TABLE I. Summary of levels observed in the present experiment and in other type reactions.

O^{16*a} (Mev)	O^{16*b} (Mev)	Γ^b (kev)	Reaction
15.83	15.79	30	(p,α)
16.04			
16.20	16.21	23	(p,n)
(16.38)	16.44	24	(p,α)
16.59			
16.81	16.75		(γ,α)
	16.82		(p,α)
17.10	17.12	41	(p,n)
	17.24[c]	280	(p,γ)
17.28	17.29	84	(p,n)
	17.30		(γ,α)

[a] Present experiment.
[b] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959).
[c] N. W. Tanner, G. C. Thomas, and W. E. Meyerhof, Nuovo cimento **14**, 257 (1959).

at 10.81 Mev which has previously not been observed. The uncertainties in the zero-order cross section indicated in Fig. 2 are due to statistical errors in the yields.

The oxygen zero-order cross section (bars) together with the final cross section (solid curve) are shown in Fig. 3. The latter curve was obtained by assuming $T(E,k)$ to be triangular with a small negative component for values of $k \geqslant E-10\Delta$. The results indicate the presence of a number of excited states in O^{16}. The energy assignments for these states are tabulated in Table I and compared with the known level scheme. The resonance observed at 16.38 Mev is indefinite and requires further investigation. The excited states at 16.04 Mev and 16.59 Mev have previously not been reported. The cross section presented in Fig. 3 is based on analysis in 55-kev intervals for two sets of data displaced 27 kev. The cross-section values are order of magnitude based on a rough estimate of the normalization factor g.

The above results were obtained from yield data taken without previous intentions of applying this type of analysis. Plans are now being implemented to acquire data specifically for this purpose.

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The author is indebted to Professor J. Halpern for many helpful discussions and to Dr. E. G. Muirhead for assistance in obtaining data.

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Evidence for the Statistical Model Obtained from (p,n) Spectra of the Odd-Even Elements V, Mn, Co, Nb, Rh, and In†

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Spectra of neutrons emitted from (p,n) reactions have been measured for the essentially monoisotopic odd-even elements V, Mn, Co, Nb, Rh, and In. The 7–8 Mev protons used were obtained from the Livermore 90-in. cyclotron. Neutron energy distributions were determined using time-of-flight techniques. Experimental results indicate agreement with the compound statistical model of the nucleus. Relative level densities obtained in this manner were found to increase with atomic weight as theoretically expected. Assuming a level density of the form $\exp[2(a\epsilon)^{\frac{1}{2}}]$, a values were obtained which varied as $a=A/13$.

INTRODUCTION

MEASUREMENTS of particle spectra emitted from nuclear reactions in the energy region below 30 Mev have been carried out by many investigators. Results of these measurements have been compared with theoretical calculations derived from the compound statistical model[1] of the nucleus, with various direct interaction models of the nucleus, and with various combinations of the two models.

Discrepancies between experiment and theoretical predictions of the statistical model have been observed.[2–8] Gugelot[2] measured inelastic scattering in various medium-atomic-weight targets using 18-Mev protons. He also measured neutron spectra arising from nuclear excitation produced by 16-Mev protons. Both of the experiments showed a considerable excess of high-energy particles over that expected according to the compound statistical model of the nucleus. Moreover, anisotropic behavior was observed; an excessive

† This work was done under the auspices of the U. S. Atomic Energy Commission.
[1] J. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952).

[2] P. C. Gugelot, Phys. Rev. **81**, 51 (1951), and Phys. Rev. **93**, 425 (1954).
[3] E. R. Graves and L. Rosen, Phys. Rev. **89**, 343 (1953).
[4] E. B. Paul and R. L. Clarke, Can. J. Phys. **31**, 267 (1953).
[5] O. Hirzel and H. Waffler, Helv. Phys. Acta **20**, 373 (1947); and H. Waffler, Helv. Phys. Acta **23**, 239 (1950).
[6] B. L. Cohen, E. Newman, R. A. Charpie, and T. H. Handley, Phys. Rev. **94**, 620 (1954).
[7] S. G. Forbes, Phys. Rev. **88**, 1309 (1952).
[8] R. M. Eisberg and G. J. Igo, Phys. Rev. **93**, 461 (1954).

