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# Protons from the Bombardment of Several Elements with 40-Mev Alpha Particles*

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Thin targets of Au, Ag, and Cu were bombarded with 40-Mev alpha particles and the energy distributions of protons emitted at 150° were measured. According to the compound-nucleus model, the level density of the residual nucleus is equal to: const $N/E\sigma_c$, where $N$ is proportional to the probability that the compound nucleus emits a proton of energy $E$, and $\sigma_c$ is the cross section for the inverse reaction. For each element, $\log(N/E\sigma_c)$ plotted as a function of the excitation energy of the residual nucleus, $E_r$, is concave downward. This is in qualitative agreement with the Fermi gas level density formula: const $\exp(AE_r)^{\frac{1}{2}}$. For Au, $N/E\sigma_c$ fits this formula with $A=5.8$ Mev$^{-1}$ when $E_r>2$ Mev; when $E_r<2$ Mev, $N/E\sigma_c$ increases less rapidly with increasing $E_r$ than the formula. For Ag, $N/E\sigma_c$ fits with $A=4.7$ Mev$^{-1}$ for all $E_r$. For Cu, $N/E\sigma_c$ fits with $A=5.6$ Mev$^{-1}$ when $E_r>4.5$ Mev; when $E_r<4.5$ Mev, $N/E\sigma_c$ increases more rapidly than the formula. In the region of 150°, the cross section for the emission of lower-energy protons is isotropic, but the cross section for high-energy protons decreases slightly with increasing angle. Thus the energy distributions in the region of small $E_r$, are probably contaminated with protons from noncompound-nucleus processes.

## I. INTRODUCTION

In the past few years, experiments have been performed to measure the density of energy levels of nuclei as a function of the nuclear excitation energy. In these experiments, measurements were made of the energy distributions of neutrons[1] and of protons[2] inelastically scattered from various nuclei, and of the energy distributions of neutrons from $(p,n)$ reactions on various nuclei.[3] The bombarding energies were between 14-Mev and 18-Mev. In interpreting these experiments, it was assumed that the relation between the measured nucleon energy distributions and the energy level densities was provided by the following formula[4]:

$$N(E)dE = \text{const } E\sigma_c(E)\rho(E_r)dE, \quad (1)$$

where $N(E)dE$ = number of nucleons emitted with energy between $E$ and $E+dE$, $\sigma_c(E)$ = cross section for capture of a nucleon of energy $E$ by the residual nucleus, and $\rho(E_r)$ = density of energy levels of the residual nucleus at excitation $E_r = E_{\max} - E$. $E_{\max}$ is the maximum energy which the emitted nucleon may have. This formula follows from the assumption that the reaction proceeds through the compound-nucleus mechanism and depends upon detailed balancing between the compound system and the system consisting of the residual nucleus plus the emitted nucleon.

Recent developments indicate that noncompound-nucleus processes play an important part in nuclear reactions.[5–7] It has been pointed out that the higher energy nucleons, emitted in the reactions investigated in experiments mentioned above, very probably come from noncompound-nucleus processes.[8] The presence of noncompound-nucleus processes casts serious doubt on the interpretation of these experiments and prompts a search for new experiments which provide less ambiguous information about nuclear energy level densities.

According to one of the models of the noncompound-nucleus process, the incident nucleon makes a two-body collision with a nucleon of the target nucleus.[5,6] Either the struck nucleon or the incident nucleon escapes, carrying off a large fraction of the total available energy. In this model, emission of such nucleons at backward directions in the laboratory system is possible only by virtue of the initial internal momentum of the struck nucleon. If this is the case, the use of bombarding particles of high momenta should inhibit the noncompound-nucleus emission of nucleons at backward directions in the laboratory system. On the other hand, to increase the probability that a reaction proceed by the compound-nucleus mechanism, high bombarding energies should be avoided. An alpha particle, which has the same energy as a nucleon, has twice as much momentum. Consequently, reactions induced by alpha particles may lead to the emission of fewer nucleons at backward directions, by noncompound-nucleus processes, than reactions induced by nucleons. These considerations motivated the experiment which is reported in this paper.

