TABLE I. Experimental results. Given are the Q's for each reaction, the mass, the mass excesses $(M-A)$, and the energy of the first excited state.

	Ar^{42}	Cl^{39}
Q value	7.046±0.040 Mev [$Ar^{40}(t,p)$]	7.259±0.040 Mev [$Ar^{40}(t,\alpha)$]
Mass ($C^{12}=12$)	41.963043±0.000043 amu	38.968037±0.000043 amu
Mass ($O^{16}=16$)	41.976384±0.000043 amu	38.980425±0.000043 amu
$(M-A)$ ($C^{12}=0$)	−34.423±0.040 Mev	−29.772±0.040 Mev
$(M-A)$ ($O^{16}=0$)	−21.990±0.040 Mev	−18.227±0.040 Mev
First excited state	1.138±0.030 Mev	0.364±0.030 Mev

the ground-state decay is energetically favorable. A rough calculation using this assumption, a reasonable ft value (10^{-7} or 10^{-8}), and a value for the half-life of 10 to 100 years (compatible with the known value[2] of "greater than 3.5 years") leads to a prediction for the $(M-A)$ of Ar^{42} in the range from −34.0 to −34.4 Mev ($C^{12}=0$), in good agreement with our measured value of −34.42 Mev. Even larger values of the half-life do not significantly change this result. Our measurements predict a beta-decay energy of 0.583±0.045 Mev.

To eliminate the possibility that we had missed the ground-state group for Ar^{42}, a search was made for a higher-energy proton group. No proton groups were found for several Mev higher than the assigned ground-state group; if the ground-state group were higher than the range of our search, Ar^{42} would have to be stable with respect to beta decay to K^{42}. Our value for the mass excess ($C^{12}=0$) of Cl^{39} of −29.772±0.040 Mev agrees with the previously determined value of −29.803±0.021 Mev.[3]

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Protons from Alpha-Induced Reactions*

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The results of proton energy spectra measured at several angles from 30.5-Mev alpha particle induced reactions on Al^{27}, V^{51}, Co^{59}, As^{75}, Nb^{93}, Rh^{103}, In^{115}, and Ta^{181} were analyzed using the statistical model. The analysis yielded the differential cross section $d^2\sigma/d\Omega dE$ and the relative level density $\omega(E)$ of the residual nucleus as a function of proton and excitation energy of the residual nucleus. The nuclear temperature $1/T\equiv d(\ln\omega)/dE$ and the level density parameter a of $\omega=C\exp[(aE)^{\frac{1}{2}}]$ were obtained. The energy and angular dependence of the spectra are adequately described by the statistical model at back angles, with the indication of the presence of a direct-reaction mechanism contribution at forward angles, which extends to high excitation energies.

1. INTRODUCTION

A VARIETY of nuclear reaction mechanisms have been proposed to implement the understanding of medium-energy nuclear reactions. In particular, descriptions such as the compound nucleus model and direct reaction mechanisms have enjoyed varying amounts of success for different reaction particles and conditions. The direct (fast) interaction description and the compound nucleus model (slow) are logical extreme limits of reactions proceeding through a compound nuclear system as visualized by Weisskopf[1] as an intermediate stage between the initial independent particle stage and the final emission stage. Once the compound system has been formed by the removal of a particle from the entrance channel, the reaction may proceed to the final emission stage by one of two courses. It may lead to compound nucleus formation and subsequent decay, or it may proceed by a direct-reaction mechanism to the final stage.

The description of an actual reaction, the present experiment being no exception, lies rarely on one of these limits but usually somewhere between them.

If it is desired to obtain information about one of these limits (compound nuclear process in this experi-

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[1] V. F. Weisskopf, Revs. Modern Phys. **29**, 174 (1957).

ment), it is necessary to know how the relative importance of different reaction mechanisms change with such things as bombarding energy, excitation energy of the residual nucleus, angle of emission, and target mass.

Inasmuch as the number of degrees of freedom involved in the reaction varies continuously from only a few in the limit of simple direct reactions to many in the limit of complete compound-nucleus formation, the excitation of the residual nucleus may be expected to show a similar variation, yielding correspondingly more energetic particles from direct reactions.

Although sometimes insignificant in their contribution to the total reaction cross section, the presence of the direct process is readily detected as forward deviations from the isotropy in the angular distribution of reaction products, since the statistical model predicts isotropy (or symmetry about 90° c.m. at a minimum) in the angular distribution.[2,3] Such deviations from isotropy constitute a substantial part of the basis of reaction mechanism discrimination in the experiment reported here. The discrimination may be clouded by events of character intermediate between strict compound-nuclear processes and simple direct-interaction mechanisms. Special cases of transitions to discrete final states which have unmistakable direct-interaction character show strong peaking in the backward hemisphere.[4–6]

With regard to the relative success of the two mentioned reaction mechanisms in describing previous experimental evidence, the energy distribution (Maxwellian for neutrons) of reaction products is predicted fairly well by the statistical model in the experiments of Graves and Rosen, Gugelot, and many others too

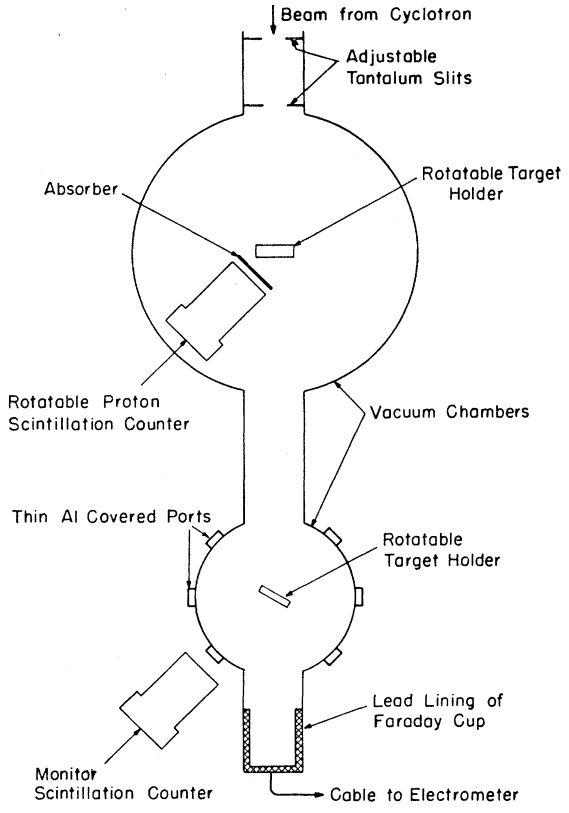

FIG. 1. Schematic diagram of the scattering chambers, slit system, and Faraday cup.

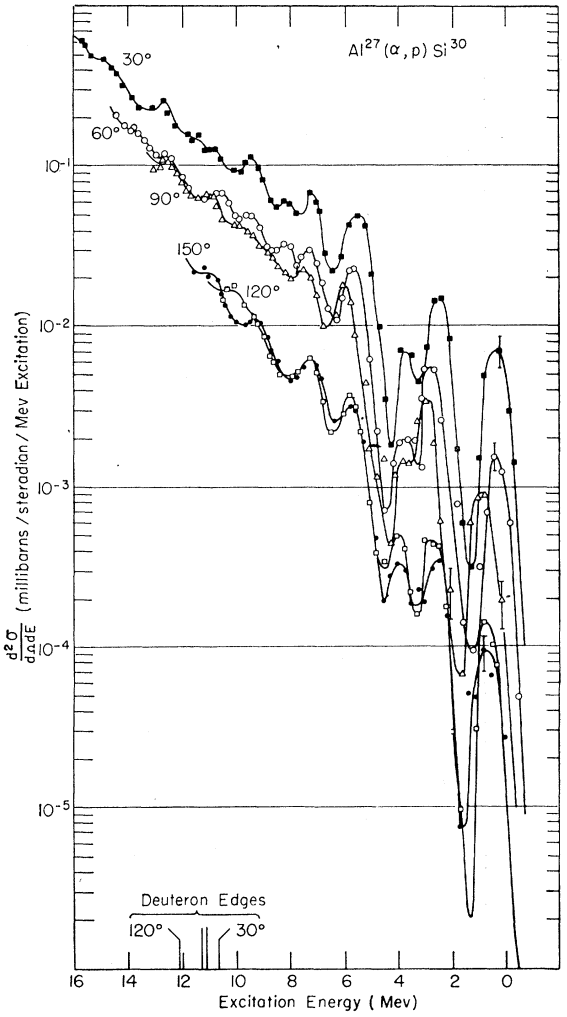

FIG. 2. The differential cross sections of the (α,p) reaction on Al^{27} at five laboratory angles from 30° to 150° are represented as a function of the excitation energy of the residual nucleus. The cross sections are in units of mbarns/sr Mev of excitation energy. The calculated threshold energy at which deuterons from (α,d) reactions may appear in the proton spectrum at each angle is labeled the deuteron edge.