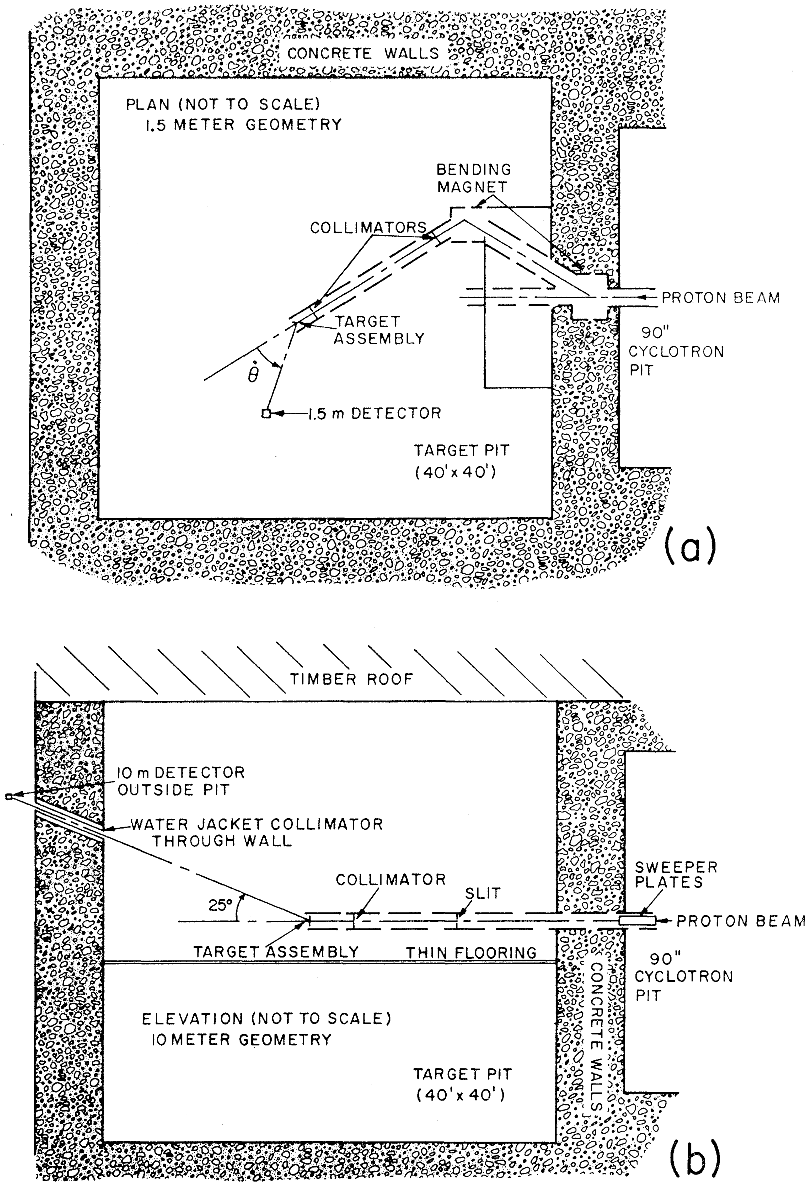

FIG. 1. Experimental geometry for (a) 8-Mev and (b) 7-Mev measurements.

number of high-energy particles were emitted in the forward hemisphere, particularly at the higher bombarding energies. Similar behavior was observed by Graves and Rosen[3] who studied inelastic scattering of 14-Mev neutrons. These results were explained as possibly due to contributions to the cross section from direct reactions. Also, experimental data on the cross sections for emission of charged particles when compared with predictions of the compound statistical model have suggested that this theory is unsatisfactory.[4–8]

Brown and Muirhead[9] have attempted to explain the above discrepancies as due to neglect of direct interactions and lack of suitable level-density data. They compared experimental data[2,4] with a model based on a combination of direct and compound nucleus interactions. The theory correctly reproduced shapes of energy spectra and angular distributions but failed to predict correct cross-section magnitudes.

Since the energy of the incident particle in the above-mentioned experiments was large enough to permit evaporation of more than one nucleon, it is necessary to unravel the primary spectrum from the experimental data, thereby introducing additional uncertainties. In the present experiment, the incident proton energy was chosen low enough to prohibit secondary particle reactions and to reduce the likelihood of direct interactions.

