[1] Alikhanian, Morozov, Muskhelishvili, and Khrimian J. Exptl. Theoret. Phys. (U.S.S.R.) 18, 673 (1948).
[2] A. I. Alikhanian, and A. I. Alikhanov, J. Exptl. Theoret. Phys. (U.S.S.R.) 21, 1023 (1951).
[3] Alikhanian, Samoilovich, Gurevich, Babaian, and Gerasimov, J. Exptl. Theoret. Phys. (U.S.S.R.) 19, 664 (1949).
[4] C. Franzinetti, Phil. Mag. 41, 86 (1950).
[5] J. Barbour. Phys. Rev. 78, 518 (1950).
[6] Alikhanian, Dadaian, and Shostakovich, Dokl. Akad. Nauk SSSR 82, 693 (1952).
[7] A. Alikhanian and V. Kharitonov, Dokl. Akad Nauk SSSR 85, 295 (1952).
[8] Amaldi, Fabri, Hoang, Lock. Scarci, Touscher, and Vitale. Suppl. Nuovo cimento 12, 419 (1954).
[9] C. F. Powell. Suppl. Nuovo cimento 11, 165 (1954).
[10] Baldo, Belliboni, Ceccarelli, Grilli, Sechi, Vitale, and Zorn, Nuovo cimento 1, 1180 (1955).
[11] Inoki, Yasaki, and Matsukawa, Phys. Rev. 95, 1565 (1954).
[12] M. S. Kozodaev and A. I. Filippov, Izv. Akad. Nauk SSSR, Fiz. Ser. 19, 711 (1955).
[13] Liubimov, Eliseev, and Kocmachevskii, Izv. Akad. Nauk SSSR, Fiz. Ser. 19, 720 (1955).
[14] H. Bridge, Nuovo cimento 1, 874 (1955).
[15] Alikhanian, Shostakovich, Dadaian, Fedorov, and Deriagin, J. Exptl. Theoret. Phys. (U.S.S.R.) 31, 955 (1956); Soviet Phys. JETP 4, 817 (1957).
[16] W. T. Scott, Phys. Rev. 76, 212 (1949).
[17] D. Morellet, Suppl. Nuovo cimento 1, 209 (1955).
[18] P. E. Hodgson. Phil. Mag. 41, 725 (1950).
[19] Y. Goldschmidt-Clermont, Nuovo cimento 7, 331 (1950).
[20] Biswas, George, and Peters, Proc. Ind. Acad. Sci. 38, 418 (1953).
[21] S. Biswas, George, Peters, and Swamy, Suppl. Nuovo cimento 12, 369 (1954).
[22] Holtebekk, Isachsen, and Sörensen, Phil. Mag. 44, 1037 (1953).
[23] N. Page, Proc. Phys. Soc. A63, 250 (1950).
[24] Harding, Lattimore, and Perkins, Proc. Roy. Soc. A196, 325 (1949).
[25] *Progress in Cosmic Ray Physics*, p 49, 1952.
[26] K. L. Le Couteur, Proc. Phys. Soc A63, 259, 498 (1950).
[27] G. F. Chew and M. L. Goldberger, Phys. Rev. 77, 470 (1950).
[28] B. H. Bransden, Proc. Phys. Soc. A65, 738 (1952).
[29] A. B. Migdal. J. Exptl. Theoret. Phys. (U.S.S.R.) 28, 3 (1955); Soviet Phys. JETP 1, 2 (1955).

Translated by G. L. Gerstein
266

SOVIET PHYSICS JETP VOLUME 5, NUMBER 6 DECEMBER 15, 1957

Interaction of Nitrogen and Gold Nuclei

S. A. BARABOSHKIN, A. S. KARAMIAN AND G. N. FLEROV

(Submitted to JETP editor January 21, 1957)
J. Exptl. Theoret. Phys. (U.S.S.R.) 32, 1294-1297 (June, 1957)

The dependence of the cross sections on the energy of nitrogen ions has been determined for the reactions Au(N, 4*n*), Au(N, 5*n*) and Au(N, 6*n*). The irradiation was carried out at the internal test chamber of the cyclotron with monoenergetic ions accelerated up to 115 Mev. In accord with the theory of competitive processes, curves with pronounced peaks were obtained.