[2] L. Wolfenstein, Phys. Rev. **82**, 690 (1951).
[3] W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952).
[4] P. R. Klein, N. Cindro, L. W. Swenson, and N. S. Wall, Nuclear Phys. **16**, 374 (1960).
[5] I. Nonaka, H. Yamaguchi, T. Mikumo, I. Umeda, T. Tabata, and S. Hitaka, J. Phys. Soc. Japan **14**, 1260 (1959).
[6] R. Sherr and M. Rickey, Bull. Am. Phys. Soc. **2**, 29 (1957) and C. E. Hunting and N. S. Wall, *ibid.* **2**, 181 (1957).

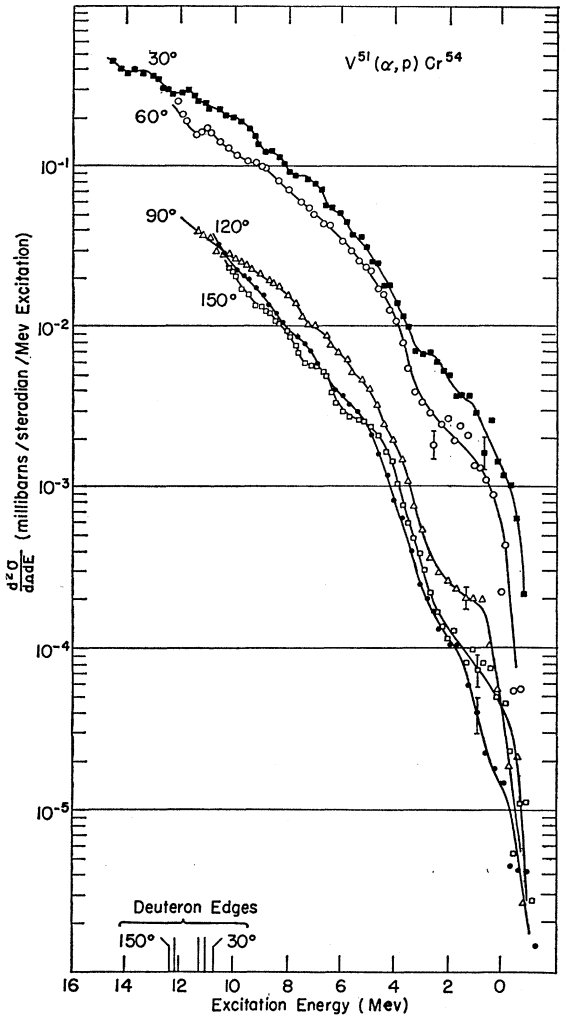

FIG. 3. The differential cross sections of the (α,p) reaction on V^{51}. See caption to Fig. 2.

numerous to mention,[7] and the predicted statistical model parameters are reasonable. In many other experiments of this type, part of the emitted spectrum may be attributed to evaporation, but part of the spectrum is not attributable to evaporation, as indicated by the forward peaking of the angular distribution of emitted particles.[8] Despite the considerable area of agreement between statistical evaporation theory and the large body of experimental work that could be included in reference 8, there are very few experiments among them which do not indicate the possibility of a non-compound nuclear contribution. It is not always clear to what extent non-compound nuclear processes contribute. Many results are further clouded by the uncertainty of multiple particle emission.

In general, irrespective of reaction type, insufficient experimental information presently exists concerning emission spectra in the region of overlapping states and corresponding derived statistical model parameters. To attain a more complete understanding of the degree to which direct reactions contribute to the total cross section, it is necessary to acquire more complete information about the experimental angular distribution. A broader coverage of target masses would also seem desirable.

Alpha particles were chosen as the bombarding par-

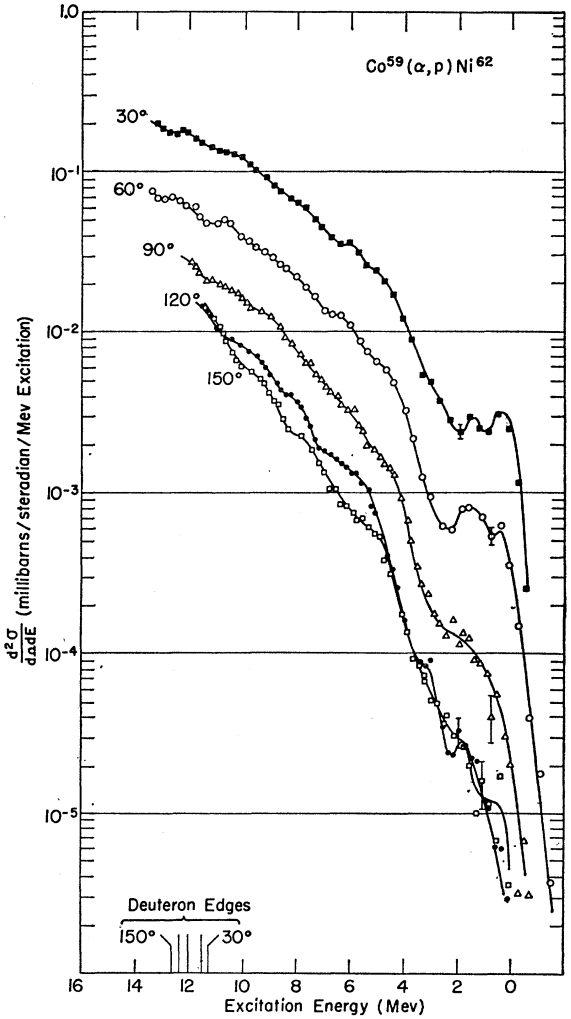

FIG. 4. The differential cross sections of the (α,p) reaction on Co^{59}. See caption to Fig. 2.

[7] E. Graves and L. Rosen, Phys. Rev. **89**, 343 (1953), P. C. Gugelot, *ibid.* **81**, 51 (1951); P. H. Stelson and C. Goodman, *ibid.* **82**, 69 (1951); E. G. Whitmore and G. E. Dennis, *ibid.* **84**, 296 (1951); G. K. O'Neill, *ibid.* **95**, 1235 (1954); I. Kunabe *et al.*, *ibid.* **106**, 155 (1957).

[8] A few of these experiments may be mentioned: P. C. Gugelot, Phys. Rev. **93**, 425 (1954); R. M. Eisberg and G. Igo, *ibid.* **93**, 1039 (1954); R. M. Eisberg, G. Igo, and H. E. Wegner, *ibid.* **100**, 1309 (1955); L. Rosen and Stewart, *ibid.* **99**, 1052 (1955); H. W. Fulbright, N. O. Lassen and N. O. Roy Poulsen, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **31**, No. 10 (1959); G. Igo, Phys. Rev. **106**, 256 (1957); D. Allan, Proc. Phys. Soc. (London) **A70**, 195 (1957); P. V. March and W. T. Morton, Phil Mag. **3**, 143 and 577 (1958); L. Colli and V. Facchini, Nuovo cimento **5**, 309 (1957). D. L. Allen, Nuclear Phys. **24**, 274 (1961).

ticle, as a compound system of alpha particle and target nucleus is more likely to proceed through complete compound-nucleus formation than a direct-reaction mechanism because of the short mean free path of an alpha particle in nuclear matter.[9,10] Further, if the decay mode is a direct reaction it is likely to occur at the surface and hence involve fewer degrees of freedom or less excitation of the residual nucleus.

The previously published (α,p) experiment (at 40 Mev) of Eisberg *et al.*[11] is limited in the above-named respects. The most uncomfortable aspect of the 40-Mev (α,p) experiment is that the level density parameter a of $\omega=C\exp[(aE)^{\frac{1}{2}}]$ was much smaller than expected from the Fermi gas model calculation of the level density and, even more surprisingly, did not show the expected increase with mass number while exhibiting a Fermi gas emission spectrum, as pointed out by Igo and Wegner.[12] The results of the experiment reported here (at 30 Mev) and those of the recent

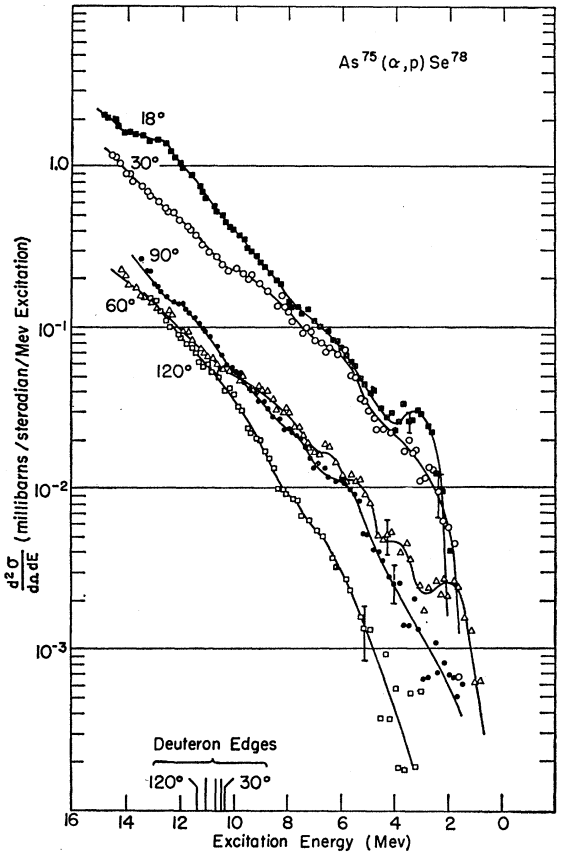

FIG. 5. The differential cross sections of the (α,p) reaction on As^{75}. See caption to Fig. 2.

