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THE (p, α) REACTION AT 20 MeV

A. P. KLYUCHAREV, G. E. KRIVETS, and N. Ya. RUTKEVICH

Physico-technical Institute, Academy of Sciences, Ukr. S.S.R.

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The (p, α) reaction induced by 20.5-MeV protons was studied on cobalt and platinum of natural composition and on nickel, copper, zinc and tin isotopes. For most of the targets the differential cross section of the reaction decreases with increasing mass number. The energy and angular distributions of the alpha particles indicate the presence of two reaction mechanisms, one direct and the other proceeding via compound-nucleus formation.

NUCLEAR reactions with alpha-particle emission have been the subject of a large number of researches [1-9]. The purpose of most of them was a study of the energy levels of light nuclei, excited by bombarding these nuclei with various particles. Recently several investigations were devoted to the study of the mechanism of nuclear reactions accompanied by alpha-particle emission, occurring when various targets are bombarded with nucleons. It was shown that for targets with mass number less than 50, the (p, α) reaction at 20 MeV proceed predominantly via a compound-nucleus, whereas for heavier nuclei a more substantial contribution is made by the direct interaction mechanism [8,9]. For the case where a compound nucleus is produced, the resultant alpha-particle spectrum is continuous and can be statistically described. However, no quantitative agreement is obtained between the experimentally-measured energy distribution of the alpha particles and the distribution calculated from the evaporation model [10]. Agreement between the two can be obtained by assuming too low a value for the potential barrier for the emission of the alpha particle from the excited nucleus.

In all the investigations of the (p, α) reactions performed to date the targets employed had as a rule natural isotopic compositions. The results obtained were therefore averaged over the various isotopes comprising the target. In the present work, an attempt is made to trace in greater detail the dependence of the properties of the (p, α) reaction on the target mass number. To this end, various targets enriched with the investigated isotope were bombarded with 20.5-MeV protons.

THE METHOD

A proton beam accelerated to 20.5 MeV in the linear accelerator of the Physico-technical Institute of the Ukrainian Academy of Sciences passed after magnetic analysis with 15° deflection through a system of collimating diaphragms, and struck a thin free foil target situated in a vacuum chamber (Fig. 1). The protons passing through the target were slowed down in a Faraday cup, to which the current integrator was connected.

The alpha particles emitted from the target as a result of the reaction were registered by nuclear emulsions placed at different angles to the direction of the incident protons. The emulsion surface made an angle of 8° with the radial direction, so that with an emulsion thickness of 100 microns it was possible to register and measure tracks of alpha particles of up to 28 MeV. To prevent exposure of the emulsion by the soft fluorescent radiation, the diaphragms ahead of the emulsions were covered with 5-μ aluminum foil. The emulsions,

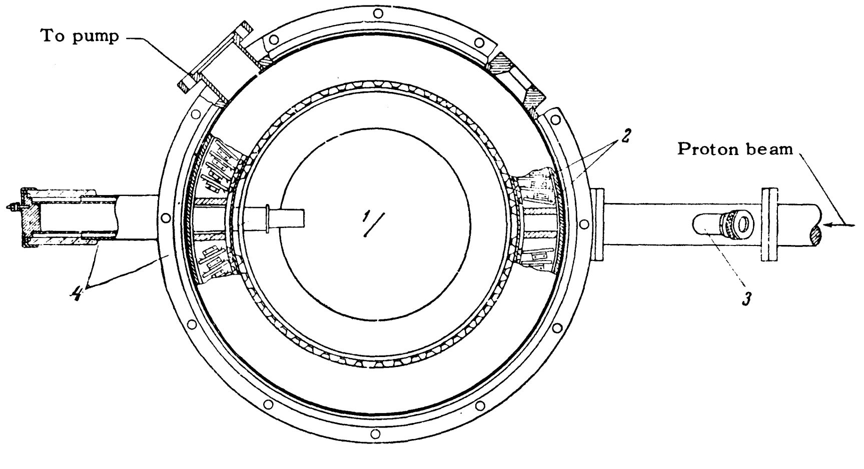


FIG. 1. Vacuum chamber for registration of charged particles: 1 – target, 2 – emulsions, 3 – collimator, 4 – Faraday cup.

