our empirical curves are for rather disparate Q values, but we have found,[1,5,6] for $l_n=1$ at least, that the position of the maximum appears to be rather insensitive to the magnitude of Q, for 10-Mev incident deuteron energy.

Comparison of empirical angular distributions with theoretical curves becomes somewhat unreliable as a method for determining l_n for moderate or high values of Z, because a complete theoretical treatment of the problem, which omits no factor of importance and from which differential cross sections can be computed without elaborate computational aids, is not available. The Butler derivation, in particular, contains several simplifying assumptions whose validity is especially questionable as Z becomes fairly large. The behavior of the empirical distributions as shown in Fig. 9 encourages us to believe that our assignments of l_n are meaningful.

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(p,α) Reactions Induced by 23-Mev Protons

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The (p,α) reactions induced by 23-Mev protons in targets of a wide range of atomic number were studied by observing the outgoing alpha particles. Alpha-particle energy distributions and absolute differential cross sections were measured at 30, 60, 90, 120, and 150 degrees. For targets of atomic number $\lesssim 50$, the energy spectra and angular distributions indicate that most of the alpha particles are produced in compound nucleus reactions; however, there is evidence that the Coulomb barriers of the excited compound nuclei are somewhat lower than those of ground state nuclei. The alpha particles from the heaviest elements and the high-energy parts of the spectra from lighter targets are strongly forward peaked and are produced by direct interaction reactions. Total (p,α) cross sections vary from 175 mb for Al to 3.8 mb for Pt.

INTRODUCTION

THE properties of particles emitted in nuclear reactions are influenced by the nuclear processes involved in the reactions. If the energy level spacings of the residual nuclei are smaller than the energy resolution of the instruments used to study the emitted particles, the observed energy distributions are smoothly varying. The statistical theory of nuclear reactions predicts particles emitted from compound nucleus reactions to have energy distributions that are Maxwellian and characterized by the temperatures of the residual nuclei; in the case of charged particles, these energy distributions are altered by the Coulomb barrier, which is usually thought to be a function of nuclear size.

A number of studies of (p,α) reactions have been reported;[1–14] however, these have all used targets of light nuclei, and most have dealt with the ground state or low-energy excited levels of the residual nuclei.

In the work reported here, a survey of (p,α) reactions induced by 23-Mev protons was made by observing the outgoing alpha particles from targets of a wide range of atomic number. Energy distributions and absolute differential cross sections were determined at several angles to the proton beam.

EXPERIMENTAL

The energy-analyzed external 23-Mev proton beam of the ORNL 86-in. cyclotron was used for these experiments. The beam was collimated and passed through thin foils of the targets being studied and into a Faraday cup which monitored the beam. The outgoing alpha particles were observed through holes located in the wall of the 11-in. diameter scattering chamber at angles of 30, 60, 90, 120, and 150 deg from the proton beam.

The particles were detected by a proportional counter—scintillation counter telescope. The scintillation counter consisted of a 0.1-in. thick CsI(Tl) crystal and a Dumont 6291 photomultiplier tube. Energy distributions were determined by pulse height analysis of the scintillation counter pulses; a coincidence gate on the 20-channel pulse height analyzer was triggered with proportional counter pulses which passed an integral

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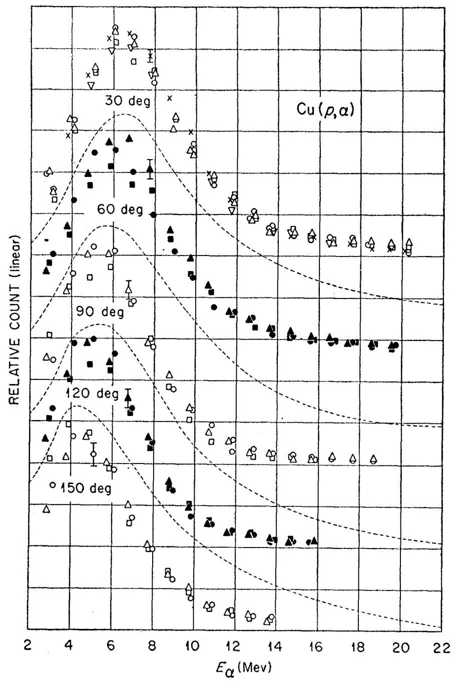

FIG. 1. (p,α) data for copper. The data are not corrected for particle energy loss or center-of-mass motion. There is no significance to the vertical position of each set of data; the high-energy parts of each set of data approach zero count.