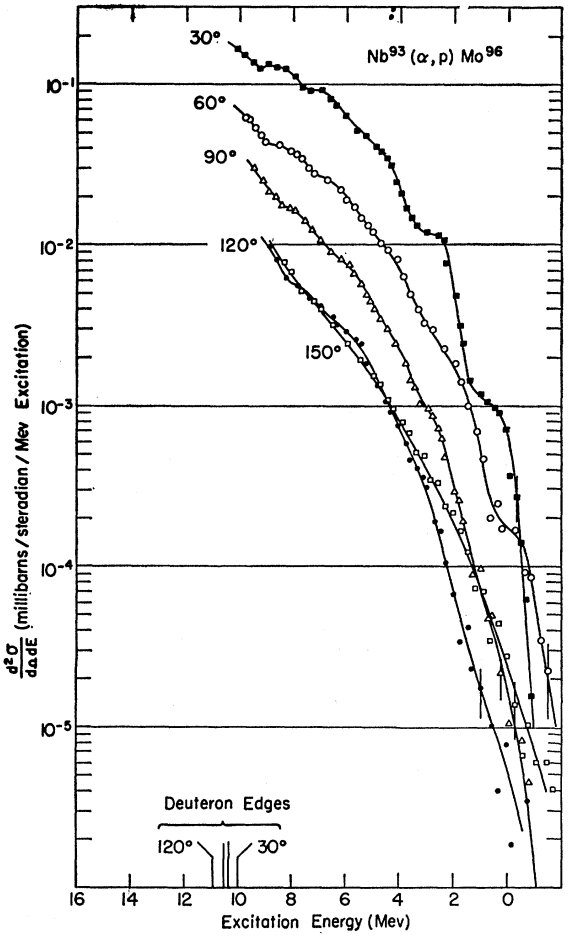

FIG. 6. The differential cross sections of the (α,p) reaction on Nb^{93}. See caption to Fig. 2.

(α,p) work of Lassen and Sidorov[13] (at 20 Mev) are in better agreement with statistical theory in the above respects.

2. EXPERIMENT

The significant physical quantity measured was the proton energy spectrum of the (α,p) reaction at several laboratory angles. The experimental approach was to use absorbers for particle selection and a scintillation spectrometer in conjunction with a multichannel analyzer for the determination of the energy distribution of the emitted protons. Energy calibration of the emission spectrum was accomplished by use of resolved ground-state (α,p) transitions of known energy. Cross sections were obtained by comparison of the yield to that of the $C^{12}(\alpha,p)N^{15}$ and the $Al^{27}(\alpha,p)Si^{30}$ ground-state reactions for which the cross sections are known.[14,15]

The reactions studied in the experiment were induced by alpha particles accelerated to 30.5 Mev by the

[9] G. Igo and R. Thaler, Phys. Rev. **106**, 126 (1957).
[10] W. B. Cheston and A. E. Glassgold, Phys. Rev. **106**, 1215 (1957).
[11] R. M. Eisberg, G. Igo, and H. E. Wegner, Phys. Rev. **100**, 1309 (1955).
[12] G. Igo and H. E. Wegner, Phys. Rev. **102**, 1364 (1956).
[13] N. O. Lassen and V. A. Sidorov, Nuclear Phys. **19**, 579 (1960).
[14] C. E. Hunting, Ph.D. thesis, M.I.T. (1958).
[15] C. E. Hunting and N. S. Wall, Phys. Rev. **115**, 956 (1959).

M.I.T. cyclotron. The beam passed first through the target under study in the first scattering chamber and then through a Au target in the second chamber as depicted in Fig. 1. The reaction particles from the target in the first chamber passed first through an absorber, and then into the NaI scintillation spectrometer (labeled proton counter in Fig. 1) which was mounted on a rotatable arm. The beam intensity was monitored by detecting with a CsI scintillation counter alpha particles elastically scattered from the Au target in the second chamber. Corrections in the monitor count were made to account for scattering of the beam by the target in the first chamber. The correction to be made to the monitor count was determined by taking monitor counts with and without the first target in the beam at a constant beam current. The beam was stopped in a Faraday cup and the current measured by an electronic electrometer.

The electronics used was conventional. The cathode follower output of the NaI scintillation counter passed through a preamplifier and a linear amplifier, and pulse height analysis was accomplished with an RCL 256-channel analyzer.

In the experiments involving the targets As^{75}, Rh^{103}, and In^{115}, the absorber was 309 mg/cm² of Au and the crystal a 125-mil thickness of NaI(Tl). In experiments utilizing the targets Al^{27}, V^{51}, Co^{59}, Nb^{93}, and Ta^{181} a 175-mil NaI(Tl) crystal and a 548-mg/cm² Pb absorber were used. The crystals were small enough to make the counter very inefficient as a neutron detector. The primary function of the absorber was to stop the alpha particles scattered from the target. The absorber also stopped any tritons produced in the target. Thus the counter detected only protons and deuterons besides gamma rays. Further, noting that the differential energy loss, dE/dx, is twice as great for deuterons as for protons, the energy loss in the absorber was about twice as great for deuterons as for protons of the same energy.

For all the targets used, the Q value of the (α,d) reaction is 6–8 Mev lower than the corresponding (α,p) Q value. Thus, the maximum deuteron energy obtainable in an alpha-induced reaction is 6–8 Mev less than the corresponding maximum proton energy. The separation in proton and deuteron energy is further widened by the above described absorber effect. As the response for deuterons is the same as for protons in NaI, deuterons and protons of the same energy in the detector will produce pulses of nearly equal height and hence be indistinguishable. For the 309-mg/cm² Au absorber,

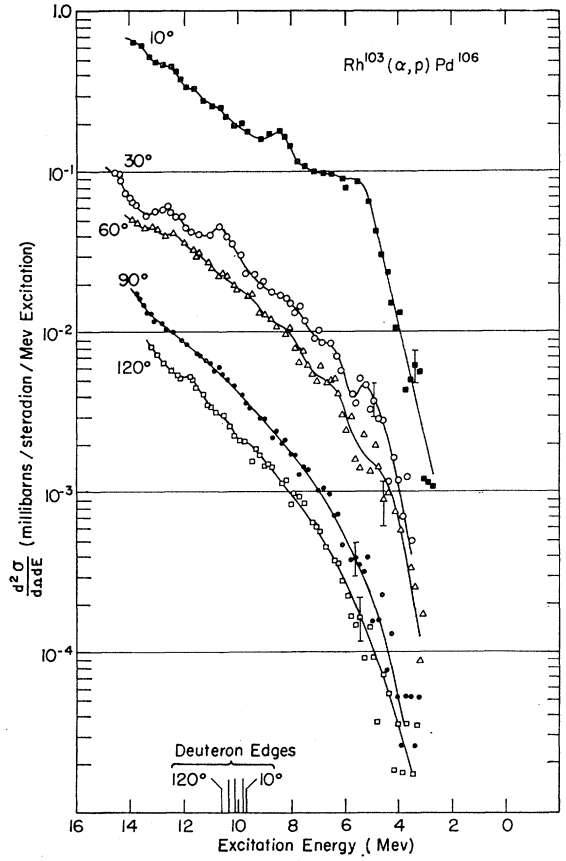

FIG. 7. The differential cross sections of the (α,p) reaction on Rh^{103}. See caption to Fig. 2.

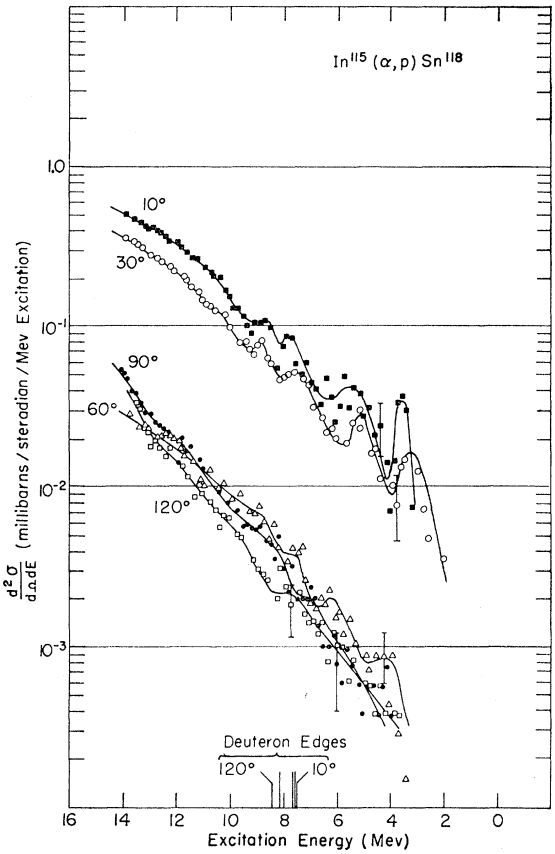

FIG. 8. The differential cross sections of the (α,p) reaction on In^{115}. See caption to Fig. 2.

