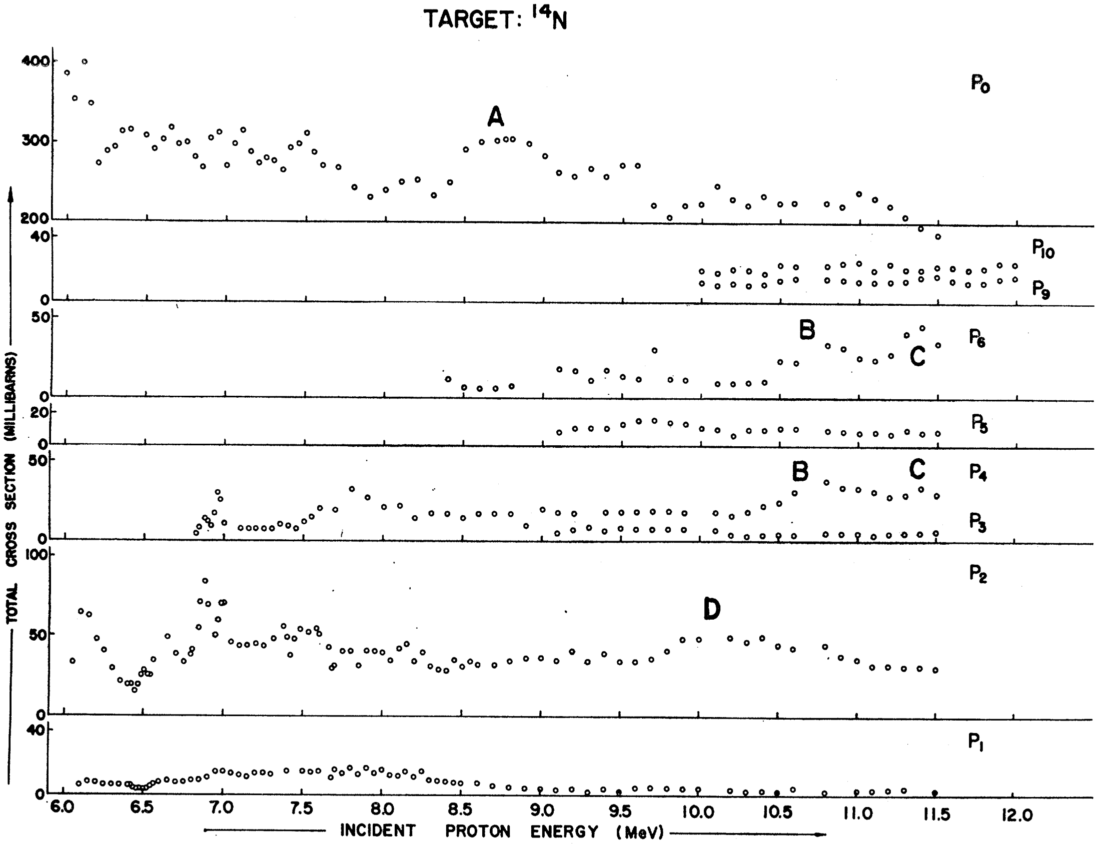

FIG. 1. Total integrated cross sections for protons scattered elastically and inelastically from nitrogen. For the elastic group (p_0) the integration is only between laboratory angles of 80° and 160°.

part of the spectrum and eliminates the peak that would otherwise be seen in the thin counter caused by protons passing through it and stopped in the thick counter. As shown by studies of the protons ejected at high angles from hydrogen contained in the target, the thin counter spectrum was fully sensitive to protons down to an energy of 0.25 MeV. The spectra from the thin and thick counters were separated by suitable electronic equipment, recorded in a PDP-7 computer, and plotted simultaneously with the aid of a line printer. The resolution of the thick detectors was found to improve markedly when they were cooled to about −20°C by passing cold methanol through the casing holding them. The resolution of the thick detectors as connected in this system was about 70 keV near 10 MeV; that of the thin detectors about 100 keV.