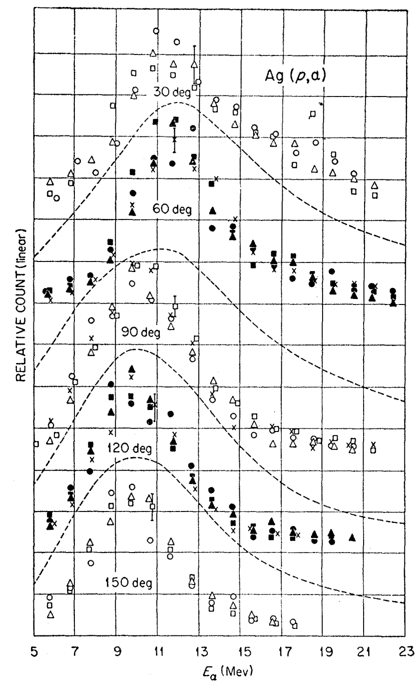

FIG. 2. (p,α) data for silver. The data are not corrected for particle energy loss or center-of-mass motion. There is no significance to the vertical position of each set of data; the high-energy parts of each set of data approach zero count.

discriminator; thus, background pulses were eliminated from the data. The 2-in. thick proportional counter was filled to a pressure of 12 cm Hg with a 90% argon–10% methane gas mixture. The scintillation crystal was mounted directly in the wall of the proportional counter. The particles passed through absorbers, including mica window and proportional counter gas, and through a light reflector equivalent to 3 mg/cm^2 of aluminum between the target foils and the scintillation detector.

An energy calibration of the scintillation detector was obtained with the ground-state alpha particles from the $F^{19}(p,\alpha)O^{16}$ reaction. A thin Teflon film was used as the target. Aluminum absorbers were used to obtain lower energy alpha particles. Natural alpha particles from Po^{212} and from U^{233} were also used. A scintillation pulse height *vs* energy curve was obtained for alpha particles ranging in energy from 2.5 Mev to 25 Mev. Pulse heights of elastically scattered protons were also measured. The results were such that if the pulse height *vs* energy curve for protons is represented by $E_p=kN$ (E_p is the proton energy in Mev and N is the pulse height), the curve for alpha particles above ~4 Mev is represented by $(E_\alpha-1.5)=kN$.

The scintillation pulse heights of protons elastically scattered from the targets were checked frequently during the experiments, and the photomultiplier tube voltage was adjusted to maintain the same value of k.

The energy calibration for alpha particles was obtained at the beginning of the series of experiments and repeated four months later. There was no shift in the energy calibration. In general, the absolute energy calibration is accurate to within $\frac{1}{2}$ Mev at all energies.

Energy losses of the particles in the target foils and between the targets and detector limited energy distribution measurements to energies $\gtrsim 5$ Mev. The energy distributions of the lightest targets studied were the only ones affected by this limitation. The peaks of the energy spectra from aluminum were observed only at angles less than 90 degrees. However, the similarity of the high-energy part of the energy distribution at all angles and the small anisotropy of the alpha-particle spectra (except the high-energy tails) for all heavier targets with $Z\lesssim 50$ indicated that the alpha particles produced by (p,α) reactions in aluminum are emitted almost isotropically. Alpha-particle spectra from a magnesium target were also observed. The target used was thick enough (6.2 mg/cm^2) that the peak of the energy distribution was not observed at any angle. The high-energy parts of the spectra were very similar to those of aluminum.