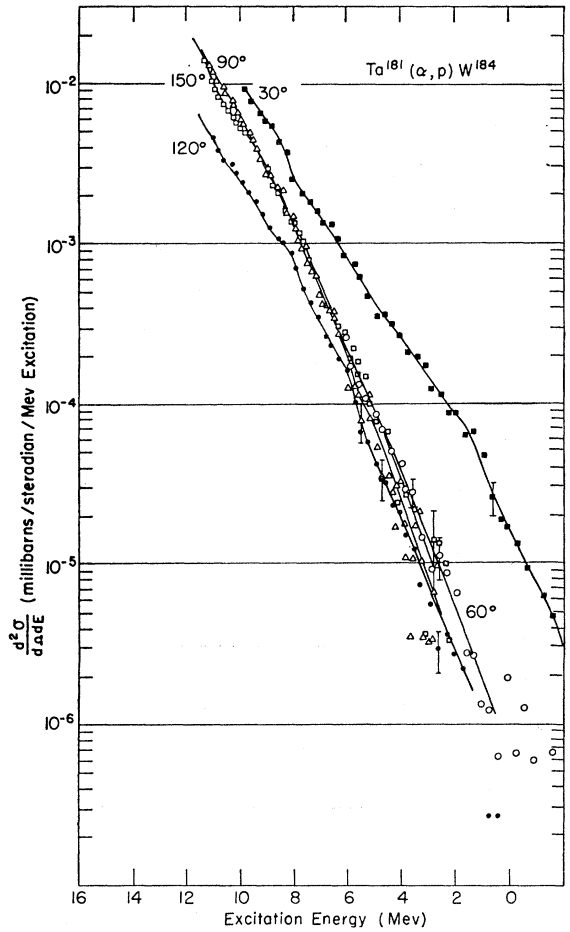

FIG. 9. The differential cross sections of the (α,p) reaction on Ta^{181}. See caption to Fig. 2.

the upper 8–10 Mev of the proton spectrum was deuteron free and the upper 10–13 Mev region was free for the 548-mg/cm² Pb absorber. Above these limits (referred to as the "deuteron edges") there may be a deuteron contamination. However, statistical model calculations indicate the deuteron contamination is less than 5%. The 309-mg/cm² Au absorber permits the detection of protons down to an energy of ~12 Mev, or ~14 Mev for the 548-mg/cm² Pb absorber, below which they are lost in the gamma-ray background. The relative importance of protons from competing $(\alpha,2p)$ and (α,np) reactions is negligible and is commented on in a later section.

A self-supporting thin carbon (1.8 mg/cm²) target was prepared by spraying Aguadag on a mirrored surface and then peeling off the layer of carbon after drying.[16] Thin foils of natural Al (3.64 mg/cm²), V (7.80 mg/cm²), Co (6.08 mg/cm²), Rh (6.35 mg/cm²), Nb (8.33 mg/cm²), In (0.92 mg/cm²), and Ta (17.15 mg/cm²) were used. The As target was prepared by sublimation onto a thin Formvar backing. The carbon target was found to contain a trace of oxygen. The As and In targets contained small amounts of hydrogen and carbon.

As the chief interest in these experiments was in the gross structure of the emission spectra, only moderate energy resolution was required. The resolution must, however, be sufficiently good to allow detection of any anomalous groups that might appear and must not obscure the gross features of the level spectrum. The fact that the ground and first excited state groups from the several residual levels in the $C^{12}(\alpha,p)N^{15}$ and $Al^{27}(\alpha,p)Si^{30}$ reactions were well resolved is evidence of fulfillment of this condition. The resolution (that is, the full width at half-maximum) of the detector without absorber was 0.6–0.7 Mev as determined using carbon and aluminum targets. The resolution exhibited no (~0.1 Mev) important energy dependence over the range 16–31 Mev proton energies.

A correction to the incident alpha-particle energy was made to account for the average energy loss of the alpha in the target before an interaction occurred.

The experimental data were acquired in the form of counts per channel as a function of channel number. The channel number was a linear function of the proton

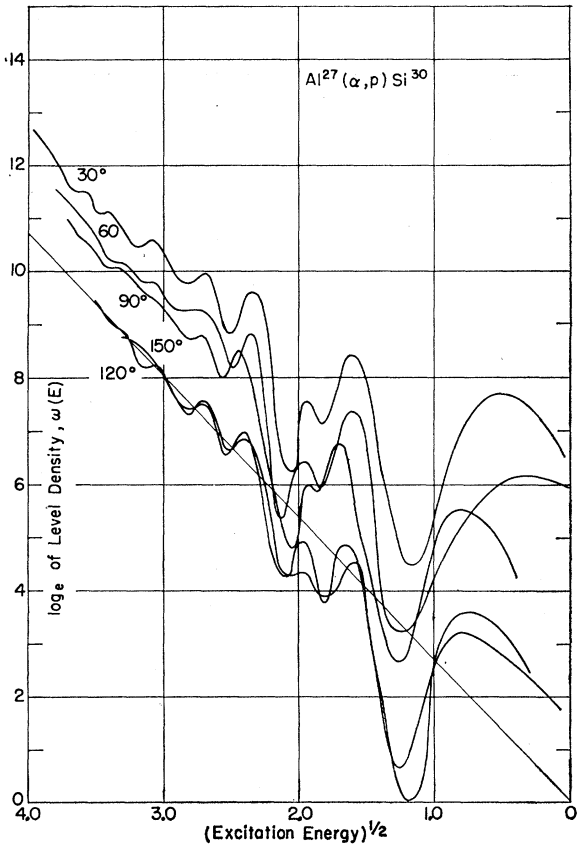

FIG. 10. The natural logarithms of the level density of Si^{30} are represented at different angles as a function of the square root of the excitation energy.

[16] C. W. Darden, Ph.D. thesis, M.I.T. (1959).

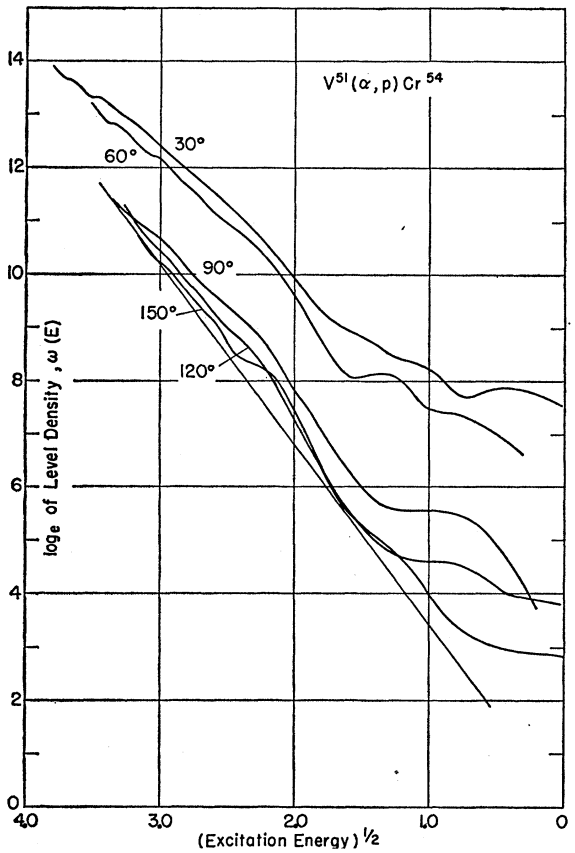

FIG. 11. The natural logarithms of the level density of Cr^{54} are represented at different angles as a function of the square root of the excitation energy.

energy in the counter (after passing through the absorber). The analyzer channel number was calibrated by using the proton ground-state group from the $Al^{27}(\alpha,p)Si^{30}$ reaction with the Pb absorber at different angles, and the proton ground-state group from the $C^{12}(\alpha,p)N^{15}$ reaction with the Au or the Pb absorber as well as without any absorber, also at different angles. Utilizing the 7.5-Mev cyclotron beam, the protons scattered from Au at 30° were also used for calibration. The two above reactions and the proton beam thus provided protons of known energies between 7.5 and 25.5 Mev, absorber corrections being made where required.

3. DATA ANALYSIS

It is desirable to represent the experimental data in a form which lends itself well to the interpretation of its physical significance. Such a form was felt to be the product of a compound nucleus analysis. The testing ground of such an analysis is the agreement between the experimental emission spectra and level density parameters and those predicted by the statistical model.

From statistical theory,[17] the relative intensity of the particles emitted from the reaction $X(a,b)Y$ in the exit-channel energy range ϵ to $\epsilon+d\epsilon$ is represented by $N_b d\epsilon = \text{const}\sigma_c(b)\omega(\epsilon_{\max}-\epsilon)d\epsilon$. $\sigma_c(b)$ is the capture cross section of the inverse reaction and $\omega(E)$ the density of states of residual nucleus at the excitation energy $E=\epsilon_{\max}-\epsilon$, where $\epsilon_{\max}$ is the maximum channel energy (total center-of-mass kinetic energy) corresponding to $E=0$. As will be seen, analysis of the present experiment from the statistical point of view surely enjoys some success, and just as surely offers evidence of a non-compound nuclear contribution. The values of σ_c used in the analysis were taken from the tables of Blatt and Weisskopf[17] for values of $Y\equiv\epsilon/B\leq 1.8$ with a radius of $r_0=1.5\times10^{-13}$ cm; B is the barrier height. An approximate form $\sigma_c=\pi(R+\lambda\!\!\!^{-})\{R[(Y-1)/Y]+\lambda\!\!\!^{-}\}$, derived on the basis of a classical model[17] which assumes that every particle striking the nucleus is captured, was used in the range $Y\geq 1.8$. The approximate form was normalized to fit smoothly to the quantum mechanical range $Y\leq 1.8$ and approach geometrical at $Y=\infty$.

