neutrons or excitation energy (E). The values of the average neutron energy (at 5.9 MeV per neutron) in Fig. 6 are proportional to $(E)^{0.4\pm0.15}$. This relationship reflects the increase in nuclear temperature with excitation energy. The excitation functions give information related to the energy and angular momentum of the first neutron emitted in the evaporation chain. A more detailed comparison of the results of this study with excitation function measurements is given in the following paper.[4]

C. Conclusions

To summarize this study we may list the following conclusions: (a) The reactions involving neutron emission that lead to Dy^{149}, Dy^{150}, and Dy^{151} proceed by compound-nucleus formation. (b) The energetics of the decay of Dy^{156} (excited to 65 to 125 MeV) to Dy^{149}, Dy^{150}, and Dy^{151} are almost the same for $C^{12}+Nd^{144}$ and for $O^{16}+Ce^{140}$ in spite of a difference of about 25% in $\langle J^2\rangle$. (c) Compound nuclei of low spin (as measured by reactions forming Tb^{149g}) have very different decay properties from those of high spin (as measured by reactions forming Dy^{149}, Dy^{150}, and Dy^{151}). (d) The low-spin compound systems dissipate less than about 12 MeV in photons; the remaining energy appears as kinetic energy of the emitted neutrons. (e) The compound systems of higher spin dissipate, on the average, about one-half their available excitation energy by photon emission. (f) For a given reaction, the average total photon energy (T_γ) increases almost linearly with the available energy, and extends to T_γ values of approximately 30 MeV for available energies of 50 to 60 MeV. (g) The average kinetic energy of the neutrons increases approximately as the square root of the excitation energy.

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Inelastic Scattering of 10.2-MeV Protons by N^{14}†

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The inelastic scattering of protons from N^{14} was studied at an incident proton energy of 10.2 MeV. Proton groups were observed corresponding to all the well-established N^{14} states below 8.0 MeV. No evidence was obtained for the levels at 7.60, 7.40, 6.60, and 6.05 MeV which were previously reported in this reaction. Angular distributions and total cross sections were measured for inelastic scattering to the N^{14} states between 3.95 and 7.03 MeV. The relative cross sections are found to be in rather good agreement with shell-model predictions.

I. INTRODUCTION

THE present investigation of the inelastic scattering of protons from N^{14} was undertaken for two reasons. First, previous work on this reaction was done at $E_p=9.5$ MeV by Burge and Prowse[1] using photographic emulsions to detect the scattered protons. These authors reported levels in N^{14} at 7.60±0.02, and 7.40±0.02 MeV, and probable levels at 6.60±0.04 and 5.95 MeV, in addition to the well-known levels[2] below 7-MeV excitation in N^{14}. Later, Hossian and Kamal[3] reported results from reading of emulsions which were a part of the same series of exposures used by Burge and Prowse.[1] Hossian and Kamal reported levels in N^{14} at 6.05±0.02 and 6.75±0.03 MeV in addition to the well-known levels. One purpose of the present work, then, was to study the proton spectrum from $N^{14}(p,p')N^{14}$ at a proton energy close to that of the previous work as a check on the existence of N^{14} levels near 7.6, 7.4, 6.7, and 6.0 MeV.

The second reason for undertaking this study was to obtain relative cross sections for excitation of the N^{14}

† Work performed in part under the auspices of the U. S. Atomic Energy Commission.
[1] E. J. Burge and P. J. Prowse, Phil. Mag. **1**, 912 (1956).
[2] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 1 (1959).
[3] A. Hossian and A. N. Kamal, Indian J. Phys. **31**, 553 (1957).

states below 8 MeV for comparison with shell-model predictions in order to gain some information concerning the wave functions of the N^{14} levels.[4]