The procedure for taking data was as follows. A target wheel with six target foils was mounted on a motor-driven shaft in the scattering chamber; to change targets, the motor was operated remotely from the counting room. The proportional counter was filled with gas at the beginning of each day's run. The scintillation pulse height spectrum without proportional counter gating was observed, and the photo-

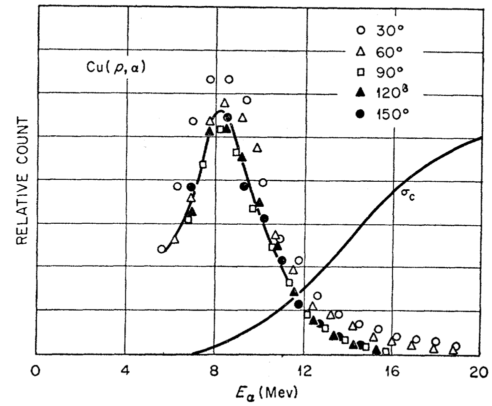

FIG. 3. Energy distribution of alpha particles observed from copper. The curve is drawn through the 120- and 150-deg data. The curve labeled σ_C shows the barrier penetration factors as a function of alpha-particle energy for the Coulomb barrier that has been measured in (α,n), (α,$2n$), and (α,$3n$) reactions.

multiplier tube voltage was adjusted to position the peak from elastically scattered protons to the proper value. The pulse height spectrum of the proportional counter pulses in coincidence with scintillator pulses was observed; from this the desired integral discrimination level was determined. The proportional counter pulses were then used to gate the 20-channel pulse height analyzer which recorded the alpha-particle spectrum.

The spectrum from each target was observed at each detector position three or more times over a period of several weeks. The data obtained from two targets are shown in Figs. 1 and 2. These data show the energy distributions of the particles observed by the scintillation detector. The counting statistics are indicated for typical data points. Smooth curves were drawn through the accumulated data plots for each target and detector position; these curves were corrected for energy absorption and center-of-mass motion to determine the energy distributions of the alpha particles.

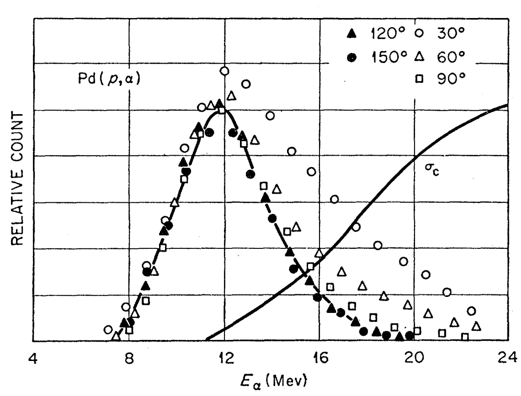

FIG. 4. Energy distribution of alpha particles observed from palladium. The curve is drawn through the 120- and 150-deg data. The curve labeled σ_c shows the barrier penetration factors as a function of alpha-particle energy for the Coulomb barrier that has been measured in (α,n), (α,$2n$), and (α,$3n$) reactions.

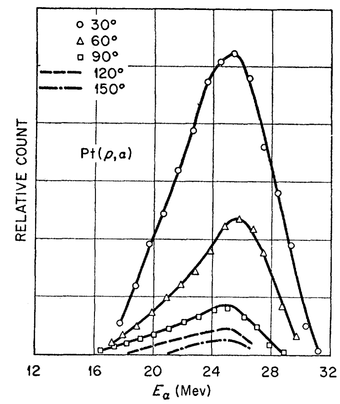

FIG. 5. Energy distribution of alpha particles observed from platinum.