Choice of a (p,n) experiment has advantages over

[9] G. Brown and H. Muirhead, Phil. Mag. 2, 473 (1957).

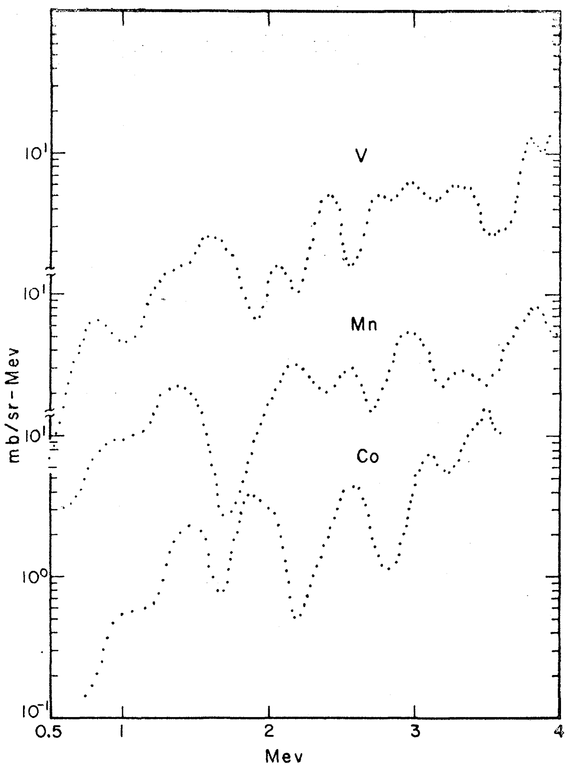

FIG. 2. (p,n) differential cross section vs excitation energy for 7-Mev protons incident on V, Mn, and Co targets.

an (n,n') experiment of lower neutron background and avoidance of multiple scattering corrections. It has an advantage over a (p,p') experiment in that no large Coulomb corrections are needed to interpret the data. Furthermore, at the low energies neutron emission dominates proton emission due to the effect of the Coulomb barrier.

EXPERIMENTAL PROCEDURE

The Livermore 90-inch variable-energy cyclotron was utilized as a source of 7–8 Mev protons. (p,n) spectra were obtained for the essentially monoisotopic elements V, Mn, Co, Nb, Rh, and In, which span the medium-weight region of the periodic table.

The time-of-flight instrumentation used to obtain these results has been previously described.[10] The physical arrangement of the apparatus is shown in Fig. 1. The 7-Mev measurements were obtained at a flight path of 10 meters, corresponding to a resolution of about 4% for 2-Mev neutrons. The 8-Mev measurements were obtained at a flight path of 1.5 meters with a resolution of about 15% for 2-Mev neutrons.

The detector was a 1-in. diam by 1-in. thick plastic scintillator. For angular distribution measurements it was mounted on a remotely controlled angle changer which was centered at the target. The system utilized an Argonne-type 256-channel pulse-height analyzer.

Targets were prepared by evaporating the metals on highly polished 20-mil thick tantalum plates. Target thicknesses were about 3 mg/cm², and the evaporation geometry was such that there was less than 1% non-uniformity. Beam collimation defined a spot about $\frac{1}{2}$ in. in diameter centered on the 2-in. diam target area. The position of the beam was checked periodically by means of a television camera which transmitted the fluorescent spot produced when a quartz disk was remotely inserted into the target position. The results indicated no serious effect from beam wandering in these experiments.

The beam energy spread due to target thickness was about 200 kev. Since compound-nucleus level spacings are generally less than 1 kev in this region, a large number of compound-nucleus levels participate in these reactions. Also, the instrumental resolution was generally broad enough to include a large number of levels in the residual nucleus.