II. EXPERIMENTAL PROCEDURE

The proton beam of the Brookhaven 60-in. Cyclotron was magnetically analyzed to a precision of ± 10 keV. The absolute energy was 10.25 ± 0.1 MeV. The beam of 3×10^{-9} to 20×10^{-9} A was collimated by a circular aperture of 2 mm diameter and directed into an evacuated scattering chamber, through a gas cell target containing natural nitrogen at 20 lb/in.^{2} absolute pressure, and into a Faraday cup. The gas cell target was 2 cm in diameter with the wall made of 0.15-mil Havar foil. Two detectors examined the particles emitted from the target. One detector, which served as a monitor, was left fixed at an angle of 90°; the other detector could be moved to any angle and was used to study the angular distribution of scattered particles. Each detector consisted of a stack of two fully depleted 0.5-mm thick gold-silicon surface barriers, about 12 mm in diameter. Each detector was collimated by a series of two rectangular slits; the first slit 2 mm wide and 3 mm tall located 1.4 cm distant from the center of the gas target, and the second slit 2 mm wide and 6 mm tall, located 8 cm from the center of the gas target. The detectors were located immediately behind the second slits. At the extreme forward and backward angles (20° and 160° to the beam) the target-to-slit distances of the movable counter were somewhat larger.

The pulses from the detectors were amplified in a conventional fashion; those originating in the movable detector were fed into a TMC 256 channel pulse-height analyzer, and those originating in the 90° monitor were simultaneously fed into a fast scaler. A channel was set so that only the pulses due to the elastic scattering were recorded by the monitor scaler. In order to obtain high dispersion in the energy region of primary interest, the ground- and first-excited states of N^{14} were not included in the energy spectrum at most of the angles.

Normalization to the monitor events at each angle permitted an accurate calculation of the relative angular distributions of the differential cross sections for the various N^{14} excited states without accurate measurements of variations in the beam current or target cell pressure.

In order to determine the absolute differential cross-section scale, the nitrogen in the gas cell was replaced with NH_3. Comparison at several angles of the $N^{14}(p,p')N^{14*}$ peaks with the peak from proton-proton scattering gave the information necessary for the calculation of the absolute cross sections, since the proton-proton scattering cross sections can be obtained to several percent accuracy by interpolation of the measured cross section in the energy region near 10-MeV

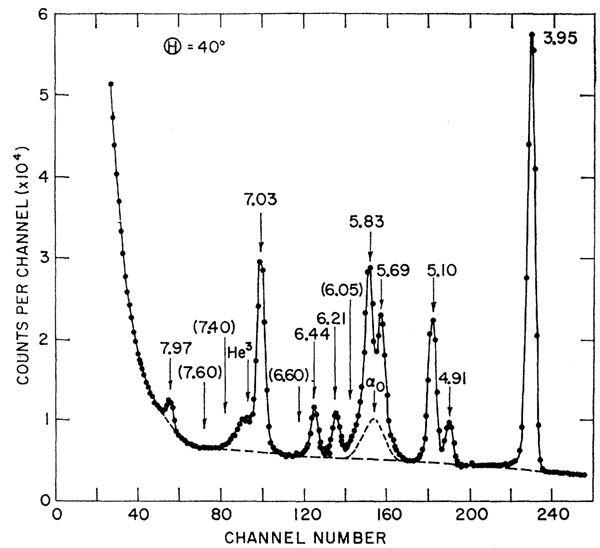

FIG. 1. Pulse-height spectrum of $N^{14}+p$ observed at 40° to the proton beam at a proton energy of 10.2 MeV. The proton peaks are labeled by the N^{14} excitation energy in MeV of the levels to which they are assigned. Unobserved peaks are indicated by arrows and excitation energies in parenthesis. The dashed curve shows the assumed course of the background including the α group from the $N^{14}(p,\alpha)C^{11}$ (ground state) reaction. The solid curve between channels 70 and 200 is a computer fit to the data (closed circles).

proton energy.[5] The effective gas target thickness was assumed to vary as $\csc\theta$, which is appropriate if the angular dispersion of the beam and of the inelastic protons can be neglected. Deviations from this assumption are estimated to amount to less than 10%; however, to allow for this uncertainty and others, a $\pm 10\%$ uncertainty is assigned to the absolute cross section which we shall quote.