Target	Thickness, μ	Enrichment, %	Target	Thickness, μ	Enrichment, %
$_{27}Co^{59}$	3.7	—	Zn^{67}	4.5	71.5
$_{28}Ni^{58}$	3.3	98.6	Zn^{68}	2.66	86.6
Ni^{60}	0.9	78	$_{50}Sn^{112}$	3.1	66.2
Ni^{61}	2.5	23.8	Sn^{116}	3.2	92.8
Ni^{62}	3.4	94.5	Sn^{117}	3.6	85.6
Ni^{64}	4.0	80.0	Sn^{118}	3.3	88.4
$_{29}Cu^{63}$	3.3	98.0	Sn^{119}	5.5	74.8
Cu^{65}	5.6	98.0	Sn^{120}	5.0	99.0
$_{30}Zn^{64}$	2.8	91.0	Sn^{124}	4.3	96.3
Zn^{66}	6.2	97.0	$_{78}Pt$	2.5	—

2 × 3 cm in size, were placed in a special light-tight cassette which in turn was placed in the vacuum chamber.

The alpha particles could be registered simultaneously at angles from 24 to 170° in steps of 2°.

Type NIKFI-D emulsions were used, in which the alpha particles could be reliably separated by scanning the irradiated emulsions under a microscope.

The target thicknesses and the degrees of enrichment are listed in the table.

RESULTS

Nickel, cobalt, copper, zinc. The alpha-particle energy distribution obtained by proton bombardment of nickel isotope targets is shown in Fig. 2. The spectra for all isotopes are of similar form—one sees in the hard part groups of alpha particles corresponding to the ground and first-excited states of the residual nuclei Co^{55}, Co^{59}, and Co^{61}. The bulk of the alpha particles is in the region of the continuous spectrum.

Figure 3 shows the angular distribution for the hard part of the spectrum, in which individual alpha-particle groups were separated. It is characterized by a sharply pronounced forward directivity, unlike the regular distribution of alpha particles from the region of the continuous spectrum shown in Fig. 4. In the latter case it is spherically symmetrical for Ni^{60} and Ni^{64} and has a slight rise in the region of small angles for Ni^{58} and Ni^{62}. The low resolution of the method employed did not allow us to make a detailed study of the energy structure of the alpha-particle groups of the hard part of the spectrum. We therefore did not process these results theoretically in accord with the current nuclear-interaction models. However, the sharply-pronounced forward directivity in the emission of the alpha particles is charac-

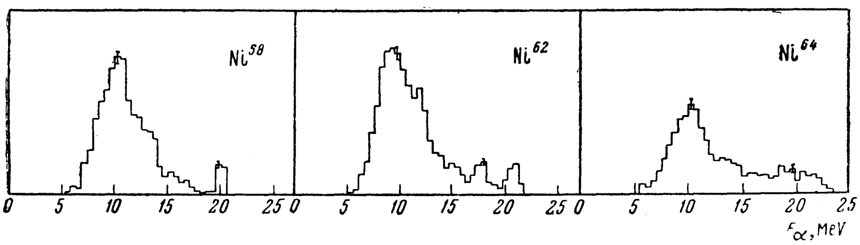


FIG. 2. Energy spectra of alpha particles produced in the (p, α) reaction for nickel isotopes (θ = 28°).

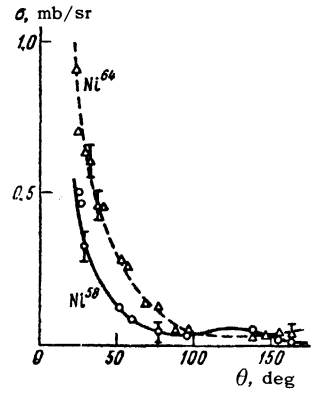
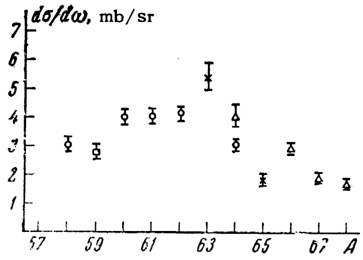


FIG. 3. Angular distribution of alpha particles from the (p, α) reaction for the high-energy part of the spectra for Ni^{58} and Ni^{64}.