TABLE I. Known characteristics of the excited states of ^{14}N formed by inelastic scattering of protons from ^{14}N.[a]

Reaction	Q value in MeV	J^π and T
$^{14}N+p \rightarrow {}^{15}O \rightarrow {}^{14}N+p_0$		$1^+, T=0$
$^{14}N+p \rightarrow {}^{15}O \rightarrow {}^{14}N+p_1$	−2.31	$0^+, T=1$
$+p_2$	−3.95	$1^+, T=0$
$+p_3$	−4.91	$(0^-), T=0$
$+p_4$	−5.10	$2^{(-)}, T=0$
$+p_5$	−5.69	$1^{(-)}, T=0$
$+p_6$	−5.83	$3^{(-)}, T=0$
$+p_7$	−6.05	
$+p_8$	−6.21	$1^{(+)}, T=0$
$+p_9$	−6.44	$3^{(-)}, T=0$
$+p_{10}$	−7.03	$(2), T=0$

[a] Taken from T. Lauritsen and F. A. Selove, technical report, 1962 (unpublished). J^π values in parentheses are uncertain.

The products of disintegration were identified by means of detailed calibration curves made for each detector. These calibration curves were constructed by using the predicted laboratory energies for some of the more easily identified groups of particles in the spectrum. The complete spectra in detectors A and B were taken in 10° intervals from 30° to 160° for each proton energy. The incident proton energy range between 7 and 12 MeV was covered in steps of 100 keV.

2. Results

The measurements concerned the elastically scattered protons (p_0) and inelastically scattered protons leading up to the tenth excited state of ^{14}N (hereafter referred to as p_1, $p_2 \ldots p_{10}$). α particles were identified by the effects of a thin filter of Mylar (0.5 mg cm^{-2}) which could be placed in front of the thin detectors with the aid of a relay. Their yield is discussed elsewhere.[11] The positions and the characteristics of the

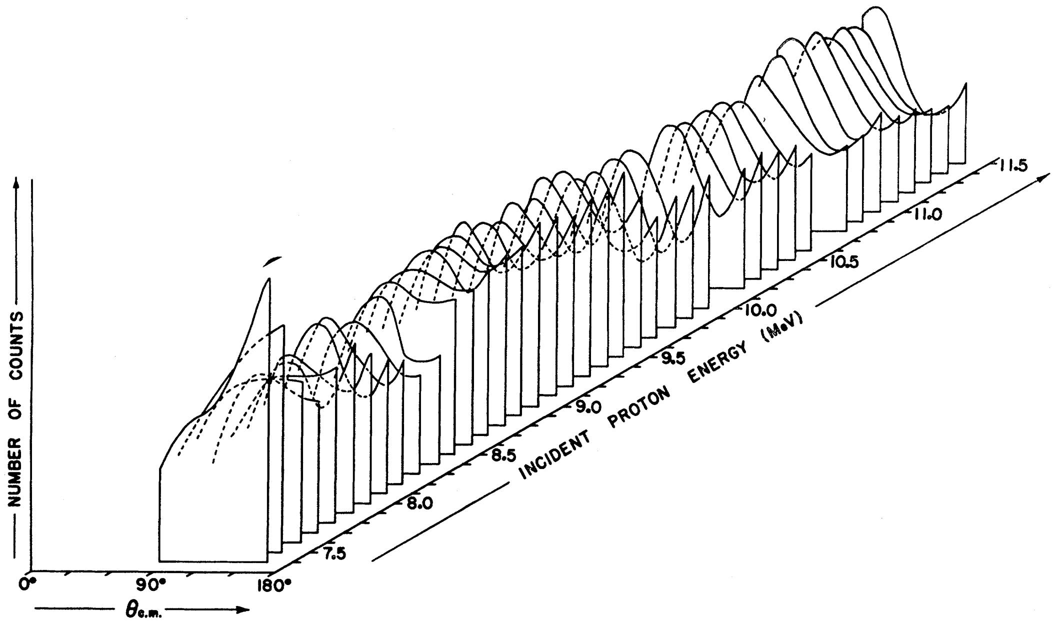

FIG. 2. Angular distribution for protons elastically scattered from ^{14}N.

states of ^{14}N, as far as they are known, are shown in Table I.