The detector bias used limits the usable data to the energy region above 2 Mev. The usable data are limited at high neutron energies by the reduction of intensity which becomes comparable to the experimetal background. The useful range of measurement is further restricted by unfavorable reaction Q values. Consequently, at 8 Mev the region of useful data is

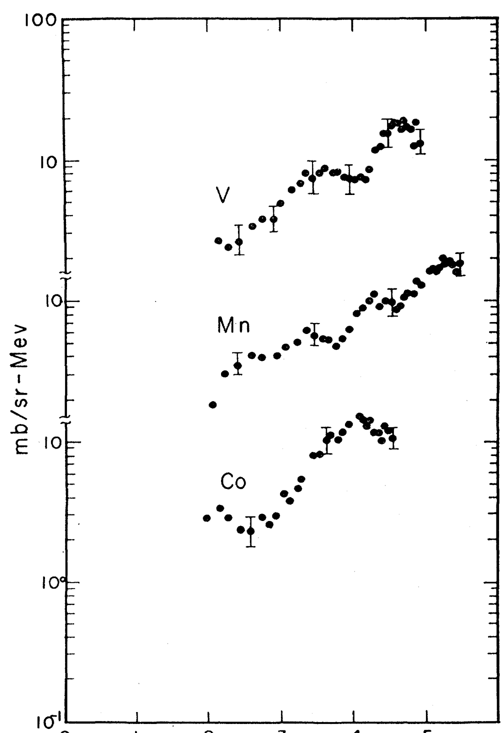

FIG. 3. (p,n) differential cross section vs excitation energy for 8-Mev protons incident on V, Mn, and Co targets.

[10] C. Wong, J. D. Anderson, C. Gardner, J. W. McClure, and M. P. Nakada, Phys. Rev. 116, 164 (1959).

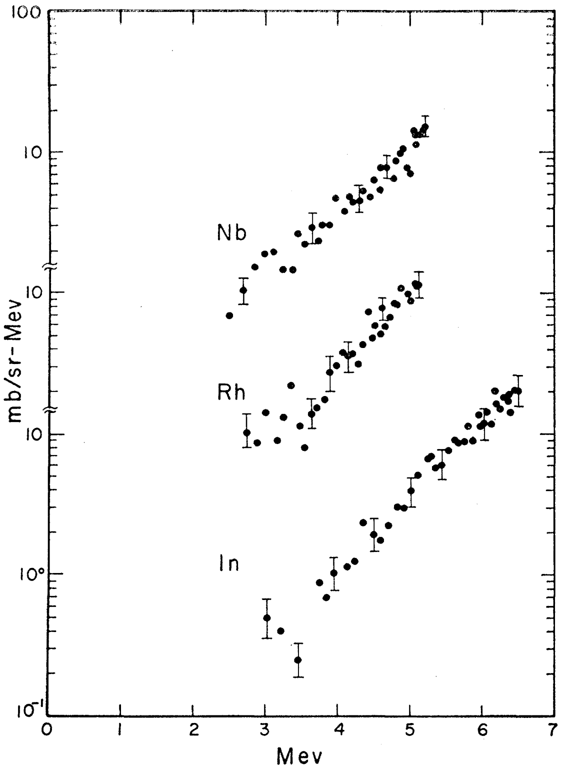

FIG. 4. (p,n) differential cross section vs excitation energy for 8-Mev protons incident on Nb, Rh, and In targets.

restricted to an excitation energy range of about 2.5–5 Mev.

As shown in Fig. 1, in the 7-Mev experiment neutrons were collimated and detected outside the (5 ft thick) concrete wall of the target pit. The smaller background plus the higher resolution enabled extension of these measurements to lower residual nucleus excitations than was possible for the 8-Mev measurements. The region of useful 7-Mev data is in the excitation energy region of about 1–4 Mev. The 7-Mev measurements were all carried out for a scattering angle of 25°. The 8-Mev data were measured as a function of scattering angle for angles between 0° and 120°.

Neutron spectra obtained for 7-Mev incident protons on V, Mn, and Co targets are plotted against excitation energy in Fig. 2. (p,n) thresholds of 1.56, 1.02, and 1.89 Mev were used for V, Mn, and Co nuclei, respectively.[11] Available level-spacing information indicates that the structure observed in these spectra is due to several groups of levels. It is interesting to note general similarities in the group structure observed for these three nuclei.

Results for 8-Mev incident protons are shown in Figs. 3 and 4, which are neutron spectra obtained at 30° plotted as a function of excitation energy. Broadly resolved groups of levels are again observed, in agreement with the 7-Mev data, although not as pronounced as before because of the poorer resolution of the 8-Mev measurements. The angular distributions which were measured at 0, 30, 60, 90, and 120° indicate isotropy for the entire spectrum to within about 10% experimental error. It is planned to study angular distributions of these prominent groups in future experiments.