In this experiment, thin targets of Au, Ag, and Cu were bombarded with 40-Mev alpha particles, and the energy distributions of protons emitted at 150° were measured.[9] Measurements were also made of the angular distributions for the emission of protons of several energies in order to determine to what extent the

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reactions proceed through the compound-nucleus mechanism.

## II. EXPERIMENTAL PROCEDURE

By means of a magnetic strong-focusing lens, the external alpha-particle beam of the Brookhaven 60-inch cyclotron was brought to a focus on a thin target at the center of a scattering chamber located 30 feet from the cyclotron in a shielded room. The beam was monitored by a NaI scintillation counter which detected alpha particles elastically scattered from the target at a fixed angle of 26°. The energy of the beam was determined by measuring its range in Al. The energy was $41.0\pm0.3$ Mev. Since the beam lost 2.0 Mev in traversing the target foils, the average alpha-particle energy in the target foils was $40.0\pm0.3$ Mev.

Protons emitted from the target foils passed through thin exit windows of the evacuated scattering chamber and were detected. The detector was a NaI scintillation counter mounted on an arm which could rotate about the center of the scattering chamber. The energy resolution of the detector was 4 percent full width at half-maximum.

Pulses from the detector passed through a cathode follower and into an Atomic Instrument Company twenty-channel pulse-height analyzer. The energy sensitivity of the entire system was calibrated with pulses from the 0.661-Mev gamma rays of $Cs^{137}$ and with pulses from elastically scattered alpha particles. The latter calibration was corrected for the nonlinear response of NaI for alpha particles.[10] The two calibrations agreed within 2 percent.

In order to render the detector insensitive to alpha particles, 170 mg/cm$^2$ of Al absorber was placed between the detector and the target. This absorber stopped the most energetic alpha particles but produced only a small decrease in the energy of the protons.

With the detector at an angle of 150°, energy distributions were measured for the protons emitted from three targets: Cu, Ag, and Au. Each distribution was obtained in two runs with the twenty-channel pulse-height analyzer; the highest channel in the first run was overlapped with the lowest channel in the second run.

The background in this experiment consisted of gamma rays and neutrons emitted from the target and from a shielded Faraday cup located several feet behind the target. (The focused beam passed through a $\frac{1}{2}$ inch diameter diaphragm located in front of the scattering chamber without a significant amount of the beam striking the edges.) Experimental runs were made with the target removed and also with an absorber between the target and the detector thick enough to stop all protons. From these data the background was estimated and subtracted from the measured energy distributions. The background was less than 5 percent at the low-energy end of the distributions, and negligible at intermediate and high energies.

Since the counting rate decreases rapidly with increasing energy, the high-energy end of the energy distributions could be distorted by "pile-up" due to the large number of low-energy pulses. This effect was observed at the highest available beam intensity. The energy distributions were measured with sufficiently low beam intensities so that the observed distributions were independent of beam intensity. Similar distortions of the energy distributions would result from nonlinearity in the detector or pulse-height analyzer. The agreement between the energy calibration made with pulses from $Cs^{137}$ gamma rays and the calibration made with elastically scattered alpha particles indicated that the system was linear. To confirm this, an energy distribution was measured using a certain pulse-height analyzer amplifier gain and a certain voltage on the photomultiplier tube. It was then remeasured using twice the original amplifier gain and with the photomultiplier voltage reduced so that, for elastically scattered alpha particle pulses, the over-all gain was the same as in the first measurement. The energy distributions, measured under these two conditions, were identical to within the accuracy with which the gains could be equated. Nonlinearity would have caused the shape of the energy distributions to be different in the two measurements.

An investigation was made of the effects of the energy resolution of the detector and of the thickness of the target foils, on the measured energy distributions. The true energy distributions were approximated by unfolding the effect of a square resolution function 2.5 Mev broad. It was found that the resolution did not significantly change the distributions and consequently this correction was not applied.