The cross section for a given inelastic proton group will fall rapidly if the energy available for emission in the center-of-mass system falls below the Coulomb barrier height. For the inelastic proton groups whose cross section could be followed as the energy of the bombarding protons was decreased, counting rates fell below the limit of detectability (corresponding to a cross section of about 0.1 mb/sr) when the protons had a center-of-mass energy below about 1.5 MeV. For a square-well potential of radius $1.5A^{1/3}$ F, where A is the nuclear mass number, the expected barrier height is 2.5 MeV. The difference, no doubt, demonstrates the diffuseness of the nuclear surface.

Angular distributions were obtained for most inelastic groups between 30° and 160°. Low-energy groups could not always be detected below 40° because the peaks were lost in the rise in the spectrum caused by recoil nuclei, even though these recoils could be very largely stopped by the Mylar filter. For elastically scattered protons the angular distribution could not be obtained below 80° because they could not be separated from protons scattered elastically by ^{12}C in the target.

The integrated cross section for each channel was obtained by measuring the area under the angular distribution curve and using a normalization factor to convert it into millibarns. The cross section, then, does not include the angular distribution below 30° and above 160°. This contribution however, is small; it is 6% if the angular distribution is isotropic. The normalization factors were obtained by measuring the differential elastic cross sections at 125° and 150° for a proton energy of 3.6 MeV and comparing the results with the absolute measurements of Bashkin *et al.*[12] Such an indirect method was necessary because some adenine decomposes in the process of evaporation so that the amount of nitrogen in the target could not be obtained reliably from the weight of the target.

The total integrated cross sections for the various proton groups are shown in Fig. 1. The results for the p_7 and p_8 groups are not shown because the cross sections for them were very small in this region of energies and they were too close to be separated and measured accurately. Similarly the p_3 group which had an energy very close to that of the p_4 group was almost always weak compared with the latter and was therefore difficult to separate from it. It could not be measured accurately below 9 MeV. The differential cross sections for the p_0 group taken from 80° to 160° only, for the reasons mentioned above, are shown in Fig. 2. The integrated cross sections are plotted in Fig. 1.

The cross-section results generally show fluctuations far in excess of experimental errors in measurement. Presumably these are fluctuations of the Ericson type caused by fluctuations in level density and width. Superposed on these features, however, are broad rises in cross section; they are clearly far greater than can be accounted for by fluctuations. One of these occurs in the elastic channel between 8.3 and 9.7 MeV (the anomaly A) with no corresponding rise either in the cross section of any of the inelastically scattered protons or in the α_0, α_1, or ^3He groups.[11] Broad peaks in cross section (B, C, and D) also occur at different energies in the inelastic proton groups, without corresponding

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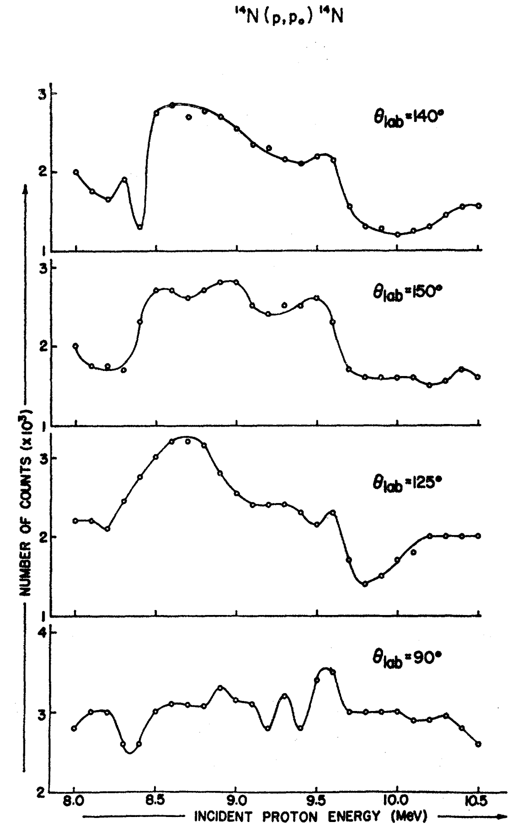