An IBM 704 computer program was used in the data analysis.[18] The program computes for each channel the

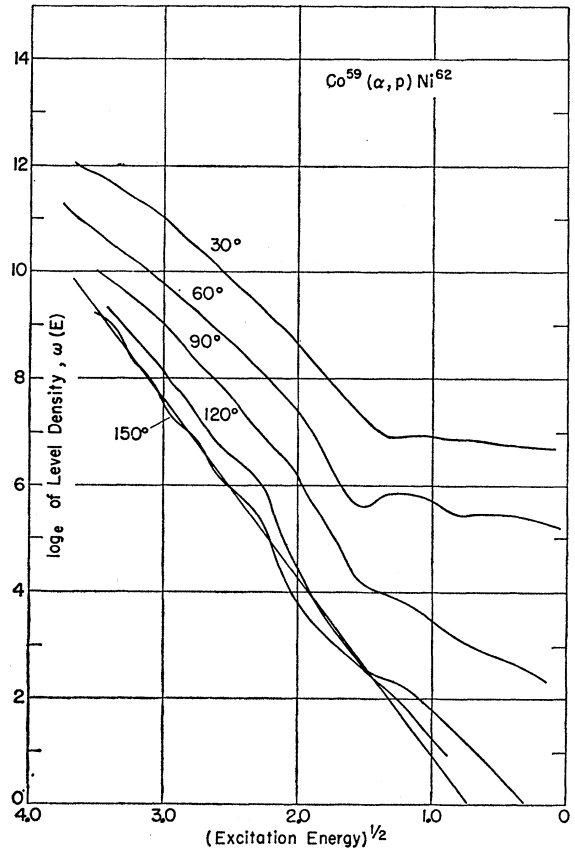

FIG. 12. The natural logarithms of the level density of Ni^{62} are represented at different angles as a function of the square root of the excitation energy.

[17] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics*, (John Wiley & Sons, Inc., New York, 1953).

[18] The CONDAC program deck was generously supplied by C. D. Goodman and B. Williams at the Oak Ridge National Laboratories. It was tested and used at the M.I.T. computation center.

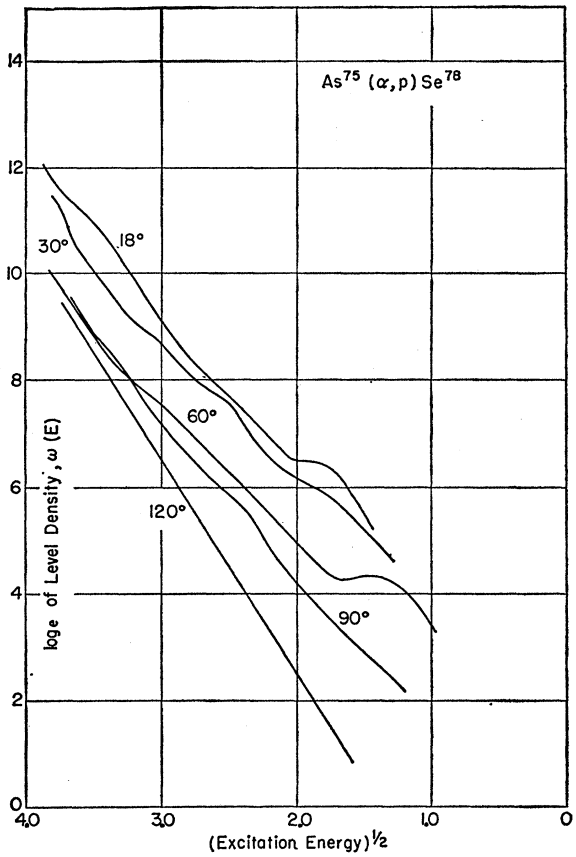

FIG. 13. The natural logarithms of the level density of Se^{78} are represented at different angles as a function of the square root of the excitation energy.

laboratory proton energy, the exit channel energy, and the excitation energy of the residual nucleus. A quantity N, the number of counts per energy interval dE in the center of mass, is calculated for each channel. N is equal to the differential cross section $d^2\sigma/d\Omega dE$ when the appropriate monitor count is included in the program input data. A quantity $N/\epsilon\sigma$, proportional to the level density, is also calculated for each channel and hence as a function of laboratory proton and excitation energy. Without the program the analysis of a large amount of data would be considerably more exhausting, if not impossible. The alternative of analyzing a small sample or an averaged, smooth spectrum would not seem to be in the best interests of discovering the salient properties of the emission spectra, for instance, the periodic structure at forward angles and high excitation energy.

4. RESULTS

The differential cross sections $d^2\sigma/d\Omega dE$ for the (α,p) reactions on Al^{27}, V^{51}, Co^{59}, As^{75}, Nb^{93}, Rh^{103}, In^{115}, and Ta^{181} are represented in Figs. 2–9, respectively. The points in the figures are experimental, and the solid curves are smooth curves drawn through the experimental points. The errors indicated are the statistical errors.

The energy dependence of $d^2\sigma/d\Omega dE$ is, in general, smooth and slowly varying. With the exception of the ground states of Si^{30}, Ni^{62}, and Mo^{96}, and in the case of Si^{30} and Ni^{62} low-lying excited states, the protons from discrete states of the residual nuclei are not resolved, resulting in most cases in a continuous proton spectrum. In the case of Si^{30}, in addition to the ground-state group there appears a group from the 2.2-Mev level, a group from the 3.5- and 3.7-Mev levels, and another from the 5-Mev state. Above 5 Mev no further states should be resolved in Si^{30}.[19] However, in the case of Si^{30} there is evidence of structure in the proton spectrum at excitation energies >5 Mev. That is, the regular appearance of groups may be noted at a definite excitation energy at different angles. The spacing between these groups seems to be nearly regular and about 1.5 Mev. Sn^{118} also offers considerable evidence of structure at high excitations $\sim$3.5 and $\sim$5.5 Mev in the 10°–60° range. Sn^{118} is a magic nucleus. A hint of structure is to be seen in the forward angle spectra of Cr^{54}, Mo^{96}, and

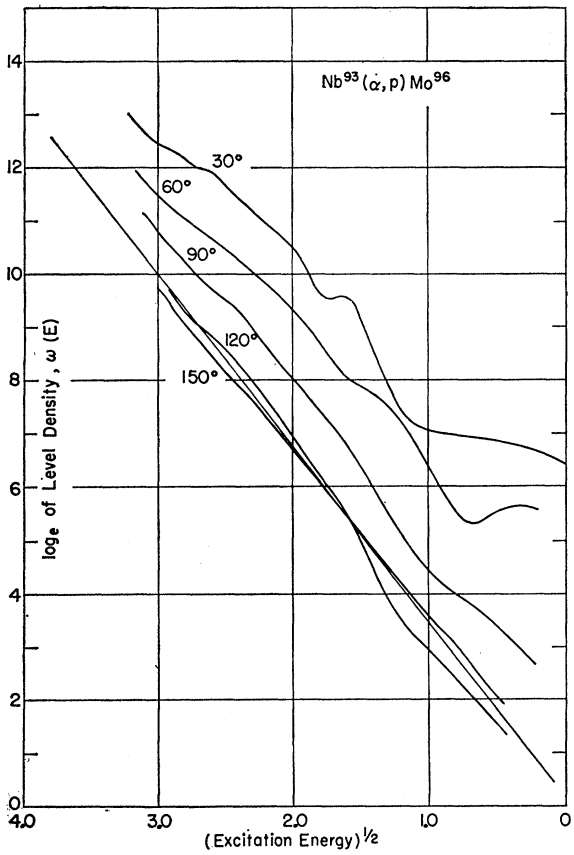

FIG. 14. The natural logarithms of the level density of Mo^{96} are represented at different angles as a function of the square root of the excitation energy.

[19] P. M. Endt and J. C. Kluyver, Revs. Modern Phys. **26**, 95 (1954).

Pd^{106}. A group from the 1.1-Mev level in addition to the ground-state group appears in the spectrum from Ni^{62}, but no structure above 2 Mev where the levels occur at 2.05, 2.30, 2.33, 2.89 Mev, etc.[20] This type of forward-peaked structure at high excitations has been reported in the (α,p) reaction studies of several nuclei in the Cu, Ni region by Nonaka *et al.*[21] at 28 Mev. No important structure above 2 Mev is indicated in the spectra from the residual nuclei Ni^{62}, Se^{78}, and W^{184} or any nuclei at back angles (except Si^{30}). Quite generally it may be said of the spectra investigated, that no "anomalous" groups appear that resemble those reported in the inelastic scattering experiments of Cohen and Rubin,[22] Crut *et al.*,[23] Yntema and Zeidman,[24] and others.