III. EXPERIMENTAL RESULTS

Spectra were recorded every 10° from 20 to 160°. The 40 and 120° spectra are shown in Figs. 1 and 2. In both figures the inelastic proton groups are labeled by the excitation energies of the N^{14} levels to which they are assigned. All the well-established levels of N^{14} below 8.0 MeV are found to contribute to the proton inelastic scattering. In Fig. 1 the α group and He^3 group from the $N^{14}(p,\alpha)C^{11}$ and $N^{14}(p,He^3)C^{12}$ ground-state reactions are also evident. The various particle groups were identified by their energies and by their energy shift with angle. The detector could not view the foil of the gas cell directly; however, protons which were elastically scattered from the Havar foil could suffer a second elastic scattering, either from the Havar foil or the slits, and enter the detector. Most of the background in Figs. 1 and 2 above channel 60 is due to such events while some of the background also arises from

[4] E. K. Warburton and W. T. Pinkston, Phys. Rev. 118, 733 (1960).

[5] N. Jarmie and J. D. Seagrave, Los Alamos report LA-2014 (1957) (unpublished).

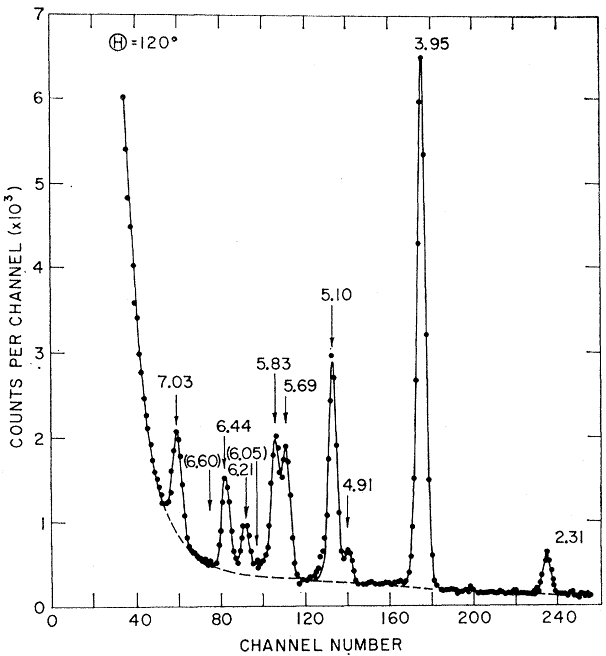

FIG. 2. Pulse-height spectrum of $N^{14}+p$ observed at 120° to the proton beam at a proton energy of 10.2 MeV. The proton peaks are labeled by the N^{14} excitation energy in MeV of the levels to which they are assigned. Unobserved peaks are indicated by arrows and excitation energies in parenthesis. The dashed curve shows the assumed spectrum of the background. The solid curve between channels 70 and 150 is a computer fit to the data (closed circles).

slit scattering. The sharply rising background which sets in below channel 60 is mainly due to neutrons. The detectors were encased on the sides by plastic and neutrons striking this plastic gave rise to recoil protons which could then enter the detector. In both figures the assumed spectrum of the background is indicated by dashed lines. At all angles the areas in isolated peaks were obtained by summing the counts in the region of the peak and subtracting the assumed background. This was true, for instance, for the 3.95- and 7.97-MeV peaks in Fig. 1, and the 2.31-, 3.95-, and 7.03-MeV peaks in Fig. 2. The areas in nonresolved peaks were obtained from a least-squares Gaussian-peak-fitting program for the IBM 7090 computer.[6] The regions between channel 70 and channel 200 in Fig. 1 and between channel 70 and channel 150 in Fig. 2 were analyzed in this manner. For these regions the solid line through the experimental points is the result of the computer fit. At $\theta=40°$, the intensity of the unresolved α peak corresponding to the $N^{14}(p,\alpha)C^{11}$ reaction leading to the C^{11} ground state (marked α_0 in Fig. 1) was estimated by the computer program. The greater widths of the He^3 and α groups is due to the energy spread resulting from energy loss in the N^{14} gas and the Havar foil. The proton peaks have the usual low-energy tails associated with solid state detectors. This tail is evident for the 3.95-MeV peaks in both Figs. 1 and 2, and for the 5.10-MeV peak in Fig. 1. The computer program assumes a Gaussian shape for the proton peaks; however, it was found that the error introduced by this assumption was negligible.

In Figs. 1 and 2 the expected positions of proton groups corresponding to energy levels at 7.60, 7.40, 6.60, and 6.05 MeV are indicated by excitation energies enclosed in parentheses. No evidence was seen at any angle for proton groups near these energies.