FIG. 3. Yield of elastically scattered protons as a function of incident energy for laboratory angles of 90°, 125°, 150° and 160°.

effects in the elastic proton group or in the α and ^{3}He groups.

A. Anomaly 'A'

The rise in the elastic cross section between 8.3 and 9.7 MeV does not have the shape of a single resonance. The yield of elastically scattered protons as a function of energy has been plotted in Fig. 3 for laboratory angles of 90°, 125°, 140°, and 150°. These angles correspond approximately to the angles in the center-of-mass system where the Legendre polynomials P_1, P_2, P_3, P_4 are zero. The rise above the mean level of scattering cross section is least at 90°. At other angles prominent peaks are seen. This behavior suggests a resonance for which the proton is scattered as a p wave. There is no corresponding anomaly in the inelastic channels. One must conclude that the width for decay into the inelastic channels is negligible in comparison with the elastic width. The resonance, therefore, corresponds to a single-particle state.

B. Anomalies in the Inelastic Scattering

There are three anomalies in the inelastic scattering, labeled B, C, and D in Fig. 1. The anomaly D centered near 10.5 MeV in the p_2 cross section has a width of about 1 MeV. There are no peaks in any of the other open channels. The angular distributions of this group in the energy region of this anomaly are shown in Fig. 4. Except, possibly, for an enhanced scattering in the forward direction, the angular distribution of this group does not change much with energy in the region of this peak.

The anomalies B and C are common to the p_4 and p_6 groups but are not seen in any of the other channels. Neither has the shape of a single resonance. The angular distributions of the two groups are given in Figs. 5 and 6. Both show significant changes at energies corresponding to the rise in cross sections.

NEUTRON MEASUREMENTS

We have used the spherical shell method to measure the total elastic and nonelastic scattering cross sections of neutrons on nitrogen in the region of 4–6.5 MeV. The method of measurement was similar to that used by us for the study of neutron resonances in carbon.[3] Liquid nitrogen was contained in the space between two con-

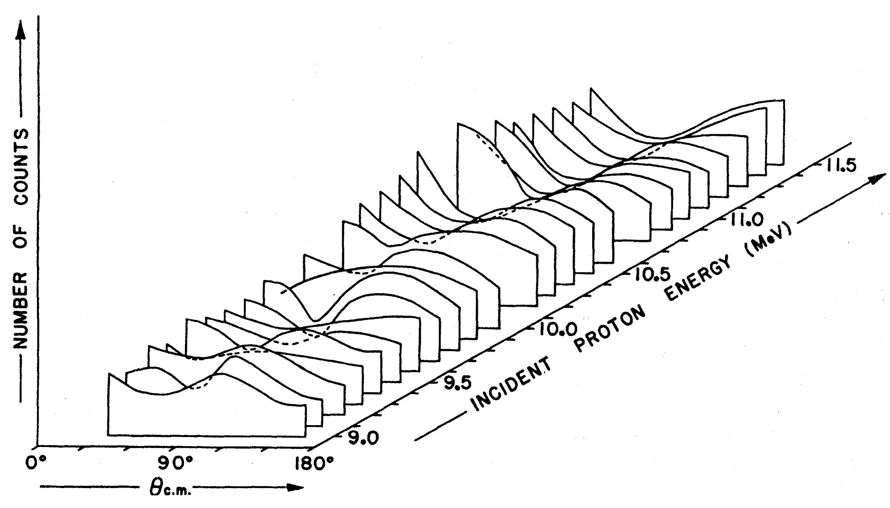

FIG. 4. Angular distributions for the p_2 protons in the region of anomaly D.