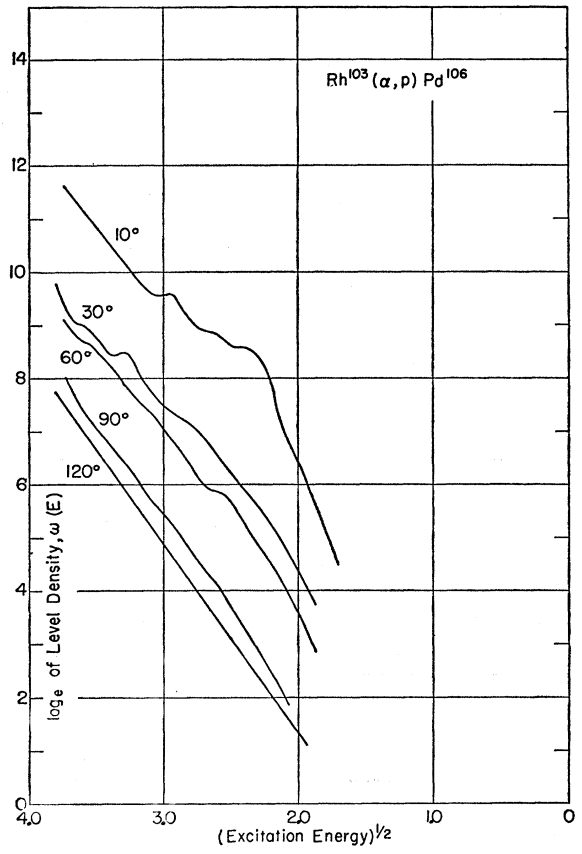

FIG. 15. The natural logarithms of the level density of Pd^{106} are represented at different angles as a function of the square root of the excitation energy.

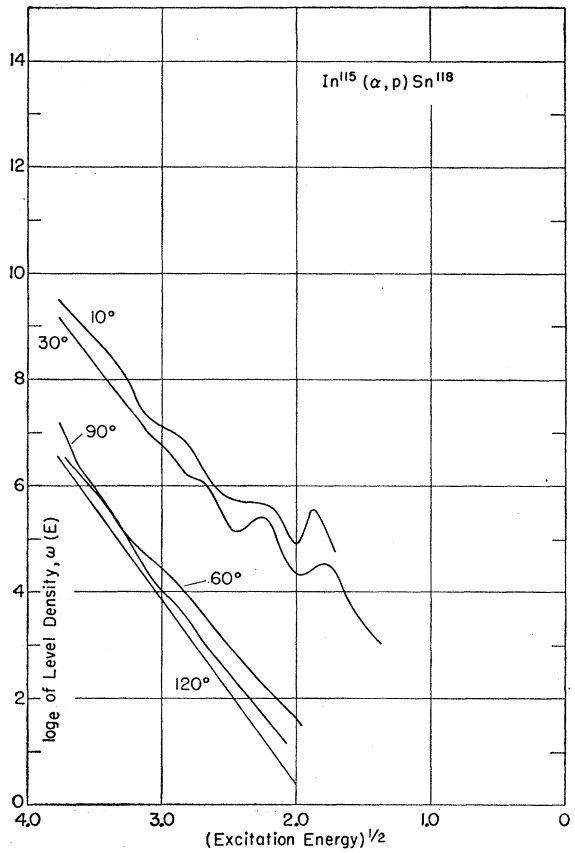

FIG. 16. The natural logarithms of the level density of Sn^{118} are represented at different angles as a function of the square root of the excitation energy.

In Figs. 2–9 the differential cross sections at different angles may be compared directly as a function of angle. Comparison in this manner makes manifest the following points: (1) The cross section increases proceeding from back to forward angles; (2) the forward peaking of the cross section is more pronounced for light elements than for heavy elements; (3) the forward peaking is greater at low excitation energy than at high excitation energy, but in general (except for the heaviest elements) does not completely vanish at high (>10 Mev) excitation energies.

The natural logarithms of the quantities, $\omega(E) \equiv (d^2\sigma/d\Omega dE)/\epsilon\sigma(\epsilon)$, which we shall call the relative level densities, are represented in Figs. 10–17 as a function of $\sqrt{E}$. The curves represent the best smooth curves that may be drawn through the experimental points. The three points made regarding the cross-section curves are true of the level density curves, the third being more obvious in these plots, since the $\ln(E)$ curves are more nearly straight lines.

A straight-line representation of $\ln(E)$ vs $\sqrt{E}$ is expected if the energy dependence of the level density may be expressed in the form $\omega(E)=\text{const}\exp[(aE)^{\frac{1}{2}}]$, where a is a constant parameter relating the tempera-

[20] C. H. Paris and W. W. Buechner, *Comptes Rendus du Congrès International de Physique Nucléaire, Paris, 1958*, edited by P. Guggenberger (Dunod, Paris 1959), p. 515.
[21] *Proceedings of the International Conference on Nuclear Structure, Kingston, Canada, 1960*, edited by D. A. Bromley and E. W. Vogt (University of Toronto Press, Toronto, Canada, 1960).
[22] B. L. Cohen and A. Rubin, Phys. Rev. **111**, 1568 (1958).
[23] M. Crut, C. D. Sweetman, and N. S. Wall, Nuclear Phys. **17**, 655 (1960).
[24] J. L. Yntema, B. Zeidman, and B. J. Raz, Phys. Rev. **117**, 801 (1960).

ture and excitation energy. Within the statistical errors, the 150° curves for the heavy elements are straight lines. In all cases at back angles (150°) the curves may be considered straight at high (>4 Mev) excitations and even at low excitations of the heavier nuclei. Plots of $\ln(E)$ vs E were not found to be linear, but rather concave downward.

Proceeding from back to forward angles, the curves of Figs. 10–17 deviate from a straight line. The deviation from linearity is most pronounced at low excitation energies and less pronounced, but still present, at higher excitations. Further, the isotropy and linear character of $\ln\omega$ vs $\sqrt{E}$ persist to smaller angles for the heavy elements (to $\theta=60°$ in the case of Ta). For the lighter elements isotropy is not clearly indicated even at 150°, even though the $\ln\omega$ vs $\sqrt{E}$ curve may be linear (at least for high excitations).

The ultimate success of the statistical analysis depends on the degree of completeness by which the reaction mechanism may be described as proceeding through the compound nucleus. It is clear that compound-nucleus formation and decay is not the only mechanism involved in the (α,p) reaction initiated by 30.5-Mev alpha particles, since the statistical model

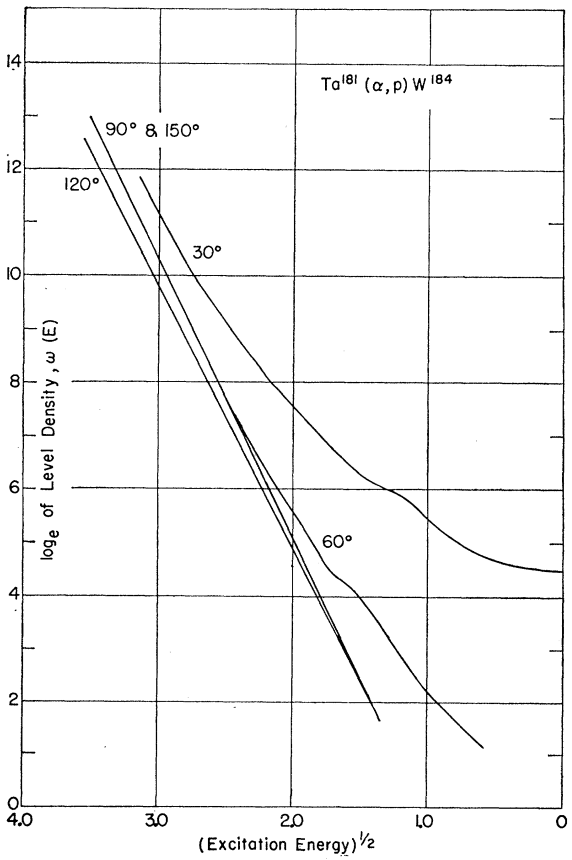

FIG. 17. The natural logarithms of the level density of W^{184} are represented at different angles as a function of the square root of the excitation energy.

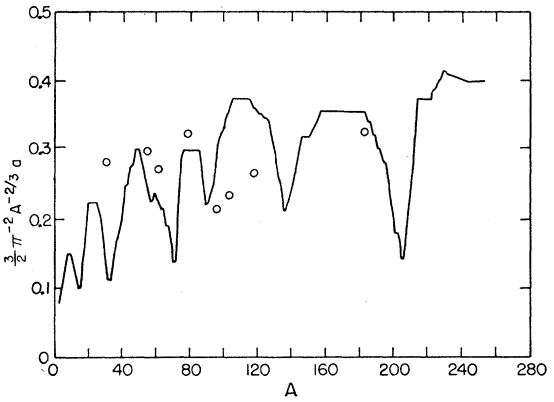

FIG. 18. The experimental level density parameters a are compared through the function $3a/2\pi^2A^{\frac{1}{3}}$ to the prediction of Newton's shell development formula. A is the mass number.

prediction of angular isotropy (or at a minimum symmetry about 90° c.m.) of the reaction products is at variance with the experimental angular distributions. Recalling the three points made of the angular, energy, and mass dependence of the cross section, they seem typical of direct-reaction mechanisms.