Angular distributions were obtained from analysis of

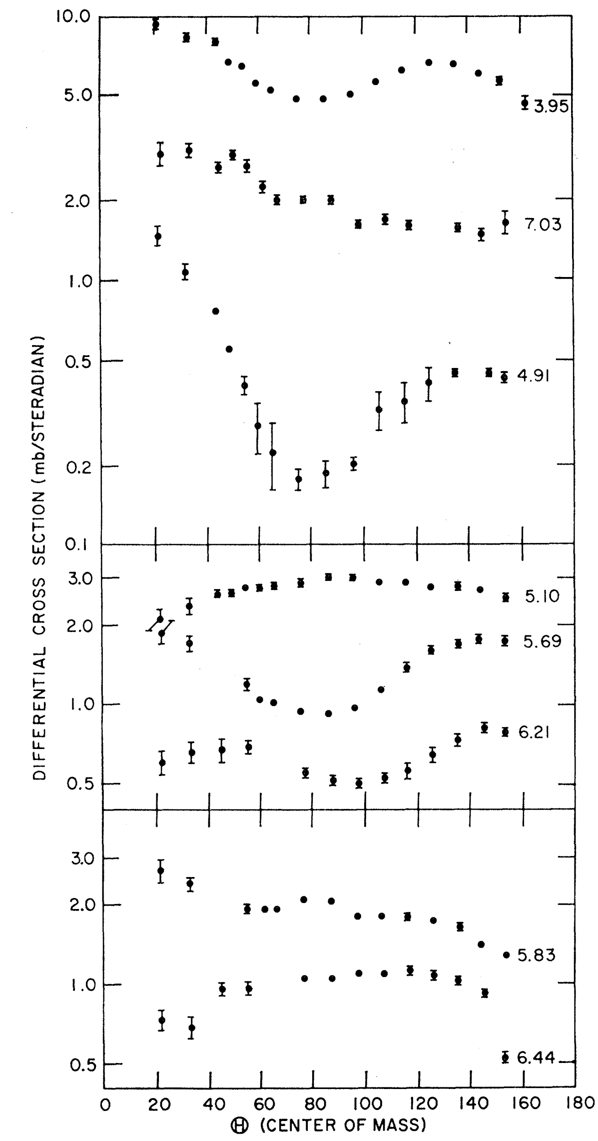

FIG. 3. Angular distributions for the inelastic scattering of 10.2-MeV protons from N^{14}. The distributions are labeled by the excitation energy in MeV of the N^{14} level involved. The cross-section scale has an uncertainty of 10% in addition to the errors assigned to the individual points. Error bars are omitted where they would fall within the diameter of the circles.

[6] P. McWilliams, W. S. Hall, and H. E. Wegner, Rev. Sci. Instr. **33**, 70 (1962).

the proton spectra for inelastic scattering to the levels between 3.95 and 7.03 MeV and are shown in Fig. 3. There does not appear to be any simple correlation between the known properties of the N^{14} states and the shapes of the angular distributions. The distributions are all asymmetric with respect to 90° and have the general form found for (p,p') distributions in light nuclei, and associated with the direct interaction mechanism with initial and final state interactions.[7]

IV. CONCLUSIONS

We observed no evidence for N^{14} levels near 7.6, 7.4, 6.6, and 6.0 MeV. Because the relative cross sections for any of these levels, if they exist, must be many times smaller than reported previously,[1,3] and since we used the same reaction but with much better statistics, we conclude that the previous evidence from the $N^{14}(p,p')N^{14}$ reaction for the existence of levels near these excitation energies is clearly refuted by our results. In the course of our work we found that the inelastic scattering of protons from N^{14} has been investigated recently by Brown[8] at $E_p=10.5$ MeV with results quite similar to ours. In this investigation spectra were taken every 10° at laboratory angles between 20 and 80° to the beam and no evidence was found for any but the well-established levels of N^{14} in agreement with the present results. We also note that the inelastic scattering of α particles from N^{14} has been studied with magnetic analysis of the scattered α particles[9] and in this work no evidence was found for N^{14} levels near 7.6, 6.6, or 6.0 MeV. Thus, there is no evidence for N^{14} states near these energies from the inelastic scattering of either protons or α particles. In the $N^{15}(He^3,\alpha)N^{14}$ reaction, however, Clayton[10] has reported observation of a state at 6.05 MeV, while admitting that some doubt might remain concerning its assignment to N^{14}. No evidence for the 7.6-, 7.4-, or 6.6-MeV states was seen in this reaction.