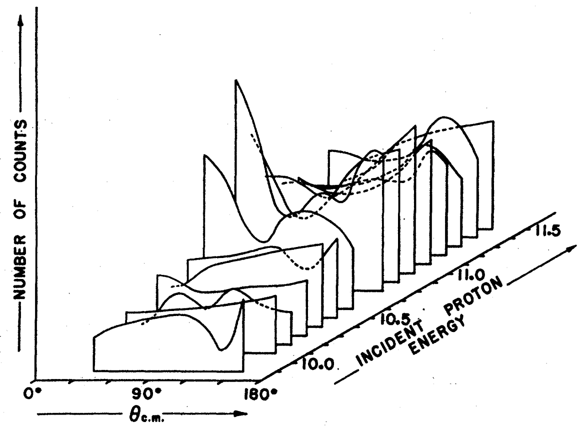

FIG. 5. Angular distributions for the p_4 protons in the region of anomalies C and B.

centric spherical containers made of Styrofoam. A liquid-scintillator[13] detector was located at the center of the inner container as shown in Fig. 7. The neutrons for the present measurements were obtained by bombarding an occluded deuterium target 1 mg/cm^2 in thickness with deuterons from the 4-MeV accelerator of The University of Texas. Only the neutrons in the forward direction were used and the neutron energy was changed by varying the incident deuteron energy between 0.75 and 3.3 MeV. The detector was connected to a photomultiplier through a Lucite light guide and a circuit which discriminated between neutrons and γ rays was used. The lowest neutron energy at which discrimination was effective was about 1.0 MeV. To eliminate inelastically scattered neutrons forming the first excited state of ^{14}N at 2.3 MeV, a bias was set so that only those recoil protons were recorded for which the energy was greater than the neutron energy less 2.3 MeV. This bias point, and the level of discrimination, fixes at about 3.0 MeV the lower limit of neutron energy for which this method is useful.

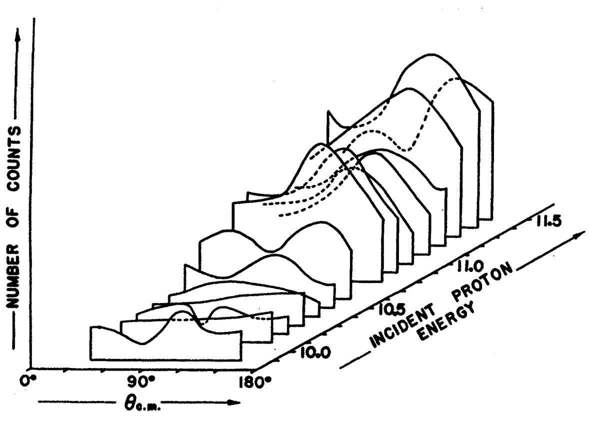

FIG. 6. Angular distributions for the p_6 protons in the region of anomalies C and B.

[13] Ne 213. Supplied by Nuclear Enterprises, Winnipeg, Man., Canada.

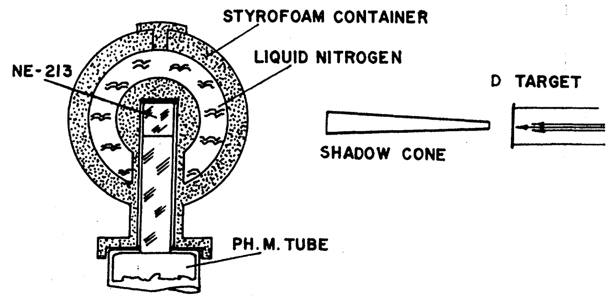

FIG. 7. Experimental arrangement for neutron measurements.