Each energy distribution was measured at least twice. The data always agreed within the statistical fluctuations and other uncertainties mentioned above. In the case of Au, energy distribution measurements were also made with an Atomic Instrument Company single-channel pulse-height analyzer and found to be in agreement with the other data.

Measurements were made of the angular distributions for the emission of protons of two energies from Au and Cu. Data for both energies were obtained simultaneously on the twenty-channel pulse-height analyzer. The angular resolution of the detector, including the effect of the size of the beam and the size of the counter aperture, was $\pm1.5°$.

## III. EXPERIMENTAL RESULTS

The proton energy distributions measured in this experiment are analyzed according to the compound-nucleus model. The extent to which this procedure is justified will be indicated by the results of the angular distribution measurements discussed at the beginning of the next section.

[10] Taylor, Jentschke, Remley, Eby, and Kruger, Phys. Rev. **84**, 1034 (1951).

Rewriting Eq. (1), of the Introduction, one obtains:

$$N(E)/E\sigma_c(E)=\text{const}\,\rho(E_r). \quad (2)$$

The assumption that Eq. (2) is valid provides a relation between $N(E)$, the measured quantity, and $\rho(E_r)$, the desired quantity.

The energy of the protons, measured in this experiment, is always greater than the height of the Coulomb barrier of the residual nucleus. Under these circumstances $\sigma_c(E)$, which is obtained from the calculations of Shapiro,[11] will change very slowly with $E$. Consequently, uncertainties in the calculated values of $\sigma_c(E)$ introduce a negligible uncertainty into the dependence of $N/E\sigma_c$ on $E$.

The energy distributions, measured at 150° in the laboratory system, are first corrected for the energy loss of the protons in traversing the 170 mg/cm² of Al which is placed between the detector and the scattering foil to stop alpha particles. The energy distributions are then transformed to the center-of-mass system. Figure 1 shows the center-of-mass energy distribution of protons emitted at 150° from a thin Au foil bombarded with 40-Mev alpha particles. The upper abscissa is the energy of the emitted proton. The ordinate is the quantity, $N/E\sigma_c$.

It is desirable to present $N/E\sigma_c$ as a function of $E_r$, the excitation energy of the residual nucleus. The relation between $E$ and $E_r$ is determined by the $Q$ of the $(\alpha,p)$ reaction, $Q_{\alpha,p}$. The $Q$ is calculated from the semiempirical mass formula.[12] The lower abscissa in Fig. 1 is the excitation energy of the residual nucleus.

Since $|Q_{\alpha,d}|$, the energy threshold for an $(\alpha,d)$ reaction, is of order 6 Mev greater than $|Q_{\alpha,p}|$; the high-energy end of the distribution contains no deuterons. The separation is amplified by the difference, $\Delta$, between the energy loss of deuterons compared to protons, in traversing 170 mg/cm² of Al between detector and scattering foil. In Fig. 1, that part of the spectrum to the right of the "deuteron end point" consists entirely of protons. To the left of the "deuteron end point," the distribution may contain deuterons.

According to the compound-nucleus model, the ratio of the number of deuterons to protons detected with energy, $E$ to $E+dE$, after passing through 170 mg of Al, is

$$\frac{N_d(E)dE}{N_p(E)dE}=\frac{M_d}{M_p}\frac{\sigma_{c,d}(E)}{\sigma_{c,p}(E)}\frac{\rho_{R'}(E)}{\rho_R(E-(|Q_{\alpha,d}|-|Q_{\alpha,p}|)-\Delta)}\cong\frac{12\rho_R(E)}{\rho_R(E-8)}.$$

The quantities $M_p$ and $M_d$ are the mass of proton and deuteron; $\sigma_{c,p}$ and $\sigma_{c,d}$ are cross sections for the formation of the compound nucleus, by protons and deuterons; $E$ is in units of Mev; and the remaining quantities have been defined before. The ratio of deuterons to protons is calculated to be less than 0.02 for all energies and for all elements investigated in this experiment. Therefore, if the reaction proceeds by compound nucleus formation, the contribution of deuterons to $N/E\sigma_c$ is negligible. Similar considerations indicate reactions of the type $(\alpha;x,p)$, where $x$ may be a neutron, alpha particle, or deuteron emitted preceding the proton, will also have a negligible effect on the quantity, $N/E\sigma_c$.