FIG. 5. Dependence of differential cross sections on the mass number in the (p, α) reaction for isotopes of nickel, copper, and zinc at an angle 120°: o – Ni, x – Cu, Δ – Zn.



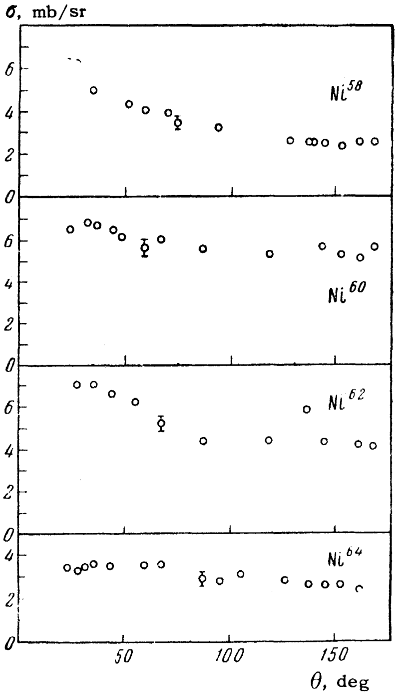


FIG. 4. Angular distribution of alpha particles from the (p, α) reaction on Ni^{58-64} without the high-energy part of the spectrum.

teristic of the direct interaction mechanism. Our data on the angular distribution give grounds for assuming that the (p, α) reaction on nickel nuclei with emission of high-energy alpha particles, corresponding to the ground and the first-excited states of the residual nuclei, proceeds essentially via the direct-interaction mechanism, whereas the alpha particles from the continuous spectrum, which have an isotropic distribution, are due to the reaction with formation of a compound nucleus.

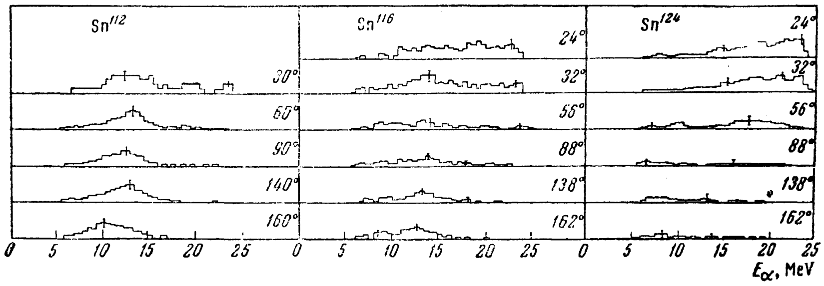
The energy distribution of the alpha particles obtained by proton bombardment of Co, Cu^{63}, Cu^{65}, Zn^{64}, Zn^{66}, Zn^{67}, and Zn^{78} turned out to be similar to the alpha-particle spectra from the (p, α) reaction on nickel isotopes. We therefore do not present these data.

An essential difference was found for the dependence of the differential cross section on the mass number, shown in Fig. 5 for the angle $\theta = 120°$. For copper and zinc it decreases noticeably with increasing A, something not observed for the nickel isotopes.

Tin. We investigated the (p, α) reaction on seven targets, with the tin isotopes from 112 to 124, with the exception of Sn^{112} and Sn^{122}. The most typical results are presented for the three isotopes Sn^{112}, Sn^{116}, and Sn^{124}. The alpha-particle energy distribution obtained for these isotopes at different angles is shown in Fig. 6. The spectra are continuous, but differ noticeably both in shape and in angular dependence. We note first that in the Sn^{112} target the enrichment with the investigated isotope is 66%, while the remaining 34% is made up predominantly of heavy isotopes. In this connection we can assume, not without reason, that the hard part of the alpha particle spectrum, above 18 MeV for Sn^{112}, is due principally to the admixtures of heavy isotopes in the investigated target. The alpha-particle energy distribution obtained as a result of the (p, α) reaction on Sn^{112} is thus a statistical distribution, with a maximum in the 10–15 MeV region, obtained as a result of "evaporation" of the alpha particles from the compound nucleus.