The results for the elastic scattering cross section are shown in Fig. 8. The scale of cross sections was fixed by assuming that the cross section at 6.3 MeV is 0.70 b, from the work of Bauer *et al.*[14] There is clear evidence of the broad resonance at 3.8 MeV. As anticipated, there is also a broad rise in the cross section centered at 5.3 MeV, having a width at half-maximum of about 0.4 MeV. A neutron energy of 5.3 MeV corresponds to an excitation energy of 15.8 MeV in the compound nucleus ^{15}N. This resonance therefore seems to be the analog of the 8.8-MeV proton resonance discussed above.

The energy spread of the neutrons used in these measurements was between 150 to 270 keV and arose partly from the thickness of the neutron source and partly from the energy variation in the angle subtended by the spherical scatterer at the source. This spread is sufficient to smooth out the numerous sharp resonances which appear in this energy region.

The results of the nonelastic cross-section measurements are shown in Fig. 9. There the scale in barns was fixed by calculating the cross section at 6.02 MeV by the standard method developed by Bethe *et al.*[15] for the sphere geometry. The transport elastic cross section was calculated taking the elastic scattering data of Chase *et al.*,[6] the effective density of liquid nitrogen being 0.746 g cm^{-3}.[3] There is clearly no resonance in the sum total of nonelastic processes near 5 MeV. The rise in nonelastic cross section above 5.7 MeV cannot be accounted for in terms of what is known about

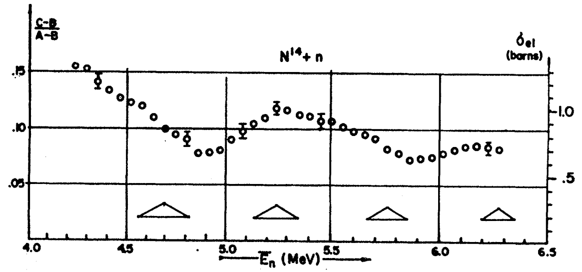

FIG. 8. Cross section for neutrons scattered elastically from nitrogen in the energy region between 4 to 6.5 MeV.

[14] R. Bauer, J. Anderson, H. Lutz, C. Wong, J. McClure, and B. Pohl, Nucl. Phys. A93, 673 (1967).

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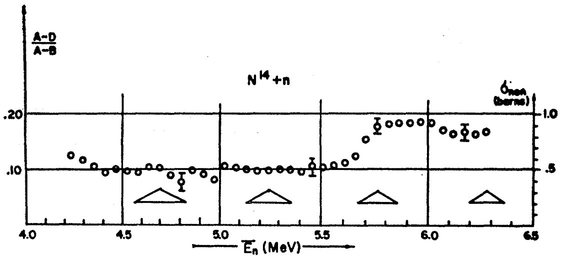

FIG. 9. Total nonelastic cross section for neutrons on ^{14}N in the energy range between 4 and 6.5 MeV.

inelastic scattering, the (n,t) or the (n,α) processes.[16] The (n,p) cross section, however, does not seem to have been measured in this energy range. If the cross sections of Figs. 8 and 9 are added, the total neutron cross sections so obtained are in good agreement with those of Becker and Barschall[10] in the energy range in which the two measurements overlap (4 to 5.5 MeV).

It had been intended to explore the elastic scattering cross section also in the interesting region between 6.5 and 13 MeV, which can be reached (in this laboratory) only with a deuteron beam using the tandem accelerator. However, the beam intensity available did not permit of making such measurements. Above 13 MeV, the elastic cross section was examined using neutrons from the $^3H(d,n)^4He$ reaction and the same arrangement, again using a bias on the neutron detector sufficient to remove neutrons scattered inelastically from the 2.3-MeV state of ^{14}N. These results also are shown in Fig. 10. There is no sign of any resonant effects up to a neutron energy of 20 MeV.