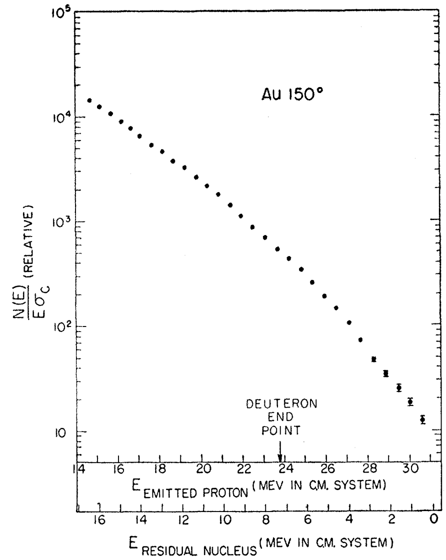


FIG. 1. The quantity, $N/E\sigma_c$, from the $(\alpha,p)$ reaction on gold.

It is interesting to compare these data with the Fermi gas level density formula,[13]

$$\rho(E_r)=\text{const}\,\exp(AE_r)^{\frac{1}{2}}, \quad (3)$$

where $\rho(E_r)$ = the density of energy levels of the nucleus at excitation energy $E_r$, and $A$ = a constant. This level density formula follows from the assumption that the nucleus consists of a gas of fermions confined to a region of space the size of the nucleus. In Fig. 2, $N/E\sigma_c$, at 150° for Au, is plotted as a function of $E_r^{\frac{1}{2}}$. It is seen that the data fit the Fermi gas level density formula with $A=5.8$ Mev$^{-1}$, when $E_r>2$-Mev. When $E_r<2$-Mev, $N/E\sigma_c$ increases less rapidly with increasing $E_r$ than the formula.

$N/E\sigma_c$, measured at 150° for Ag, is plotted in Fig. 3 as a function of $E_r^{\frac{1}{2}}$. The data fit the Fermi gas level density formula with $A=4.7$ Mev$^{-1}$, for all $E_r$ measured. In Fig. 4, $N/E\sigma_c$, at 150° for Cu, is plotted as a function of $E_r^{\frac{1}{2}}$. The data fit the Fermi gas level density formula with $A=5.6$ Mev$^{-1}$, when $E_r>4.5$ Mev. When $E_r<4.5$ Mev, $N/E\sigma_c$, increases more rapidly with increasing $E_r$ than the formula.

[11] M. M. Shapiro, Phys. Rev. **90**, 171 (1953). Values of $\sigma_c$ were obtained by using $R=1.5A^{\frac{1}{3}}\times10^{-13}$ cm.

[12] N. Metropolis and G. Reitwiesner, *Table of Atomic Masses*, Atomic Energy Commission Report NP-1980, 1950 (unpublished).

[13] V. F. Weisskopf and D. H. Ewing, Phys. Rev. **57**, 472 (1940).

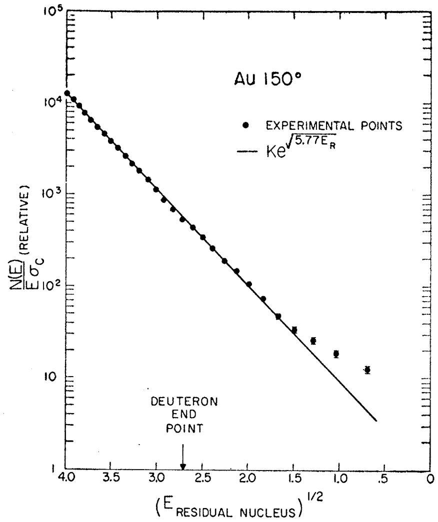


FIG. 2. The quantity, $N/E\sigma_c$, from the $(\alpha,p)$ reaction on gold plotted as a function of $E_r^{\frac{1}{2}}$.