The angular distribution being consistent with expectation from compound nucleus theory,[12] a comparison of the energy spectra with theory according to the compound statistical model was made. If a sufficient number of nuclear levels are involved in both the compound nucleus and the residual nucleus, the energy distribution of neutrons emitted for an incident proton energy ϵ_0 is given by[1]

$$P(\epsilon)d\epsilon = K\epsilon\omega(\epsilon_0+Q-\epsilon)\sigma_c(\epsilon)d\epsilon, \quad (1)$$

where $\omega(\epsilon_0+Q-\epsilon)$ is the level density of the residual nucleus at its excitation energy, which is determined by the incident proton energy ϵ_0, the Q value of the reaction, and the emitted neutron of energy ϵ; $\sigma_c(\epsilon)$ is the reaction cross section for the inverse reaction between the residual nucleus and a neutron of energy ϵ. The constant K is a function of the incident proton energy.

If we represent the nucleus by means of a degenerate

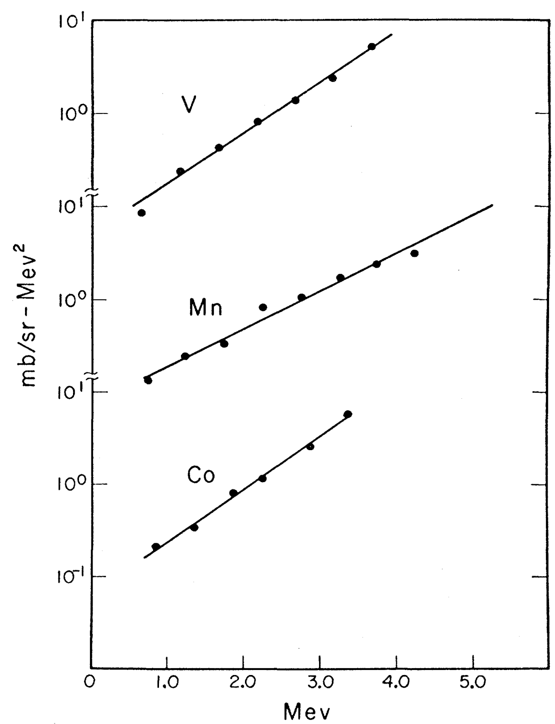

FIG. 5. Semilogarithmic plot of $n(\epsilon)$ vs excitation energy for 7-Mev protons incident on V, Mn, and Co targets.

[11] V. J. Ashby and H. C. Catron, University of California Radiation Laboratory Report UCRL-5419, February, 1959 (unpublished).

[12] W. Hauser and H. Feshbach, Phys. Rev. 87, 366 (1952).

Fermi gas, the level density is of the following form[13]:

$$\omega(\epsilon_0+Q-\epsilon)=C\exp\{2[a(\epsilon_0+Q-\epsilon)]^{\frac{1}{2}}\},\qquad(2)$$

where C and a are constants determined by the detailed structure of the model. Thus we obtain

$$n(\epsilon)=\text{const}\times\exp\{2[a(\epsilon_0+Q-\epsilon)]^{\frac{1}{2}}\},\qquad(3)$$

where $n(\epsilon)=P(\epsilon)/\epsilon$, since it has been shown that the reaction cross section varies slowly with neutron energy in the energy region of interest.[14]

The experimental spectra were divided by neutron energy to obtain $n(\epsilon)$. Figure 5 is a plot of $n(\epsilon)$ versus excitation energy for the 7-Mev V, Mn, and Co data. These curves were obtained by averaging the experimental data over large energy intervals. The 0.5-Mev width of the energy interval was chosen to smooth out the spectral structure referred to previously. Figure 6 is a plot of $n(\epsilon)$ versus excitation energy for the 8-Mev data which was also averaged over 0.5-Mev energy intervals.