DISCUSSION

The present work shows a resonance in the elastic scattering of protons from nitrogen at a proton energy near 9 MeV and a resonance in the elastic scattering of neutrons from nitrogen at a neutron energy near 5.3 MeV. These two resonances correspond to the same excitation energy of about 15.5 MeV in the mirror nuclei ^{15}O and ^{15}N. The proton resonance is obviously not a single resonance, nor would one expect it to be for the coupling between the orbital angular momentum of the proton and the spin of the ^{14}N nucleus would be expected to give rise to states separated at most by a few hundred keV.

The proton resonance, as already noted, has no counterpart in the inelastic channels. That the neutron resonance is also mainly an elastic scattering resonance is clear from a consideration of its peak cross section, which is about 0.5 b (Fig. 8). Assuming that the resonance corresponds to a single state, this peak cross section should be $[330(2J+1)/6]\Gamma_n^2/\Gamma^2$ mb, where J is the spin of the compound state and Γ_n and Γ are the neutron width and the total width, respectively. Optical-model calculations of neutron transmission coefficients show that only s, p, and d waves are effective in nitrogen under these conditions.[17] It is clear that whatever spin is chosen consistent with these orbital angular momenta, the ratio Γ_n/Γ must be near unity. The Wigner limit for the reduced width is about 2.5 MeV. Thus the reduced width, which is here equal to the actual width (taking the transmission coefficient to be 0.5 [17]), is about 15% of the limit.

Two p-wave resonances of a single-particle type have been found[3] at excitation energies of 19.6 and 23 MeV in ^{13}C. If these are to be ascribed to shell structure one would expect similar states to appear in ^{15}N and ^{15}O at lower energies of excitation. If the 8.8-MeV proton resonance is of this type, then one might expect to see another at an energy 3 or 4 MeV higher or lower. There is no evidence for such a resonance up to an energy of 12 MeV, the upper limit of the present measurements. Results above 12 MeV are not yet available. Below 5.5 MeV, the elastic scattering of protons by nitrogen has been described by West.[18] There is again nothing in these results which would indicate the presence of such a resonance.

We assume that the 5.3-MeV neutron resonance in nitrogen is the ^{15}N analog of the 8.8-MeV proton resonance in ^{15}O (excitation energy, 15.8 MeV). There is no direct evidence of broad resonances in the work of Fowler and Johnson,[19] in which neutron resonances in nitrogen up to 2 MeV were studied (excitation energy 12.7 MeV). Mani and Dutt,[20] using the reaction $^{11}B(\alpha,n)^{14}N$, demonstrated the existence of a broad $\frac{3}{2}^-$ state with a large neutron width near 14.0 MeV ($E_\alpha=4.0$ MeV) and another ($\frac{1}{2}^+$) state at a lower energy ($E_\alpha=2.7$ MeV). The former presumably is the 3.8-MeV neutron resonance of Gabbard *et al.*[8] Lee and Schiffer,[21] using the reaction $^{11}B(\alpha,p)^{14}N$, showed that a predominantly proton emitting state of even parity also exists in this region. If the 5.3-MeV neutron resonance is p wave and has a partner nearby, such a state might be identified with a single-particle neutron state superposed on

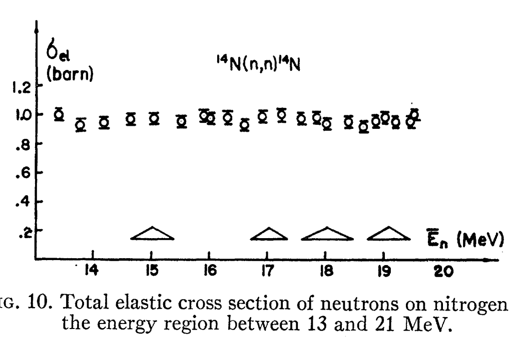

FIG. 10. Total elastic cross section of neutrons on nitrogen in the energy region between 13 and 21 MeV.