There are several factors which introduce uncertainty into the relation between $E$ and $E_r$. These are: uncertainty in the calibration of the $E$ scale, uncertainty in the energy of the incident alpha-particle beam, the presence of two isotopes with differing $Q$'s (in the case of Ag and Cu, a weighted average $Q$ was taken), and the uncertainty in $Q$ values determined from the semi-empirical mass formula. These factors combine to produce an uncertainty in the location of the origin of the $E_r$ scale, which is estimated to be of the order $\pm 0.75$ Mev. In order to investigate what effect this additive uncertainty in $E_r$ can have on the shape of the curve of $N/E\sigma_c$ as a function of $E_r^{\frac{1}{2}}$, the Au data have been plotted in Fig. 5 for different assumptions concerning the relation between $E$ and $E_r$. In curve $b$, the calculated relation between $E$ and $E_r$ is used. Curve $a$ shows the effect of increasing $E_r$ by 0.75 Mev and curve $c$ shows

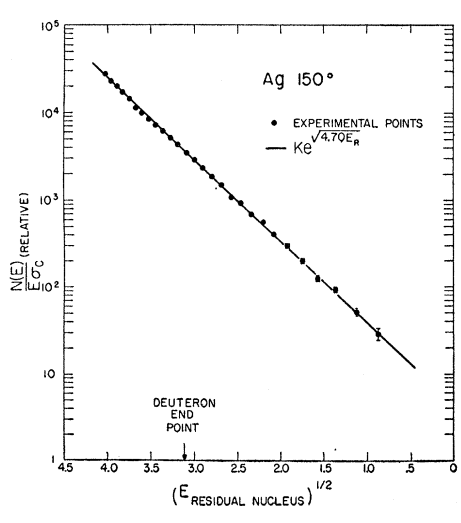


FIG. 3. The quantity, $N/E\sigma_c$, from the $(\alpha,p)$ reaction on silver.

the effect of decreasing $E_r$ by 0.75 Mev. It is seen that the over-all shape of the curve is not appreciably changed. The value of $A$ which fits the data best is, in the first case, increased to 6.3 Mev$^{-1}$ and, in the second case, decreased to 5.4 Mev$^{-1}$.

It is noted that the intermediate-weight element, Ag, has the smallest value of the parameter, $A$. In view of the uncertainty in $A$ mentioned above, the decrease in $A$ might have doubtful significance. However, only the last two sources of error mentioned in the preceding paragraph introduce an uncertainty into the relation between $E$ and $E_r$ which is not the same for the three elements. The relative uncertainties in $A$ for the three elements are estimated to be one-half of the total uncertainty quoted in the last paragraph. Therefore, the relatively low $A$ measured for Ag cannot be explained only on the basis of experimental error.

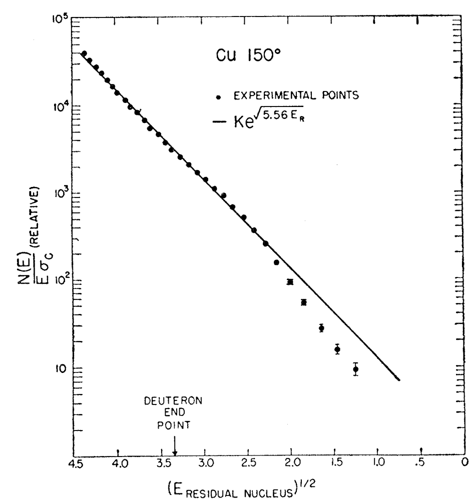


FIG. 4. The quantity, $N/E\sigma_c$, from the $(\alpha,p)$ reaction on copper.