RESULTS

Energy distributions of the alpha particles observed at 30, 60, 90, 120, and 150 deg to the proton beam for targets of Cu, Pd, and Pt are shown in Figs. 3, 4, and 5, respectively. Each group of points represents the average of three or more runs corrected for energy losses between target and detector and for center-of-mass motion. The spectra from Ni and Zn are almost identical to those from Cu; the spectra from Ag and Rh are almost identical to those from Pd; and the spectra from Au are almost identical to those from Pt. Energy distributions of the alpha particles observed from Al, Cu, Pd, and Pt targets at 90 deg are shown in Fig. 6 for comparison.

In Fig. 7 measured values of the differential cross sections for (p,α) reactions induced by 23-Mev protons are shown for all targets studied. In Table I average Q values for (p,α) and (p,n) reactions are listed for all targets studied. The total (p,α) cross sections are also listed in Table I; in addition, the best estimates of cross sections for (p,α) reactions by direct interaction are shown.

The energy distributions for targets of atomic number less than ~50 are characterized by broad maxima that fall sharply to zero on the low-energy side; the energies of the maxima increase with atomic number of the target; the angular distributions are peaked forward, but the anisotropies are not large

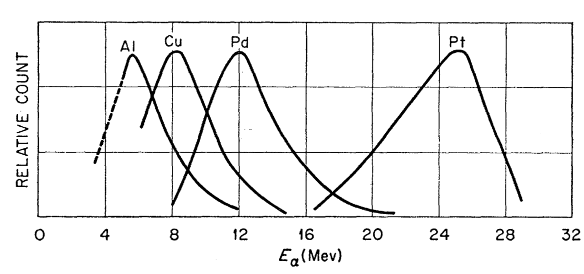

FIG. 6. Energy distribution of alpha particles observed from aluminum, copper, palladium, and platinum at 90 deg.

except in the high-energy tails (see Fig. 8). For the heaviest elements studied, the maxima in the energy distributions occur near the highest energy, and the angular distributions are strongly forward at all energies.

The alpha-particle energy distributions and the cross sections for targets of neighboring atomic number are very similar. The data show no large effects associated with variation of Q values or to evenness or oddness of mass or atomic number of the residual nuclei.

DISCUSSION

The general features of the data from all but the heaviest elements are in qualitative agreement with the expectation from a compound nucleus theory. In particular, the angular distributions are generally quite isotropic and the energy spectra are peaked at low energy. In fact, in the latter lies the most striking difficulty in explaining the data in detail, namely, that the majority of the alpha particles are emitted with an unusually low energy. This may be explained to be due to either an unusually low Coulomb barrier, or unusually low nuclear temperature.

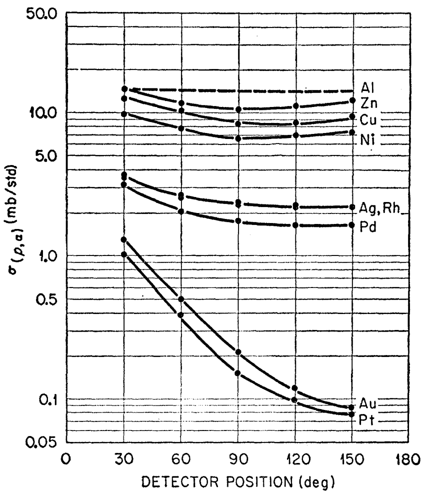

FIG. 7. Differential (p,α) cross sections for 23-Mev protons on the various targets studied.

The low Coulomb barrier explanation is, at first, not appealing since, in accordance with the reciprocity theorem, the barrier encountered by alpha particles leaving the nucleus must be identical with that encountered by alpha particles entering the nucleus. The latter has been well measured in experiments which determine (α,n), ($\alpha,2n$), ($\alpha,3n$), (α,pn), and (α,fission) excitation functions[15–20]; the results of several such experiments are given in Table II where the barrier penetration factors are expressed in terms of the radius parameter r_0 that corresponds with the tables of Blatt and Weisskopf.[21] Optical model analyses of the data from elastic scattering of alpha particles yield reaction cross sections and interaction radii[22–24] for alpha particles that correspond to r_0 values as large as 1.7 fermis (1 fermi$\equiv 10^{-13}$ cm); however, these include contributions from direct interaction processes and are therefore overestimates.