[16] *Brookhaven National Laboratory Report No.* 325 (U. S. Government Printing Office, Washington, D. C., 1964), Vol. 1.

[17] G. S. Mani, M. A. Melkanoff, and I. Iori, CEA 2380, Saclay, 1963 (unpublished).

[18] M. West, thesis, University of Texas, Austin, 1966 (unpublished).

[19] J. Fowler and C. Johnson, Phys. Rev. **98**, 728 (1955).

[20] G. S. Mani and G. C. Dutt, Nucl. Phys. **78**, 613 (1966).

[21] L. Lee and J. Schiffer, Phys. Rev. **115**, 160 (1959).

the 3.8-MeV resonance for the latter is remarkable in having a very high cross section for production of α particles, a fact which implies very high reduced widths relative to the Wigner limit for both neutrons and α particles. The possible existence of such a state was mentioned by Mani and Dutt.[20] However, if another broad p-wave state exists, it seems more likely that it will be found for neutrons above 6.5 MeV and for protons above 12 MeV.

Turning now to the anomalies in the elastic scattering of protons, it is clear that the only possible mechanism for these phenomena would seem to be the resonances to be expected for intermediate states. That they are not accompanied by rises in the integrated elastic cross section is to be expected, for a small elastic width relative to the total width will, at these energies, reduce the effect to invisible proportions. Clearly the configuration of the intermediate state should be reflected in the cross section of the inelastically scattered group. That the p_4 and p_6 groups are affected simultaneously is to be ascribed to a similarity in their structure, similar also to that of the intermediate state forming them. That these two groups do not respond to the excitation of p_2 shows clearly that their configurations are very different. [*Note added in proof.* One of us (BBK), through the courtesy of the Oak Ridge National Laboratory, has extended the measurements of the elastic scattering of neutrons from nitrogen up to an energy of 8.7 MeV, using a deuterium target and a deuteron beam in the 5.5-MeV Van de Graaff accelerator of that laboratory. These experiments confirmed the existence of the resonance at 5.3 MeV but gave no evidence of other resonant effects between it and 8.7 MeV.]

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Intermediate Structure and Particle-Hole States in Nuclear Reactions*

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The effects of nuclear two-particle–one-hole (2p-1h) states on the energy-averaged cross section are studied to see when they cause observable fluctuations. This is done by using the self-consistent perturbation methods of Brueckner to derive an optical potential for the elastic scattering of neutrons. It is then shown that for the case where the interaction between different 2p-1h states can be neglected and the coupling to more complicated configurations is small, the scattering matrix can be approximated to second order in the interaction by a slowly varying background term plus a resonant term. The width of this resonant term is shown to be equal to the escape width plus a spreading width caused by the coupling to the more complicated configurations. These widths are calculated for a number of 2p-1h configurations in various spherical nuclei in order to determine when the isolated resonance condition ($\Gamma < D$) is satisfied. It is found that for the light and doubly magic nuclei, individual resonances of this particluar type should be observable only for incident neutron energies below 2–3 MeV. At higher energies, the density of 2p-1h states and the widths are too large for the occurrence of individual resonances. In the heavier nuclei ($A \gtrsim 60$) with partially filled shells, the 2p-1h states are broadened so much by the decay to the more complicated states that individual 2p-1h states cause no observable effects. The possibliity of other types of states causing observable fluctuations is not considered.

I. INTRODUCTION

IT was originally shown by Brueckner *et al.*[1] that the relatively simple two-particle–one-hole (2p-1h) excitations in nuclei could cause observable fluctuations in nuclear-reaction cross sections. Recently, it has been suggested[2] that the intermediate structure observed in the energy-averaged neutron cross sections is an example of this type of excitation. The observed fluctuations appear with widths intermediate between those of the fine structure observed in low-energy high-resolution scattering experiments and those of the gross structure of the giant resonances. Much of the experimental evidence and the general philosophy of intermediate resonances are given in the papers by Rodberg and by

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