Measurements have been made of the angular distribution for the emission of 15-Mev and 28-Mev protons from Au bombarded with 40-Mev alpha particles. The results are presented in Fig. 6. The abscissa is angle in the center-of-mass system. The ordinate is relative center-of-mass differential cross section. The two curves have been displaced vertically by an arbitrary amount, so that they would fit on the same figure. Although it is not shown in Fig. 6, the differential cross sections, at both energies, continue to increase with decreasing angle in the forward hemisphere. Angular distributions for the emission of protons of 19 Mev and 31 Mev from Cu are shown in Fig. 7.

In the case of 15-Mev protons from Au (corresponding to points in the region of $E_r^{\frac{1}{2}}=4.0$ in Fig. 2) the differential cross section decreases with increasing angle but becomes isotropic at angles greater than about 120°. In the case of 28-Mev protons from Au ($E_r^{\frac{1}{2}}=1.7$ in Fig. 2) the differential cross section continues to decrease slowly with increasing angle, even at 150°. In a similar fashion, the differential cross section for the emission of 19-Mev protons from Cu ($E_r^{\frac{1}{2}}=4.2$ in Fig. 4) becomes isotropic at angles greater than about 120°, but the differential cross section for the emission of 31-Mev protons from Cu ($E_r^{\frac{1}{2}}=2.3$ in Fig. 4) decreases slowly with increasing angle to the largest angles measured.

## IV. DISCUSSION

It would seem reasonable to separate the angular distributions for the emission of 15-Mev protons from Au and 19-Mev protons from Cu into two parts. At angles greater than about 120°, the isotropic angular distributions indicate that the compound-nucleus mechanism plays a dominant role in the reactions. At smaller angles, the forward peaking of the angular distributions indicates that some noncompound-nucleus mechanism is primarily responsible for the reactions.

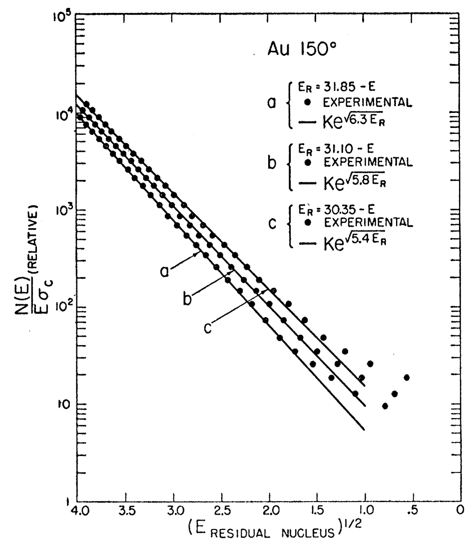


FIG. 5. The change in $N/E\sigma_c$ introduced by displacing the zero of the $E_r$ scale by $\pm 0.75$ Mev.

However, in the case of the emission of 28-Mev protons from Au and 31-Mev protons from Cu, the noncompound-nucleus mechanism appears to be significant at all angles. The angular distributions give weight to the interpretation of $N/E\sigma_c$ in terms of nuclear level densities in the case of higher excitation energies (lower-energy emitted protons). However, they indicate that this interpretation can be applied in the case of lower excitation energies only if consideration is given to the presence of noncompound-nucleus processes.

The angular distribution data show that the $(\alpha,p)$ reactions investigated in this experiment do not provide completely unambiguous information about nuclear level densities. However, it appears that in this energy range, reactions induced by alpha particles, leading to the emission of nucleons at backward directions, are less dominated by noncompound-nucleus processes than reactions induced by nucleons. In the inelastic scattering

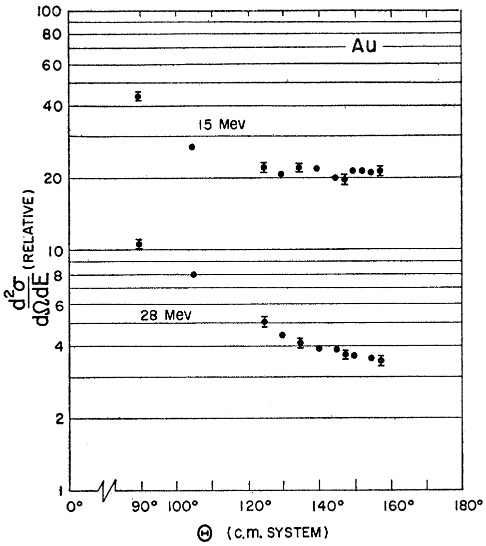


FIG. 6. The angular distributions of 15-Mev and 28-Mev protons emitted in the $(\alpha,p)$ reaction when gold is bombarded by 40-Mev alpha particles.