Most of the data for alpha particles entering the nucleus are in excellent agreement with the barrier

TABLE I. (p,α) and (p,n) Q values and (p,α) cross sections for 23-Mev protons on the targets studied. The accuracy of total $\sigma(p,\alpha)$ values, for all targets except Al, is ±20% (95% confidence interval), and the accuracy for the direct interaction values is ±15%.

Target	Average Q values (Mev) (p,α)	(p,n)	Total $\sigma(p,\alpha)$ (mb)	$\left(\frac{\sigma(p,\alpha)_{\text{direct interaction}}}{\sigma(p,\alpha)_{\text{total}}}\right)$
Al	+2.5	−4.8	175±50%	0.20
Ni	−0.7	−9.5	93.5	0.25
Cu	+3.7	−3.9	122	0.30
Zn	+2.1	−6.5	147	0.25
Rh	+6.2	−1.5	32.2	0.34
Pd	+2.9	−3.3	24.9	0.35
Ag	+6.2	−1.7	32.2	0.34
Pt	+6.3	−1.9	3.8	~1.0
Au	+7.6	−7.9	5.0	~1.0

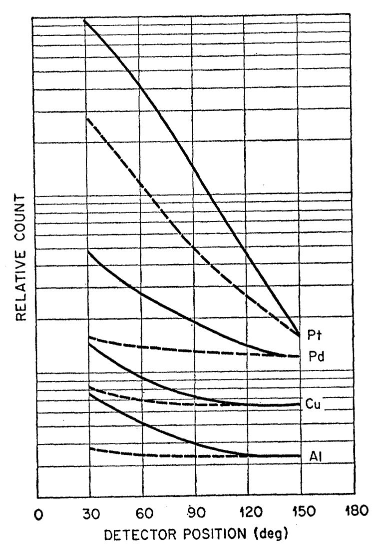

FIG. 8. Angular distributions of alpha particles from (p,α) reactions in various targets. The dotted curves show the relative heights of the peaks of the energy distributions; the solid curves show the relative height of the energy distributions at the highest energies for which data were reliable at all detection positions. There is no significance to the vertical position of each pair of curves.

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TABLE II. Measured cross sections of reactions induced by alpha-particles and protons in heavy nuclei. Results of experiments are expressed as r_0 values in tables from Blatt and Weisskopf[a] which give cross sections that fit the data.

Target	Reaction	r_0 (fermis)	Reference
Bi^{209}	$(\alpha,2n)+(\alpha,3n)$	1.5	(15)
Ni^{60}	$(\alpha,n)+(\alpha,2n)$	1.4	(16)
Ag^{109}	$(\alpha,n)+(\alpha,2n)$	1.6	(17)
Ag^{107}	$(\alpha,n)+(\alpha,2n)+(\alpha,pn)$	1.65	(18)
Cu^{63}	$(\alpha,n)+(\alpha,2n)+(\alpha,pn)$	1.5	(18)
U^{235}	(α,fission+spallation)	1.55	(19)
Bi^{209}	(α,α)	1.6	(20)
U^{238}	(p,fission)	1.55	(26)
U^{238}	(p,fission)	1.48	(27)
About 60 nuclei ranging from Ni^{60} to Gd^{157}	(p,n)	1.50 (average)	(25)

[a] See reference 21.

penetration factors (actually, the cross sections for alpha-particle capture) calculated by Blatt and Weisskopf[21] for $r_0=1.5$ fermis. There is, moreover, extensive evidence that approximately this value of r_0 corresponds to the barrier encountered by protons entering the nucleus as determined by (p,n)[25] and (p,fission)[26,27] excitation functions.