If the emitted neutron energy ϵ is small compared to the maximum excitation energy (ϵ_0+Q), a Taylor expansion of the logarithm of the level density about ϵ_0 gives the following rough approximation[1]:

$$n(\epsilon)=\text{const}\times e^{-\epsilon/\theta},\qquad(4)$$

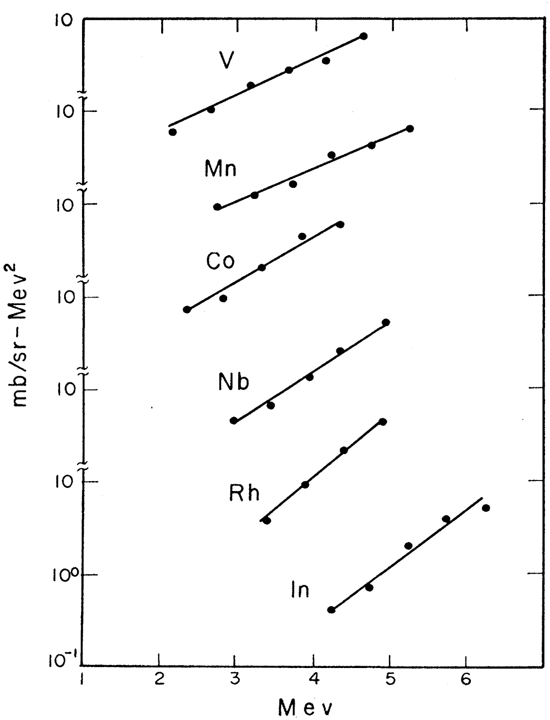

FIG. 6. Semilogarithmic plot of $n(\epsilon)$ vs excitation energy for 8-Mev protons incident on V, Mn, Co, Nb, Rh, and In targets.

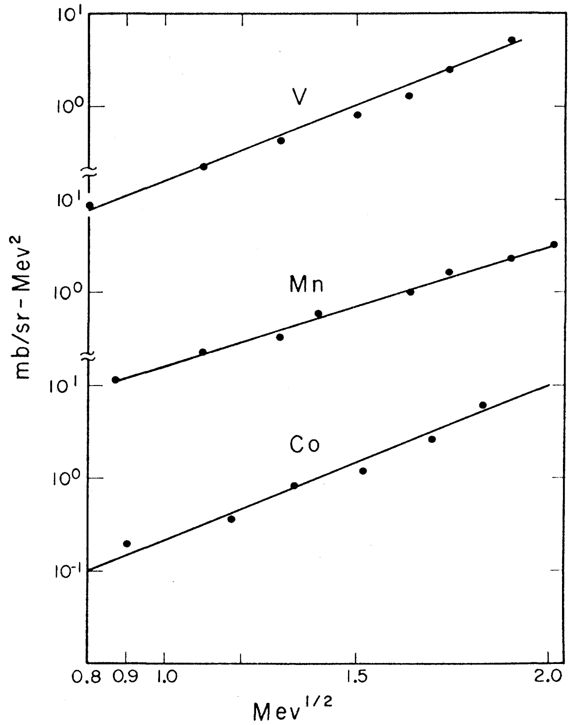

FIG. 7. Semilogarithmic plot of $n(\epsilon)$ vs square root of excitation energy for 7-Mev protons incident on V, Mn, and Co targets.

where we again assume a constant inverse reaction cross section. The quantity θ, which is called the temperature of the nucleus, can be obtained by straight-line fits to the logarithmic curves plotted against excitation energy in Figs. 5 and 6. Values of θ were obtained in this manner and are tabulated in Table I. The 8-Mev proton energy data values represent the temperature obtained by averaging the data over all scattering angles that were measured.

Figures 7 and 8 show the experimental data for $n(\epsilon)$ plotted against the square root of excitation energy. According to expression (3), there should be a straight-line fit to the data presented in this way. It is difficult to say whether the exact expression (3) or the Maxwellian approximation, Eq. (4), is in better accord with the experimental results. However, it is clear that the data can be fitted with one or the other of the theoretical expressions, in contrast to previous results obtained at higher energies[2] where neither theoretical expressions agreed with experimental data.

More accurate experimental data are needed to decide whether the exact or the approximate theoretical distributions better represent the experimental results.

In Fig. 9, values of a derived from fitting the data of Figs. 7 and 8 and (α,p) data for nickel[15] are plotted against atomic weight. Values of a, determined from

[13] H. A. Bethe, Revs. Modern Phys. **9**, 85 (1937).

[14] J. R. Beyster, M. Walt and E. W. Salmi, Phys. Rev. **104**, 1319 (1956).

[15] R. Fox and R. D. Albert, University of California Radiation Laboratory Report UCRL-5919 (unpublished).