of 31-Mev protons, the reaction is predominantly a noncompound-nucleus process, even at backward directions.[6,8] In the present experiment, despite the fact that the energy is somewhat higher, the reaction at backward directions appears to be largely a compound-nucleus process. (These comments are based on the assumption that the isotropy of an angular distribution at backward directions implies that the compound nucleus mechanism dominates in that region. This is not necessarily correct since it is possible that the noncompound-nucleus angular distributions may become

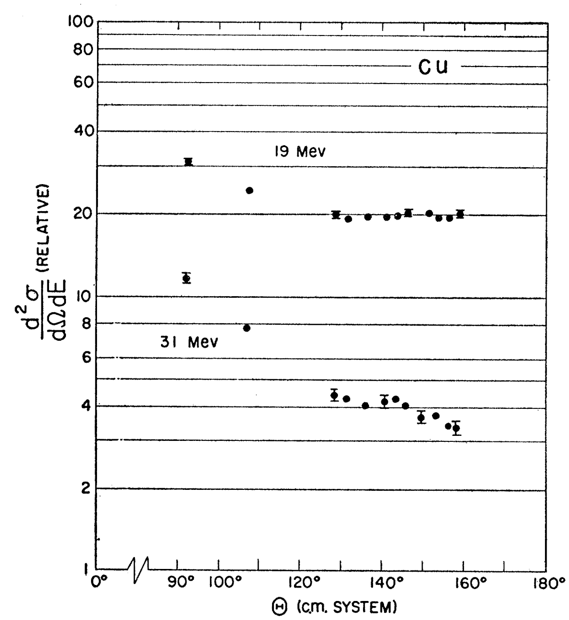


FIG. 7. The angular distributions of 19-Mev and 31-Mev protons emitted in the $(\alpha,p)$ reaction when Cu is bombarded by 40-Mev alpha particles.

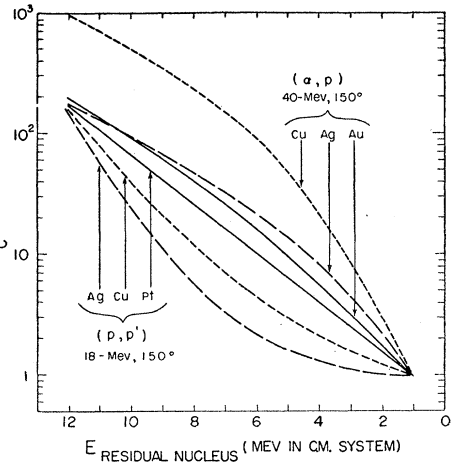


FIG. 8. The quantity, $N/E\sigma_c$, measured in the $(p,p')$ experiment and in the $(\alpha,p)$ experiment.

isotropic at large angles.) If alpha-particle bombardment does inhibit noncompound-nucleus processes at backward directions then it is not certain that this happens for the reasons presented in the Introduction. For instance, it is possible that alpha-particle bombardment favors the compound-nucleus process because the binding energy per nucleon of an alpha particle is similar to that of most nuclei. In view of these arguments, and of the encouraging results of this experiment, it would seem worth while to investigate additional reactions such as $(\alpha,\alpha')$ and $(X,p)$, where $X$ is a heavy ion such as nitrogen.

It is interesting to compare the values of $N/E\sigma_c$ measured in this experiment with measurements of the same quantity which come from the inelastic scattering of 18-Mev protons.[2] The data are presented in Fig. 8. The abscissa is the excitation energy of the residual nucleus and the ordinate is relative $N/E\sigma_c$. For purposes of comparison, all curves have been normalized to unity at $E_r=1$ Mev. The data of the $(p,p')$ experiment extend only to $E_r=12$ Mev.