IRRADIATION OF GOLD WITH N^{14} ions, accelerated up to 100 – 130 Mev, produces highly excited Rn^{211} compound nuclei. The excitation energies involved amount to ~ 75 – 100 Mev. Such excitation of the nucleus should lead either to its disintegration into fragments, or to the "evaporation" of a certain number of nucleons – chiefly neutrons. In the latter case there are produced a number of isotopes of Rn, At, Po etc., which are either α-active or disintegrate through *K*-capture. In 1954 Burcham,[1] while studying the reaction products resulting from the irradiation of Au^{197} with accelerated ions of N^{14} and C^{13}, identified several Rn, At, and Po isotopes. He used the 150-cm cyclotron of the University of Birmingham to accelerate the N^{14} and C^{13} ions. Beams of accelerated multicharged ions with a continuous energy spectrum, decreasing sharply in the direction of higher energies, were obtained in this cyclotron. The maximum energies of the N^{14} and C^{13} ions at the ultimate radius were

130 and 110 Mev, respectively. The absence of a monoenergetic beam of multicharged ions made it impossible for him to obtain the energy dependence of the yields of reactions with emission of 4, 5 and 6 neutrons.

Using the source of multiply-charged ions developed by Morozov *et al.*,[2] an intense beam of 115-Mev monoenergetic N^{14} ions with charge 5 was obtained in the 150-cm cyclotron of the U.S.S.R. Academy of Sciences, and used for: 1) the study of the dependence of the cross sections on the energy of the nitrogen ions in the reactions Au (N, 4*n*), Au (N, 5*n*) and Au (N, 6*n*); 2) the determination of the absolute values of the cross sections of these reactions; 3) the determination of the principal mechanism of the interaction of heavy ions with gold nuclei. The latter case arose in connection with reported reactions[3] proceeding by means of partial penetration of nitrogen nuclei into the nuclei of the target and not by their complete fusion (grapeshot effect).

In the experiments the irradiation was carried out on piles consisting of 10 – 15 nickel foils on which thin gold layers were deposited. The piles were fastened at the internal test chamber of the cyclotron in front of the current collector (Fig. 1). The nickel foils were 1.5 – 2.0 μ thick, the gold layer on the foils comprised 0.1–0.3 mg/cm^2.

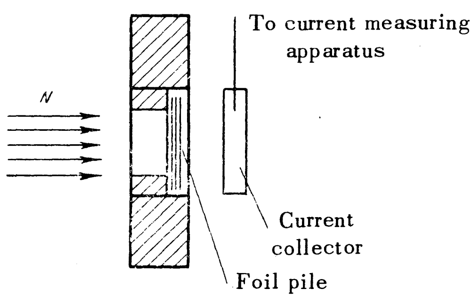

FIG. 1. Arrangement of the targets in the experiment

The energy lost by the beam in each foil was approximately 3 Mev. After irradiation the α-activity of the foils was measured during a time interval required for a unique separation of the half-lives. The α-particle were counted with the aid of an FEU-19 photomultiplier having a ZnS crystal and an amplitude discriminator. The discriminator bias used was the minimum necessary to eliminate the background produced by the superpositions of scintillations from the β-particles. The counting rates approached 10^4 pulses/min at a background of 1 – 2 pulses/min. The sensitivity of the apparatus was monitored by periodic measurement of the number of α-particles from a standard source (thick uranium foil). The solid angle of the count of the α-particles was determined experimentally.

In addition, some of the points on the excitation curve of the reaction (N, 5*n*) were obtained with the aid of photoplates, which were processed by T. F. Rasskazikhina.

The reactions were identified by the half-life periods of the α-active isotopes; moreover, the tabulated data of Ref. 4 and the results of Refs. 1 and 5, presented in Fig. 2 in the form of a schematic diagram, were taken as the base. From the schematic diagram it is evident that for the identification of the reactions (N, 4*n*), (N, 5*n*) and (N, 6*n*) the most convenient are the α-activities with the half-life periods of 108 min, 10.4 days and 25 min respectively. An essential factor in this method is the accuracy with which are determined the half-life periods and the branchings into α-disintegration and *K*-capture in the decay of the original isotopes Rn to At^{205}, At^{207}, and Po^{206}. Deviations in the values assumed for these quantities from the real values do not affect the form of the individual dependence curves of the cross sections on energy, but may lead to significant errors in the determination of the absolute values of the cross sections σ_{4n}, σ_{5n} and σ_{6n}. Therefore, in the cases where it was possible, refinements were made in some of the half-life periods and in the branchings of the α-disintegration and *K*-capture forks. For Rn^{206} and Po^{206} we have obtained half-life periods of 5.3 $\pm$ 0.1 min and 8.1 $\pm$ 0.5 days, respectively. The half-life periods of At^{207} and At^{205} in our experiments were in agreement with the data given in the schematic diagram. In several of the experiments it was possible to separate simultaneously from the disintegration curve the α-activities of Rn^{206} and Po^{206}, which permitted us to determine the branching in the disintegration fork of Rn^{206}. Considering, in accord with the schematic diagram, that At^{206} is completely disintegrated by *K*-capture, we have obtained for Rn^{206} a ratio K/α which is equal to 3.5 $\pm$ 0.2. It should be noted that this value was determined in several experiments differing in energy of the nitrogen ions by $\sim$ 15 Mev, and that within the limits of this accuracy compatible values were obtained for K/α. This result, evidently, substantiates the generatic relationship between Po^{206} and Rn^{206} and by the same token excludes the assumption regarding the formation of Po^{206} by means of partial penetration of nitrogen nuclei into Au^{197} nuclei.