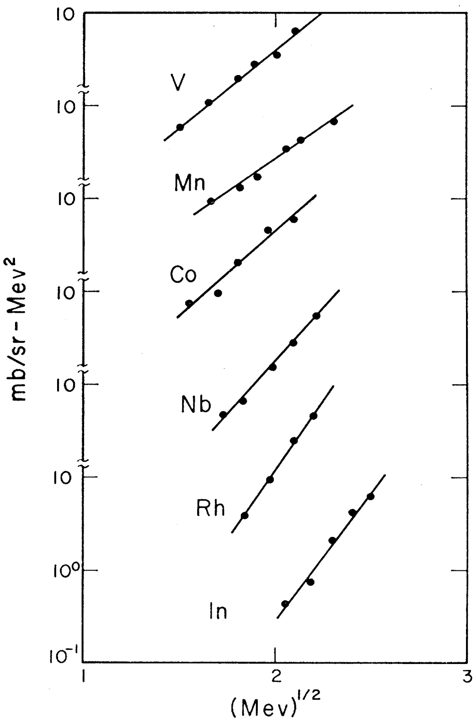

FIG. 8. Semilogarithmic plot of $n(\epsilon)$ vs square root of excitation energy for 8-Mev protons incident on V, Mn, Co, Nb, Rh, and In targets.

TABLE I. Values of a and θ as obtained from (p,n) data of this paper.

Element	$\epsilon_0=7$ Mev θ	a	$\epsilon_0=8$ Mev θ	a
V^{51}	0.78	3.6	0.98	3.3
Mn^{55}	1.1	2.2	1.1	2.7
Co^{59}	0.76	3.7	0.85	4.2
Nb^{93}			0.73	7.6
Rh^{103}			0.70	8.7
In^{115}			0.65	8.6

these slopes, are found to increase with atomic weight as predicted by theory. As shown in Fig. 9 they can be approximately represented by the relationship $a=A/13$. This is in fair agreement with the dependence, $a=A/\alpha$, with $\alpha=10.5$ predicted by the Fermi gas model.[13] A larger value of α is predicted when exchange forces are included in the theory.[16]

These results for a may be compared with those obtained from information on nuclear levels measured at low excitation energy (≈ 1 Mev) and at nucleon binding energies (≈ 7-Mev excitations). If we assume an uncertainty of a factor of 2 in level density due to poor level statistics and effect of spin selection rules, values for a can be determined with about 20% error, and to this accuracy agree with the a values reported in Table I.

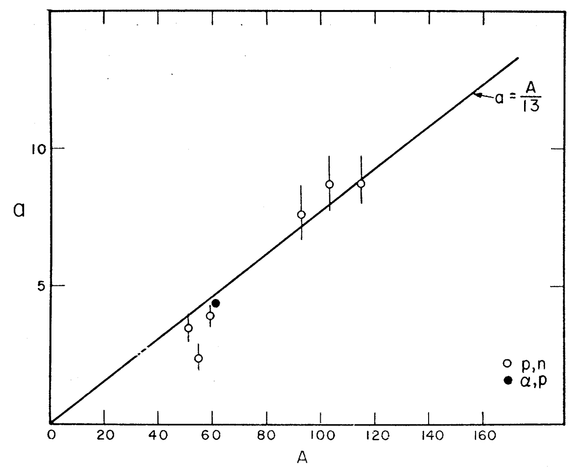

FIG. 9. Plot of a vs atomic weight as obtained from (p,n) data of this paper and (α,p) data of reference 15.

CONCLUSION

Angular distributions and energy spectra have been measured and compared with predictions of the statistical theory of the compound nucleus for odd-even nuclei in the medium-weight region of the periodic table. In contrast to the experimental results at higher energies, the present data, when averaged over detailed structure, indicate that (p,n) reactions in the 7-Mev energy region can be adequately described by the statistical model of the nucleus. Similar conclusions have been reached by Bramblett and Bonner[17] who observed neutron spectra from 5.5-Mev incident protons for elements in the region $A=90$ to $A=120$ using an experimental technique different from that of this paper.

ACKNOWLEDGMENTS

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[16] J. Bardeen, Phys. Rev. 51, 799 (1937).

[17] T. W. Bonner (private communication).