The most noticeable difference between the results of the two experiments is that the $N/E\sigma_c$ curves measured in the $(p,p')$ experiment are concave upward while the $N/E\sigma_c$ curves measured in the $(\alpha,p)$ experiment are concave downward. A concave downward dependence is predicted by several level-density formulas.[14–16] In particular, the $N/E\sigma_c$ curves from the $(\alpha,p)$ experiment are in good agreement with the shape predicted by the Fermi gas level density formula for excitation energies greater than several Mev.

A direct comparison between what is known about level densities and the results of these two experiments is shown in Table I. Column I gives the target element. Column 2 is the ratio of $N/E\sigma_c$ at neutron binding energy to $N/E\sigma_c$ at 1 Mev, as measured in the $(\alpha,p)$ experiment. Column 3 is the ratio of the level density at neutron binding energy to the level density at 1 Mev, for the residual nuclei appropriate to the $(\alpha,p)$ experiment. Column 4 is the ratio of $N/E\sigma_c$ at neutron binding energy to $N/E\sigma_c$ at 1 Mev, as measured in the $(p,p')$ experiment. Column 5 is the ratio of the level density at neutron binding energy to the level density at 1 Mev, for the residual nuclei appropriate to the $(p,p')$ experiment. The level density at neutron binding energy is obtained from slow neutron resonance experiments[17] and the level density at 1 Mev is obtained from nuclear spectroscopy experiments.[18] It is estimated that the data presented in columns 3 and 5 are accurate to within a factor of two.

TABLE I. Comparison of measured level densities.

| Target element | $(\alpha,p)$ $\frac{N/E\sigma_c(\text{neut. B.E.})}{N/E\sigma_c(1\text{ Mev})}$ | $\frac{\rho(\text{neut. B.E.})}{\rho(1\text{ Mev})}$ | $(p,p')$ $\frac{N/E\sigma_c(\text{neut. B.E.})}{N/E\sigma_c(1\text{ Mev})}$ | $\frac{\rho(\text{neut. B.E.})}{\rho(1\text{ Mev})}$ |
|---|---|---|---|---|
| Cu | $6\times10^2$ | $7\times10^2$ | $8\times10$ | $7\times10^2$ |
| Ag | $6\times10$ | $2\times10^3$ | $1\times10$ | $2\times10^3$ |
| Au, Pt | $4\times10$ | $1\times10^3$ | $2\times10$ | $5\times10^3$ |

However, it should be pointed out that neutron resonance experiments detect levels of spin $I\pm\frac{1}{2}$, where $I$ is the spin of the target nucleus in the ground state. Therefore, the level densities determined by this method are probably a lower limit to the actual level densities. The distance between levels of the same spin state was used to evaluate the ratios in columns 3 and 5 of Table I.

On the basis of this comparison, it is seen that the $N/E\sigma_c$ measured in the $(\alpha,p)$ experiment are in much better agreement with present knowledge of level densities obtained by actual counting of levels than are the $N/E\sigma_c$ measured in the $(p,p')$ experiment. For Cu, the $(\alpha,p)$ data are in excellent agreement with the level density data. For Ag and Au, the $(\alpha,p)$ data indicate an increase in $N/E\sigma_c$, from 1-Mev to neutron binding energy, which is about a factor of 30 less than the increase in level density.

Some of this discrepancy is quite probably due to noncompound-nucleus processes. The angular distribution data indicate that noncompound-nucleus processes are more important for reactions leading to lower excitation energies. Therefore, the noncompound nucleus processes tend to increase $N/E\sigma_c$ at lower excitation energies, relative to its value at higher excitation energies. Whether or not this can account for the discrepancy will be established only by further experimental and theoretical work.

The authors are grateful to the crew of the Brookhaven cyclotron for their cooperation and to Dr. C. E. Porter and Professor V. F. Weisskopf for stimulating discussions.

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[17] J. A. Harvey (private communication).
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