The alpha particle spectrum obtained on Sn^{124}, the heaviest of the investigated tin isotopes, has a

FIG. 6. Energy spectra of alpha particles produced in (p, α) reaction for tin isotopes at different emission angles.



maximum at small angles near the energy corresponding to the ground state of the residual nucleus In^{121}. This fact is evidence of the predominant role of the direct-interaction mechanism in the (p, α) reaction on this nucleus. The energy distribution obtained with the intermediate nucleus Sn^{116} is the result of a superposition of two processes, "evaporation" and the direct processes, as clearly indicated by the alpha particle spectra for Sn^{112} and Sn^{124}. This is seen especially well on the spectra obtained at large angles, where there is practically no effect due to the direct interaction and the energy distribution remaining is that due to "evaporation" of the alpha particles.

The angular dependence of the differential cross section shown in Fig. 7 for the three tin isotopes does not contradict the aforementioned point of view regarding the mechanism of the (p, α) reaction on light and heavy tin isotopes. If account is taken of the correction for the heavy isotopes in the Sn^{112} target, then the angular distribution of the alpha particles for this isotope will be spherically symmetrical, corresponding to the "evaporation" mechanism. The angular distribution for Sn^{124} is sharply pronounced forward, typical of the direct process. On Sn^{116} the angular distribution agrees to an equal degree with both mechanisms of the nuclear reaction.

The abrupt variation of the differential cross section of the (p, α) reaction for the heavy tin isotopes and the low reliability of the experimental data on the number of alpha particles emitted at low angles, due to the large background of protons elastically scattered by the target, have not enabled us to extrapolate the angular dependence to zero angle, so as to determine the total reaction cross section. We therefore show in Fig. 8 the differential cross section of the reaction at 120° as a function of the mass number. The cross section decreases sharply with increasing mass number. This reduction is apparently connected with the increase in the cross sections of the competing reactions, particularly the reactions with emission of neutrons.

Platinum. The energy distribution of the alpha particles obtained by proton bombardment of a platinum target of natural isotopic composition is shown in Fig. 9. The spectrum is continuous with a maximum in the region of high energies and with a hard edge corresponding to the alpha particle energy with production of Ir nuclei in the ground state. In the low-energy region there is observed a second maximum of low intensity. The angular distribution of the alpha particles is shown in Fig. 10 for hard and soft parts of the spectrum

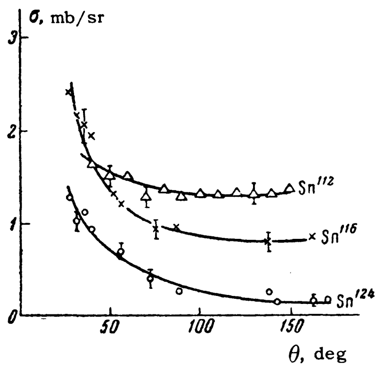


FIG. 7. Angular distributions of alpha particles from the (p, α) reaction for Sn^{112}, Sn^{116}, and Sn^{124}.

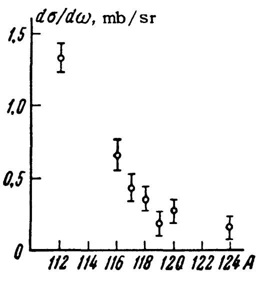


FIG. 8. Dependence of the differential cross sections on the mass number in the (p, α) reaction at 120°, for tin isotopes.

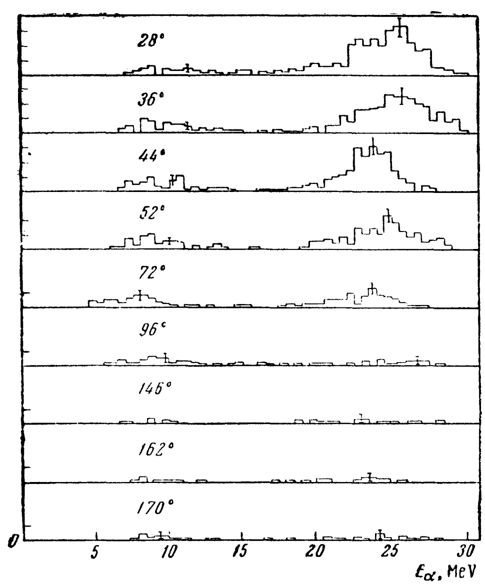


FIG. 9. Energy spectra of alpha particles from the (p, α) reaction for platinum at different emission angles.