There is thus a strong temptation to attribute the low energies of the peaks of the alpha-particle energy distributions to unusually low nuclear temperatures. The consequences of this explanation were investigated and the results are summarized in Tables III and IV. The a values are the values of the parameter a, in the level density formula $\omega(\epsilon)=c\exp(a\epsilon)^{\frac{1}{2}}$. It is seen that the low nuclear temperature explanation of the data leads to several major difficulties.

(1) The temperatures thus obtained are much lower than those encountered in any previous experiment. For example, the values obtained require the a to be about 190 Mev^{-1} for Ni-Cu-Zn and about 80 Mev^{-1} for Rh-Pd-Ag, whereas it was generally found to be between 5 and 50 Mev^{-1} in the most reliable previous experiments.[28] It is also unusual for a to decrease as A increases. The agreement is even worse when a comparison is made with the nuclear temperature obtained from (α,p) reactions, since, according to the reciprocity theorem, the reaction mechanism must be the same as that of the (p,α) reactions studied here. The values of a obtained from (α,p) experiments are ~ 5 Mev^{-1}.[29]

(2) If the nuclear temperatures were actually as low as required for this explanation of the energy spectra (0.6 Mev for the peaks of Ni-Cu-Zn energy distributions and 0.85 Mev for the peaks of Rh-Pd-Ag energy distributions), (p,α) reactions would be extremely rare. Neutron emission [i.e., (p,n) reactions] would predominate by many orders of magnitude and even inelastic proton scattering would be far more probable. Even when the large positive Q value for (p,α) reactions are taken into account, the low nuclear temperature explanation predicts that (p,n) cross sections should be, for example, about 2000 times larger than (p,α) cross sections, whereas the experimental ratio is only about 30.

(3) In addition to the difficulty in explaining the absolute values of the (p,α) cross sections, low nuclear temperatures would predict very great sensitivities of these cross sections to Q values and bombarding energy. For example, they would predict the (p,α) cross section for Ag to be 20 times as large as it is for Pd; actually, it is larger by only about 25%. The low nuclear temperature explanation predicts a (p,α) cross section decrease by a factor of 30 for a proton energy change from 17 Mev to 23 Mev. The experimental change measured for a large number of elements is an increase by a factor of ~ 2.[30]

The foregoing results of the low nuclear temperature explanation of the data are similarly obtained from Ni and Cu data (see Table IV).

These results would be exaggerated if the energy calibration of the detector were too low. The effect on the results was investigated by assuming the energy calibration to be $\frac{1}{2}$ Mev too low at tall energies. The nuclear temperature thus obtained for the peak of the energy distribution of alpha particles observed from Rh-Pd-Ag is 0.95 Mev for $r_0=1.5$. This predicts for Pd a ratio of (p,n) to (p,α) cross sections equal to 250; it predicts the ratio of the (p,α) cross sections for Ag to be 6.5 times as large as for Pd; and it predicts the (p,α) cross section for Pd to increase by a factor of 25 for a proton energy change from 17 to 23 Mev. Thus, the difficulties resulting from the low nuclear temperature explanation of the data cannot be attributed entirely to any inaccuracy in the energy calibration of the detector.

In view of the resulting difficulties of the "low nuclear temperature" explanation of the low energies of the peaks of the observed alpha-particle energy spectra, a re-examination of the "reduced Coulomb barrier" explanation seems to be in order. One difference between the barriers encountered in (p,α) reactions or (p,n) reactions and those encountered in (α,n) reactions is that in the former, ground state nuclei are involved, whereas, in the latter, the nuclei are in highly excited states. It is easily conceivable that the Coulomb barrier in a highly excited nucleus is considerably lower than in a ground state nucleus. For example, Hill and Wheeler[31] have proposed that highly excited nuclei are strongly distorted; portions of the nuclear surface are thus quite far from the center of charge, so that the Coulomb barriers are reduced. As another example, Lane[32] has pointed out that the nuclear surface should

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TABLE III. Values of the level density parameter a (in Mev^{-1}) obtained from the data for Coulomb barriers that correspond to various values of r_0 and values of a obtained from other experiments.