The total cross sections for inelastic scattering of 10.2-MeV protons from N^{14} were obtained for the N^{14} states between 3.95 and 7.03 MeV by integrating the angular distributions of Fig. 3 over the total sphere. The results are given in Table I. Also given in Table I are predictions for the relative cross sections for the plane-wave direct interaction theory of inelastic scattering. These predictions are normalized to the cross section for the 7.03-MeV level. The predictions were calculated assuming an inert spin-zero C^{12} core

TABLE I. Total cross sections for inelastic scattering of 10.2-MeV protons from N^{14}.

E_{ex} (MeV)	σ_T (mb)[a]	Shell-model assignment	Theoretical cross section[b] (arbitrary units)
7.03	27.2	$p_{1/2}p_{3/2}$, $J^\pi=2^+$	27.2
6.44	12.7	$s_{1/2}d_{5/2}$, $J^\pi=3^+$	0
6.21	7.6	$s_{1/2}^2$, $J^\pi=1^+$	0
5.83	25.0	$p_{1/2}d_{5/2}$, $J^\pi=3^-$	20.8
5.69	16.3	$p_{1/2}s_{1/2}$, $J^\pi=1^-$	12.0
5.10	34.0	$p_{1/2}d_{5/2}$, $J^\pi=2^-$	27.6
4.91	5.6	$p_{1/2}s_{1/2}$, $J^\pi=0^-$	6.4
3.95	77.0	$p_{1/2}p_{3/2}$, $J^\pi=1^+$	37.6

[a] Experiment, uncertain to ±10%.
[b] Normalized to σ_T(mb) for the 7.03-MeV level (see text).

and the jj-coupling assignments of the last two nucleons in the N^{14} state and the spin of the N^{14} state which are listed in Table I. The theoretical predictions, which are taken from Warburton and Pinkston,[4] were calculated using volume integration of harmonic oscillator radial wave functions, and have been approximately corrected for the dependence of the cross section upon excitation energy by multiplying the theoretical results by $[10.2+(15/14)Q]^{1/2}$. The wave functions for the N^{14} 6.21- and 6.44-MeV levels are taken from recent work of True[11] who obtained predominant configurations for the other levels in agreement with those listed in Table I. The approximations made in obtaining the theoretical predictions were discussed more fully by Warburton and Pinkston.[4]

We consider the agreement between the theoretical predictions and experiment to be very good for the odd parity states (i.e., $p_{1/2}s_{1/2}$ and $p_{1/2}d_{5/2}$) listed in Table I, and reasonable for the 3.95-MeV level. This agreement reinforces the configuration assignments given for these levels[4,11] and suggests that the tentative assumption we have made, namely, that the reaction mechanism is predominantly a direct interaction, is correct. The cross sections for excitation of the 6.21- and 6.44-MeV levels are predicted to be zero since these levels are assigned "doubly excited" wave functions. However, the theoretical results of True[11] suggest that the N^{14} ground-state wave function contains a $\sim$10% contribution from the "doubly excited" (s,d) configuration, while the N^{14} 6.21- and 6.44-MeV levels contain some $p_{1/2}^2$ and $p_{1/2}p_{3/2}$ impurities. Thus, we should not be surprised to find the 6.21- and 6.44-MeV levels excited with cross sections $\sim$1/10 of the cross section for the 3.95-MeV level and, at the same time, to find the other predictions to be in error, due to this admixing, by 25% or so. These results, then, give some support to the theoretical finding made by True as to the order-of-magnitude of the mixing of the low-lying p^2 and (s,d) states of N^{14}.

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[8] R. E. Brown, Astrophys. J. **137**, 338 (1963).
[9] D. W. Miller, B. M. Carmichael, U. C. Gupta, V. K. Rasmussen, and M. B. Sampson, Phys. Rev. **101**, 740 (1956).
[10] D. D. Clayton, Phys. Rev. **128**, 2254 (1962).
[11] W. W. True, Phys. Rev. **130**, 1530 (1963).