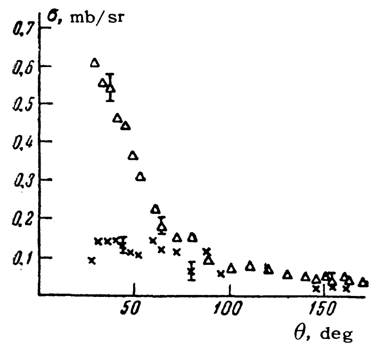


FIG. 10. Angular distributions of alpha particles from the (p, α) reaction for platinum: Δ – high-energy part, × – low-energy part of the spectra.

separately. It is easy to see that the high-energy alpha particles have a sharply pronounced forward directivity. For the group of low-energy alpha particles, this directivity is less sharply pronounced. Calculation of the energy balance of the reactions with alpha-particle emission from platinum shows that at 20 MeV, along with the (p, α) reaction there are also energetically feasible reactions with emission of three particles, one of which is an alpha particle. However, we consider it premature to state that this alpha-particle group is due to the three-particle reaction channel. The low intensity of such low-energy alpha particles is connected with the low penetrance of the potential barrier.

Our results allow us to advance some hypotheses concerning the mechanism of the (p, α) reaction on various nuclei. For the lightest of the nuclei investigated by us, with mass numbers from 58 to 68 (Co, Ni, Cu, Zn), the (p, α) reaction proceeds predominantly via production of a compound nucleus. Apparently the direct process gives rise to the low-intensity alpha-particle groups in the hard part of the spectrum, corresponding to the ground and first-excited states of the residual nuclei. Notice must be taken of the sharply pronounced forward directivity of the alpha particles of these groups.

The results obtained by us on the tin isotopes are evidence that the increased contribution of the direct interactions in the reactions of this type is determined apparently not only by the increase in energy and in the mass number, but also by the proton to neutron ratio in the nucleus. It is obvious that the heavier the isotope the more important the role played by the competing processes, particularly reactions with neutron emission, which reduce to a considerable degree the intensity of the (p, α) channel in the stage of decay of the compound nucleus. This is evidenced not only by the spectral and angular distributions of the alpha particles, but also by the sharp decrease in the differential cross sections at 120° with increasing mass number. The same dependence is observed also for the isotopes of copper and zinc.

The dependence of the cross section on A for the nickel isotopes, namely the noticeable decrease in the cross section for Ni^{58} as compared with the heavier isotopes, remains unreconciled. We find it difficult to express at present a definite opinion on this matter.

Comparison of the alpha spectra obtained by us and those calculated with the evaporation model points to a considerable lowering of the Coulomb barrier for the emission of alpha particles during the course of the reactions, as compared with the barrier for the penetration of the alpha particle into the stable nucleus. As mentioned above, analogous results were obtained in several of the earlier investigations [9,10]. It can be assumed in this case that the lowering of the barrier in the former case is connected with the deformation of the strongly excited nucleus.

In conclusion, the authors take this opportunity to express their deep gratitude to Senior Scientist of the Institute for Motion Picture Photography A. A. Sirotinskaya for developing and preparing the special type-D emulsions, which permit reliable discrimination of alpha particles and protons. The authors are also grateful to the crew of the linear accelerator, headed by A. M. Smirnov. We cannot leave unmentioned the greatly appreciated work done by microscopists T. N. Startseva and A. A. Kir'yanova in scanning the emulsions.

Note added in proof (May 15, 1963). After we obtained the results reported in the present article, an article was published by J. B. Mead and B. L. Cohen (Phys. Rev. 125, 947, 1962), reporting a study of the (d, α) reaction at 15 MeV. The spectral distribution of the alpha particles from this reaction on tin isotopes turns out to be analogous to the distribution we measured in the (p, α) reaction at 20.5 MeV.

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