	$r_0=1.5$ fermis	$r_0=1.7$ fermis	$r_0=1.9$ fermis	From other experiments[a]
Ni-Cu-Zn	190	82	46	6–30
Rh-Pd-Ag	80	66	38	5–50
Pd (if energy calibration is $\frac{1}{2}$ Mev too low)	62	39		

[a] See reference 28.

be considerably more diffuse for a highly excited nucleus than for a nucleus in its ground state. Thus, the point at which the Coulomb force is neutralized by the nuclear force is at a somewhat larger radius for the former, and the Coulomb barrier is effectively reduced. After consideration of the difficulties of the "low nuclear temperature" explanation, the "lowered Coulomb barrier" explanation seems to be the more appropriate one.

The results obtained by assuming Coulomb barriers corresponding to $r_0=1.7$ fermis and $r_0=1.9$ fermis are shown in Tables III and IV. It is seen that a barrier corresponding to $r_0=1.9$ fermis removes much of the difficulty encountered by the "low nuclear temperature" and conventional barrier explanation discussed above. For this barrier, a nuclear temperature of 1.2 Mev, corresponding to $a=46$ Mev^{-1}, satisfies the peak of the energy distributions of alpha particles from Ni-Cu-Zn, and a nuclear temperature of 1.3 Mev, corresponding to $a=38$ Mev^{-1}, satisfies the peaks of the energy distributions from Rh-Pd-Ag. The lower Coulomb barrier predicts (p,n) to (p,α) ratios that are not in sharp disagreement with experimental results. It also predicts variations of (p,α) cross sections with Q values and proton energies that agree reasonably well with experiment. Almost as good agreement with experiment is obtained if it is assumed that the energy calibration of the detector is $\frac{1}{2}$ Mev too low, and an r_0 value of 1.7 is used to compute ratios of $\sigma(p,n)$ to $\sigma(p,\alpha)$, dependence of $\sigma(p,\alpha)$ on Q values, and dependence $\sigma(p,\alpha)$ on proton energy. However, this value of r_0 is larger than any obtained from alpha-particle reactions with ground state nuclei. There is thus strong evidence that a "lower Coulomb barrier" explanation of the data gives much better agreement between experiment and theory than does the "low nuclear temperature" explanation.

In a previous paper[33] evidence was reported from a (p,αn) excitation function that Coulomb barriers are not lowered when alpha particles are emitted from nuclei. However, recent redeterminations of nuclear masses reveal that the Q values used in that work were in error by 2.5 Mev. If this correction is taken into account, those data are in good agreement with the results reported here.

The energy distributions of the alpha particles from Ni-Cu-Zn are in reasonable agreement with that of photo-alpha particles from cobalt[34] and copper.[35] The principal parts of the spectra of Rh, Pd, and Ag

TABLE IV. Some results predicted by theory for Coulomb barriers that correspond to various values of r_0; experimental results are shown for comparison.

	$r_0=1.5$ fermis	$r_0=1.7$ fermis	$r_0=1.9$ fermis	Experimental results
$\frac{\sigma(p,n)}{\sigma(p,\alpha)}$ for Pd	2000	100	20	30
	250[b]	40[b]		
$\frac{\sigma(p,\alpha) \text{ for Ag}}{\sigma(p/\alpha) \text{ for Pd}}$	20	10	4	1.25
	6.5[b]	5[b]		
$\frac{\sigma(p,\alpha);\ E_p=17 \text{ Mev}}{\sigma(p,\alpha);\ E_p=23 \text{ Mev}}$ for Pd	30	2.5	0.8	0.5[a]
	25[b]	3.5[b]		
$\frac{\sigma(p,n)}{\sigma(p,\alpha)}$ for Cu	100	10	3	6.5
$\frac{\sigma(p,\alpha) \text{ for Cu}}{\sigma(p,\alpha) \text{ for Ni}}$	35	15	8	1.3

[a] See reference 30.
[b] These values would be predicted if the energy calibration of the alpha-particle detector were $\frac{1}{2}$ Mev too low.