From the experimental results we note that the angular distributions may be considered independent of angle at the largest angles and the shape of the $\ln\omega$ vs $\sqrt{E}$ curves may be considered linear at the largest angles. These two considerations are certainly true of the heaviest elements and are approached for the lighter ones. The fulfillment of these two considerations may be taken as conditions for the successful application of statistical theory. If this point of view is adopted, then it may be said that the only important reaction mechanism at 150° is compound-nucleus formation and decay. The spectra at 150° may be taken as a reference point, and deviations from the 150° spectrum at forward angles may be considered direct-reaction contributions.

The results of statistical analysis of the 150° data (120° when largest angle observed) are presented in Table I.[25]

The temperatures defined by $1/T\equiv d(\ln\omega)/dE$ were taken as the slope of the $\ln\omega(E)$ vs E curves at excita-

TABLE I. Parameters from statistical analysis of 150° data.

Residual nucleus	T (Mev) $E=5$ Mev	T (Mev) $E=11$ Mev	a (Mev^{-1}) $E>5$ Mev
Si^{30}	1.4 ±0.25	2.3 ±0.2	7.1±1.4
Cr^{54}	1.35±0.15	2.0 ±0.05	11.2±0.8
Ni^{62}	1.2 ±0.16	1.8 ±0.08	11.2±1.2
Se^{78}	1.15±0.18	1.9 ±0.13	15.5±0.8
Mo^{96}	1.10±0.12	1.9 ±0.1	11.2±0.4
Pd^{106}	1.00±0.12	2.0 ±0.1	12.8±0.8
Sn^{118}	1.8 ±0.2	1.7 ±0.12	15.6±1.2
W^{184}	0.8 ±0.2	1.26±0.08	26.0±0.4

[25] Previously reported in Bull. Am. Phys. Soc. **5**, 76 (1960).

tions of ~5 and ~11 Mev. The level density parameters a of the Fermi gas expression $\omega(E) \propto \exp[(aE)^{\frac{1}{2}}]$ were determined from Figs. 10–17 at $E>5$ Mev. The errors indicate the uncertainty in the slope of the curves due to statistical fluctuations and nonlinearities of the curves. The temperatures are seen to decrease with increasing mass of the residual nucleus, which is consistent with the compound-nucleus idea of sharing excitation energy with all nuclear constituents, there being less average energy per nucleon for heavier nuclei. The a values show a corresponding increase with the mass number. The temperature shows an increase with excitation energy consistent with the predicted Fermi gas $E=aT^2$ equation of state. Although the parameters a and T show a mass variation qualitatively in agreement with the predictions of any nuclear model, they are not in quantitative agreement with any model. The parameter a is about 2.5 times smaller than those predicted by such model treatments as the Fermi gas calculation of Lang and LeCouteur,[26] or the Fermi gas treatment of Newton[27] with or without shell effects.

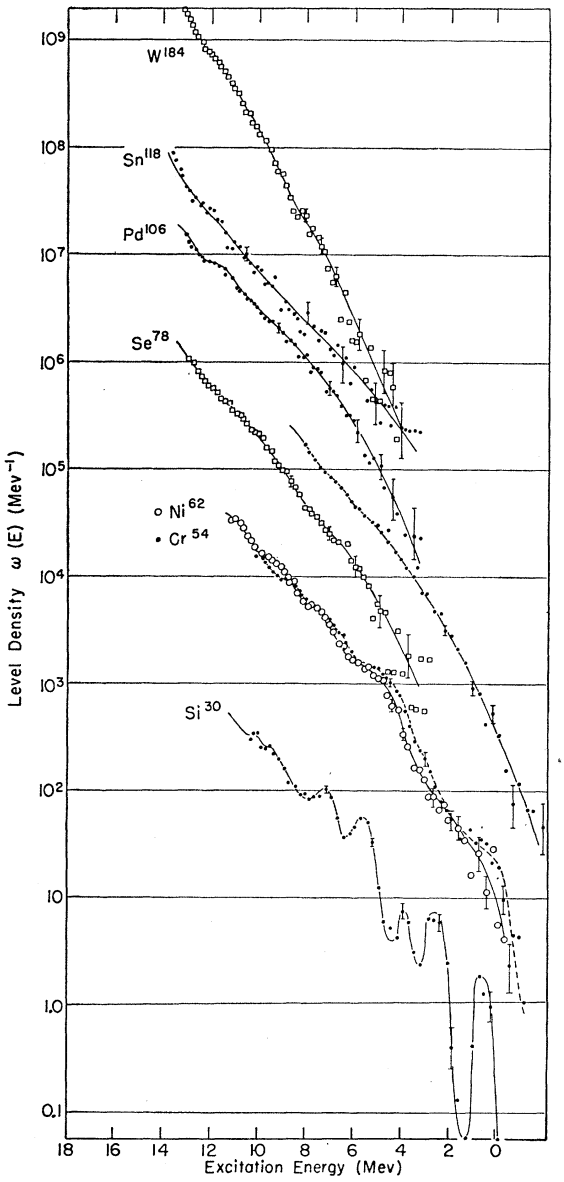

FIG. 19. Representation of normalized level densities of Si^{30}, Cr^{54}, Ni^{62}, Se^{78}, Mo^{96}, Pd^{106}, Sn^{118}, and W^{184} in units of Mev^{-1} as a function of excitation energy. The data correspond to the laboratory angle of 150°. Normalized at neutron binding.

The level density parameters a from this experiment, multiplied by a normalizing factor of 2.5, are compared with the theoretical Fermi-gas shell-dependent formulation of Newton[27] in Fig. 18. Although no very definite conclusions may be drawn, it does seem (1) that the level density parameters may be expected to show a great deal of shell structure in qualitative agreement with a shell-sensitive model like Newton's or Cameron's[28] and (2) that detailed agreement between results of the type of experiment reported here and statistical model predictions cannot be expected. Probably more weight should be given to the experimental points of heavy nuclei in Fig. 18 than to lighter ones, as the lighter elements involve more uncertainty as to the extent of direct-reaction participation. If a clear picture of the effect of shell structure on level density parameters is to be obtained it will necessitate further experiments. New experiments should involve the investigation of many more elements (~50) than did the present experiment. These elements should lead to a variety of even-even, even-odd, odd-odd, magic and nonmagic residual nuclei. Such an investigation is underway.

In the experiment here reported, all residual nuclei are even-even in character and hence exhibit no odd-even effects. The single case of Sn^{118} is distinct from those of other nonmagic residual nuclei investigated, in that it gives a higher temperature at low excitation than do the others. If shell structure or even-odd effects are present, the spacing of the single-particle states is larger and the situation may be approximated by the introduction of an energy gap near the ground state.[29] For low excitation, more energy would then be required to populate the same combination of single-particle states than is required for a normal nucleus. A higher temperature would result at low excitation for magic nuclei, and to a lesser degree for even-even nuclei.

The relative level densities obtained from the experiment may be normalized at neutron binding energy from the results of resonant slow neutron capture experiments. Level spacings from neutron capture experiments have been reviewed and compiled by several

[26] J. M. B. Lang and K. J. LeCouteur, Proc. Phys. Soc. (London) **A67**, 586 (1954).
[27] T. D. Newton, Can. J. Phys. **34**, 804 (1956).
[28] A. G. W. Cameron, Can. J. Phys. **36**, 1040 (1958).
[29] T. Ericson, Nuclear Phys. **8**, 265 (1958).

authors.[30] However, of the eight residual nuclei investigated in the experiment only the level spacings of Mo^{96}, Sn^{118}, and W^{184} are known from neutron capture. In view of the incomplete knowledge of spacings from neutron capture, the absolute density $\omega_0(E,A)$ for spin-zero states was calculated using Newton's shell-development formula. The results compare with the three existing experimental cases within a factor of two. The neutron binding energies used in the calculations were taken from the University of California Radiation Laboratory Q-value tables[31] and the pairing energies subtracted from the neutron binding energies to account for odd-even effects were taken from Newton[27] and Cameron.[28] The total density of states of all spins $\omega(E)\simeq 4\sigma^2\omega_0(E)$ at neutron binding was calculated using $\sigma=4$ for the dispersion as a best value from Ericson's[32] statistical analysis. The normalization is shown in Fig. 19 from 150° data.