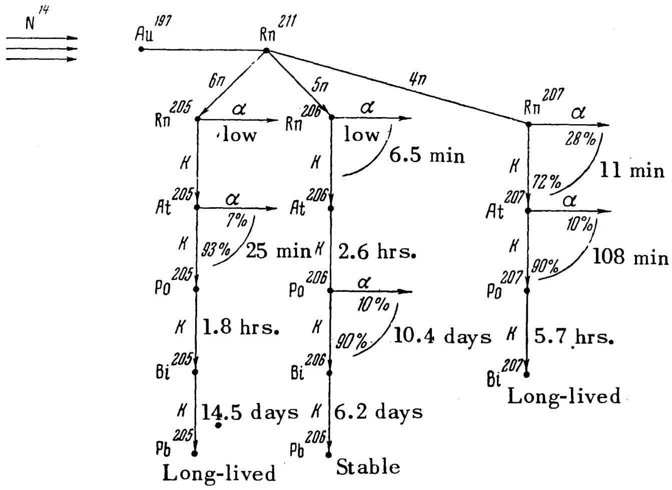

FIG. 2. Decay scheme of the products of the reaction Au^{197} (M, xn) at $x = 4$, 5, and 6.

The variation of the cross sections of the reactions Au (N, $4n$), Au (N, $5n$) and Au (N, $6n$), which we have obtained, with the nitrogen-ion energy are given in Fig. 3. The characteristic course of the curves with the maxima is due to the presence of competitive reactions with emission of a different number of neutrons, as well as to the fission of the compound nucleus. The sharp decrease in the cross section of the reaction (N, $4n$) above 90 Mev can be explained by the fact that the reaction with emission of 5 neutrons predominates in this energy region. Analogously, the decrease in the cross section of the reaction (N, $5n$) above 100 Mev is determined by the fact that at these energies the reaction (N, $6n$) predominates. And, finally, the decrease in the cross section of the reaction (N, $6n$) above 110 Mev is brought about by the sharp increase in the cross section of fission of the composite nucleus.

In fact, the dependence on energy of the nitrogen ions of the total cross section of all the reactions with the emission of neutrons also has a characteristic maximum. Figure 4 shows this curve and its sum with the curve of the cross section of the fission of Au^{197} by nitrogen, which was borrowed from Ref. 6. The latter graph gives the energy dependence of the cross section of the formation of the compound nucleus Rn^{211} in the irradiation of gold by N^{14} ions. For comparison, the dependence of the "geometric" cross section calculated by the usual formula[7] for $r_0 = 1.55 \times 10^{-13}$ cm is given in the same figure.

As is evident from Fig. 4, the course of the cross section of the formation of the compound nucleus with subsequent fission or "evaporation" of neutrons is close to the theoretical. This result apparently indicates the comparatively low probability of the processes of partial penetration during the interac-

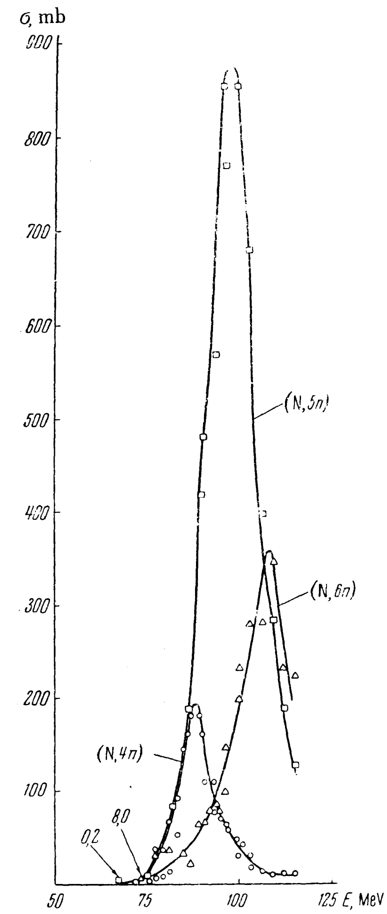

FIG. 3. Dependence of the cross sections of the reactions Au (N, $4n$), Au (N, $5n$) and Au (N, $6n$) on the energy of nitrogen ions. The arrows denote the points at which the cross sections are 0.2 and 8.0 *mb*.

tion of Au^{197} and N^{14} nuclei. Of course, the possibility cannot be excluded that a small portion of the observed activity is produced as a result of partial penetration. An analysis of the curves of Fig. 3 shows that the general form of the dependence on energy σ_{4n}, σ_{5n}, and σ_{6n} is the same as in other reactions at similar excitation energies of the composite nuclei.