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[34] M. Elaine Toms and William E. Stephens, Phys. Rev. 95, 1209 (1954).
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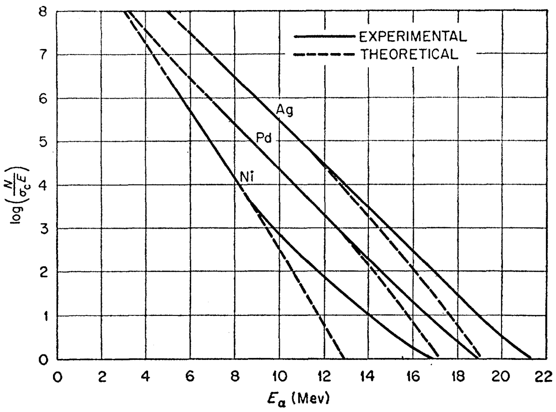

FIG. 9. Energy spectra, plotted as $\log_{10}(N/\sigma_c E)$, for alpha particles from nickel, palladium, and silver at 150 deg. The solid curves show the observed spectra. The dotted curves show the spectra that would be observed if all the alpha particles were produced in compound nucleus reactions with a single value of a for each target (see text).

reported here are in reasonable agreement with that from 17-Mev protons on Rh observed by Brady at Princeton.[36]

The high-energy parts of the observed alpha-particle energy spectra and the entire spectra from the heaviest elements are characterized by forward-peaked angular distributions. This is generally interpreted as an indication that these reactions proceed by some sort of direct interaction. If it is assumed that this direct interaction has zero cross section at 150 deg and that deviations of the spectra observed at other angles are due to direct interactions, the cross sections for the direct interactions are $<10\%$ of the total (p,α) cross section for Al and for Ni-Cu-Zn, $\sim 20\%$ for Rh-Pd-Ag, and $>95\%$ for Pt-Au.

In a detailed consideration of direct interactions, however, there is little reason to expect strongly forward angular distributions since the momenta of the emitted alpha particles are much larger in absolute value than the momenta of the incident protons. Some of the spectra observed at 150 deg are shown in Fig. 9, plotted as $\log_{10}(N/\sigma_c E)$ *vs* E. The dotted curves show the spectra one would expect if all the particles were produced in compound nucleus reactions. If the deviations are taken as a measure of direct interaction, the fraction of all (p,α) reactions with 23-Mev protons on targets with $Z \lesssim 50$ proceeding in this way is $\lesssim 35\%$.

There is little doubt that the alpha particles observed from Pt and Au are produced by direct interaction. Even the lowered Coulomb barrier, which satisfies the data from lighter targets, and a nuclear temperature of 1 Mev, which is quite low, lead to the prediction that the ratio of (p,n) to (p,α) cross sections is greater than 1000.

CONCLUSION

The results of this survey of (p,α) reactions show that some of the alpha particles from all targets and all of them from targets of high atomic number result from direct interaction. For targets of atomic number $\lesssim 50$, a large fraction of the alpha particles result from compound nucleus reactions. The most important result, however, is evidence that the Coulomb barrier encountered by an alpha particle leaving an excited compound nucleus is appreciably lower than that encountered by an alpha particle entering a ground state nucleus.

This study of (p,α) reactions is being extended by determination of (p,α) excitation functions and energy distributions of the alpha spectra for incident protons of various energy values. The results will be reported in a later paper.

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[36] The (p,α) spectra from 17-Mev protons on Rh, observed by Brady, are discussed by R. Sherr in the Proceedings of the University of Pittsburgh Conference on Nuclear Structure, June 6–8, 1957 (unpublished).