Although the level density parameters reported are taken from the 150° data, which are relatively free from direct-reaction contributions, the shapes of the level density curves at forward angles are not so very much different from those of 150°, even though forward peaking of the cross section is evident. The preceding observations are addressed to excitation energies higher than 5–6 Mev. From this observation it may be suggested that the total reaction cross section (compound plus direct) is dominated by pure phase-space considerations like those advanced by Ericson.[33]

In Fig. 20 comparison is made of the nuclear temperatures deduced from different alpha-particle-induced experiments. Their dependence upon mass number is compared. The (α,p) data of Eisberg *et al.*[11] at 40 Mev, the present (α,p) data at 30 Mev, and the Lassen and Sidorov[13] (α,p) data at 19.3 and 11.9 Mev are shown together with the temperatures from the (α,α') data of Fulbright *et al.*[34] at 20 Mev. The (α,α') data of Igo[35] were excluded because of the confusing character of the shape of the emission spectra. Several other (α,α') experiments were excluded from comparison because the authors' method of data presentation precluded easily extracting level density parameters. In each of the chosen experiments the back-angle data are presented, since they are freer of direct-reaction contributions. The temperatures from the Eisberg *et al.* 40-Mev (α,p) experiment were obtained from measured level

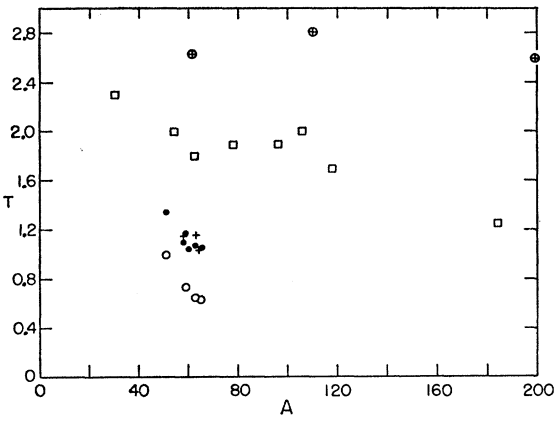

FIG. 20. Comparison is made between the temperatures T from different alpha-particle-induced experiments as a function of the mass number A. The temperatures correspond to ~10 Mev excitation. The different data are represented by the following symbols: ⊕ Eisberg, Igo, and Wegner, (α,p) 40 Mev; □ Swenson and Cindro (α,p) 30 Mev; + Fulbright, Lassen, and Poulsen (α,α') 20 Mev, ● Lassen and Sidorov (α,p) 19.3 Mev; ○ Lassen and Sidorov (α,p) 11.9 Mev.

density parameters a through the equation of state $E=aT^2/4$ at $E=10$ Mev with the exception of the mass-200 point [it also finds agreement with $E=(a/4)T^2$] which was taken from the experiment.

In Fig. 21 the level density parameters a from the same experiments are compared at the same excitation again as a function of mass number. In this figure the parameters were derived from the measured temperatures through the equation of state for the Lassen and Sidorov (α,p) experiments at 11.9 and 19.3 Mev. The

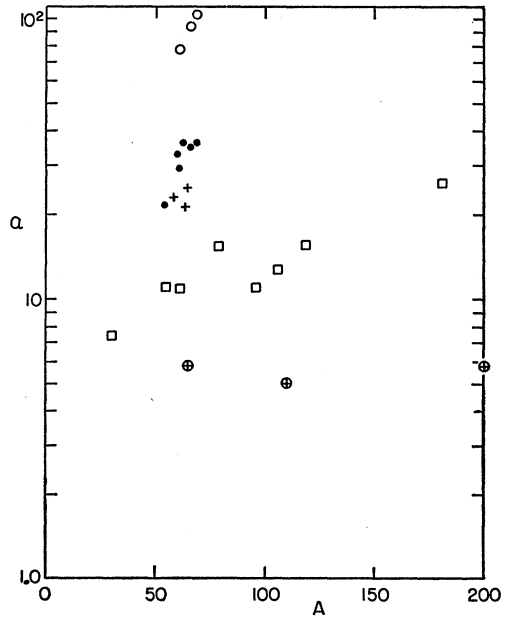

FIG. 21. Comparison is made between the level density parameter a of $\omega=C\exp[(aE)^{\frac{1}{2}}]$ for the same experiments as in Fig. 20, again as a function of mass number. The symbols have the same meaning as in Fig. 20.

[30] J. S. Levin and D. J. Hughes, Phys. Rev. **101**, 1328 (1956); J. A. Harvey, D. S. Hughes, R. S. Carter, and V. E. Pilcher, *ibid.* **99**, 10 (1955); D. J. Hughes and J. A. Harvey, *Neutron Cross Sections*, Brookhaven National Laboratory Report BNL-325 (U. S. Government Printing Office, Washington, D. C., 1955); D. J. Hughes and R. B. Schwartz, *ibid.*, Suppl. No. 1, 1957. A. Stalovy and J. A. Harvey, Phys. Rev. **108**, 353 (1957).

[31] V. J. Ashley and H. C. Catron, University of California Radiation Laboratory Report UCRL-5419 (unpublished).

[32] T. Ericson, Nuclear Phys. **11**, 481 (1959).

[33] T. Ericson, *Advances in Physics*, edited by N. F. Mott [Taylor and Francis, Ltd., London (to be published)].

[34] H. W. Fulbright, N. O. Lassen, and N. O. Roy Poulsen, Kgl. Danske Videnskab. Selskab, Mat.-fys. **31**, No. 10 (1959).

[35] G. Igo, Phys. Rev. **106**, 256 (1957).

insufficiency of the amount of available data is apparent. On the basis of what data are available it is seen that the temperature variation with mass is qualitatively acceptable, but it shows a dependence on the energy of the bombarding particle, a position untenable on the basis of the statistical model. It has been suggested[12,36] that due to the short mean free path of alpha particles[9,10] in nuclear matter, the incident energy of the alpha is shared only locally with a number of nucleons less than A before emission occurs (called "spot heating"), giving rise to high temperatures. If this approach were adopted, the temperature would be expected to show an increasing relationship with the incident particle energy. Such a trend is shown in the comparison of Fig. 20. An equation of state of the form $E=aT^2/4$ demands that the parameter a show a decreasing relationship with the incident energy from the spot-heating point of view. Such a trend is shown in Fig. 21. The group of points in Fig. 21 from the 11.9-Mev experiment are unreasonably high, which indicates that level density parameter comparisons through the equation of state cannot be expected to be completely quantitative. Though the comparisons of Figs. 20 and 21 lend support to the qualitative correctness of the spot-heating approach, this point of view should be accepted only with reserve until sufficient data become available to permit a quantitative study.

Relative to the question of competing reactions, of all the reactions involving single-particle emission, only the (α,d) reaction yields detectable particles that could not be distinguished from protons. Deuterons lose on the average an amount of energy $\Delta\simeq 2$ Mev more in passing through the absorber than protons of a corresponding energy. The maximum channel energy for proton emission is also greater than that for deuteron emission by $\Delta Q=Q(\alpha,p)-Q(\alpha,d)\simeq 6$ Mev, the difference in the ground-state Q values. On the basis of the statistical model, the ratio of the number of deuterons to protons emitted with a channel energy ϵ between ϵ and $\epsilon+d\epsilon$ after passing through the absorber is

$$\frac{N_d(\epsilon)d\epsilon}{N_p(\epsilon)d\epsilon}=\frac{M_d(2I_d+1)\sigma_{cd}(\epsilon)\omega(\epsilon)}{M_p(2I_p+1)\sigma_{cp}(\epsilon)\omega(\epsilon-\Delta Q-\Delta)}$$

$$=\frac{\sigma\omega(\epsilon)}{\omega(\epsilon-8)}=\begin{cases}0.06 \text{ for Al}\\ 0.01 \text{ for Ta,}\end{cases}$$

where M_d and M_p are channel masses, I_d and I_p are the spins, σ_{cd} and σ_{cp} are the inverse capture cross sections of deuterons and protons, respectively. The ratio has the above approximate value at $\sim$12 Mev excitation if the level densities of the residual nuclei are assumed to be the same. Even-odd and shell effects are thus not included but would not be likely to influence the calculation by more than $\sim$10%. Thus, if the reaction may be described by compound-nucleus formation and decay, the yield of deuterons is negligible compared to protons for the range of excitation studied. The He^3 and H^3 yields are even lower than the deuteron yield.

Of the reactions leading to two-particle emission, all reactions (α,xp) will be competitors of the (α,pz) reaction, where x and z may be anything. The only two likely important competitors are the (α,pp) and (α,np) reactions, and these reactions will contribute only at channel energies below $\epsilon_{\max}-B_p$, B_p being the binding energy of the proton to the final nucleus. When statistical model emission functions are evaluated, it is found that the total calculated (α,np) cross sections are 40.6 mb for Rh^{103} and 67.0 mb for V^{51}. The calculated cross sections of the (α,pz) reactions are 176 mb and 118 mb for Rh^{103} and V^{51}, respectively. The total $\sigma(\alpha,np)$ cross section is smaller than for the $\sigma(\alpha,pz)$ cross section, but more important is the fact that in the region of channel energies covered by this experiment the (α,np) emission functions are lower than those of the (α,pz) reactions by about two orders of magnitude. That this is so is due principally to the fact that the threshold of the (α,np) reaction occurs at an excitation energy $S_n\simeq 8$–10 Mev higher than does the (α,pz) proton threshold. By the same considerations, the secondary proton contribution from the (α,pp) reaction, though a little larger $(B_p<B_n)$ than from the (α,np) reaction, is also negligible. Protons from three-particle emission reactions have energies below those observed in the experiment.

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[36] V. F. Weisskopf, Proc. Am. Acad. Arts Sci. **82**, 360 (1952–1953).