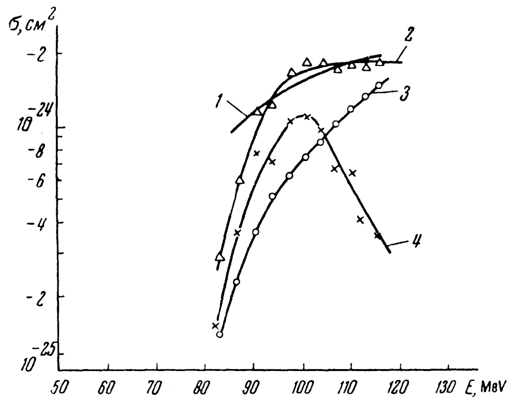

FIG. 4. Dependence on the energy of nitrogen ions of the cross sections: $\sum_{x=4}^{6} \sigma(\mathrm{N}, xn)$, $\sigma_{\mathrm{fission}} + \sum_{x=4}^{6} \sigma(\mathrm{N}, xn)$, $\sigma_{\mathrm{fission}}$ and the theoretical cross section of the formation of the composite nucleus, calculated by the formula $\sigma_T = \pi R_1^2 [1 - (B / E_N)]$: 1 — σ_T, 2 — $\sigma_f + \sum \sigma(xn)$, 3 — σ_f, 4 — $\sum \sigma(xn)$.

In 1956 Jackson[8] calculated the energy dependence of the cross sections of the reactions (p, xn) at $x = 1, 2, \ldots, 8$ in the irradiation of Bi^{206}, Pb^{206} and Pb^{208} for the range of proton energies 5 – 100 Mev. The author made the following assumptions: over the entire range of energies the temperature of the excited nucleus was considered constant and equal to 1.8 Mev; the nuclear radii were calculated by the formula $R = r_0 A^{1/3}$ at $r_0 = 1.35 \times 10^{-13}$ cm; the average energies of the neutron bonds in the above mentioned nuclei were assumed to be 7.3 Mev. The calculation took into account not only the neutrons emitted from the excited nuclei during the process of "evaporation", but also those knocked out as a result of direct nucleonic collisions between the protons and the nucleons of the target nuclei. It should be noted that, within the energy range of nuclear excitation in which we are interested, the role of the neutrons emitted as a result of a nuclear cascade is not large, therefore in its general formulation the theory can be applied also to pure "evaporation" processes. Jackson compared his calculations with the experimental data of Bell and Skarsgard.[9] This comparison has shown an agreement in the general form of the curves, but deviations in the details.

We have compared our data with the curves of Jackson and found that if we take into account the effect of the fission processes, the main difference lies in that our curves are shifted by ~ 10 – 15 Mev toward the higher energies. In this shift, apparently, is manifest the specific character of the reactions produced by multicharged ions, in particular, the formation of a "heated" compound nucleus with large angular momentum.

In the future, by an appropriate selection of the target nuclei irradiated by multicharged ions, we hope to obtain highly excited compound nuclei which will not break up into fragments. Such nuclei may serve as a good medium for the study of the processes of "evaporation" of nucleons from exited nuclei and the manifestation of the characteristics associated with excitation by multicharged ions.

We are grateful to academician I. V. Kurchatov for a number of valuable remarks during the discussion of the present paper. We also wish to express our thanks to the group of coworkers supervised by Iu. M. Pustovoit for ensuring good performance of the cyclotron during our experiments.

[1] W. E. Burcham, Proc. Phys. Soc. **67A**, 555, 733 (1954).

[2] Morozov, Makov and Ioffe, Atom. Energiia **3**, 272 (1957).

[3] Chackett, Fremlin and Walker, Phil. Mag. **45**, 173 (1954).

[4] Hollander, Perlman and Seaborg, Revs. Mod. Phys. **25**, 469 (1953).

[5] W. E. Burcham and B. C. Haywood, Proc. Phys. Soc. **69A**, 862 (1956).

[6] Druin, Polikanov and Flerov, J. Exptl. Theoret. Phys. (U.S.S.R.) **32**, 1298 (1957), Soviet Phys. **5**, 1059 (1957) (this issue).

[7] G. Blatt and V. Weisskopf, *Theoretical Nuclear Physics*, IIL, 1954 (Russian translation).

[8] T. D. Jackson, Canad. Journ. of Phys. **34**, 767 (1956).

[9] R. E. Bell and H. M. Skarsgard, Canad. Journ. of Phys. **34**, 745 (1956).

Translated by Esther Rabkin
267