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THE STRIPPING PROCESS IN THE INTERACTIONS OF ACCELERATED N^{14} IONS WITH THE NUCLEI OF SOME ELEMENTS

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The formation of the radioactive isotope N^{13} was observed when Al, Ni, Cu, Ag, Cd and Sn foils were bombarded with N^{14} ions which had been accelerated to ~ 100 Mev in a cyclotron. Angular distribution measurements showed that the N^{13} was emitted in a relatively narrow angular range. The angle corresponding to maximum intensity increases with Z. When the energy of the bombarding particle exceeds the height of the Coulomb barrier the cross section for N^{13} production is only slightly dependent on the energy. The cross section is ~ 30 mb for Ni and ~ 12 mb for Al.

WHEN atomic nuclei are bombarded with nultiply-charged ions stripping reactions can occur as well as the formation of compound nuclei. Such reactions for light nuclei at not very high energies have been studied in Refs. 1 — 7. At our Institute P. M. Morozov, B. N. Makov and M. S. Ioffe have devised a special ion source which furnishes monoenergetic beams of multiply-charged ions at considerably higher energies than those used in the investigations mentioned above. This had made it possible to study stripping reactions in heavier nuclei at higher energies.

The present work is a study of reactions involving several different elements to which N^{14} loses a neutron and is transformed into radioactive N^{13}.

EXPERIMENTAL METHOD

An internal cyclotron beam was used in all experiments. The bombarding particles were quintuply-charged N^{14} ions. Their range in nickel at the radius 66 cm was 48 μ, which corresponds to 115 Mev.[5] The energy spread of the particles did not exceed 5 to 7%.

The average beam intensity at the target was a few tenths of a microampere and was measured by a current integrator. The energy of the ions was varied by moving the target along the radius. The

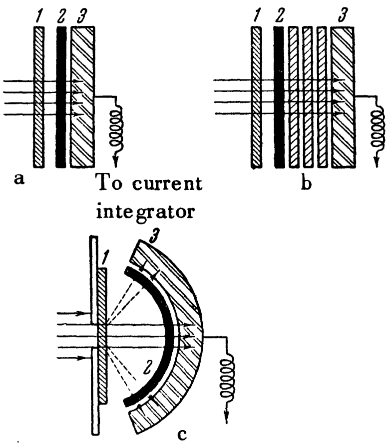

FIG. 1. Diagrams of the experiments: a — N^{13} production through bombardment of foils of different elements with nitrogen ions and the cross section measurement, b — Measurement of the angular distribution, c — Distribution of radioactivity in a stack of lead foils (there 7μ lead foils, 50μ collector). 1 — target; 2 — shield of Au or Pt foil; 3 — lead collector.

long range of the N^{13} particles was used to separate them. The experimental arrangement is shown in Fig. 1a. The acceleraged N^{14} ions lost neutrons to the element of the thin target and as N^{13} were stopped in the collector made of 50μ lead foil. The 3.5μ gold foil between the collector and the target retarded particles which had been produced through a compound nucleus. A special experiment showed that reactions with the formation of beta-active nuclei in gold and lead began to occur only at $\sim 70-80$ Mev. The activity produced in the lead collectors was registered by an end-window Geiger counter. A magnetic analyzer was used to determine the sign of the beta particles.

For measurement of the N^{13} angular distribution the lead collector was put into the form of a cylindrical surface which included all angles from $+60°$ to $-60°$ (Fig. 1b). After irradiation the collector was cut into equal strips for measurement of the beta-activity decay curve.

Cross section measurements up to ~ 70 Mev were obtained with a thin target. Above 70 Mev the target thickness was increased with the energy in such a way that the bombarding particles struck the shielding foil with the previous energy. The yield-energy relation was calculated as follows. Let Q_1 be the yield of radioactive N^{13} from a thin target at 70 Mev. We increase the energy to 80 Mev and at the same time increase the target thickness to the point where the energy loss in the additional layer will be 10 Mev; there is thus no change in the conditions under which the original target is bombarded. If Q_2 is the N^{13} yield from the thicker target the difference $Q_2 - Q_1$ is the reaction yield in the $70-80$ Mev interval. On a smooth cross section-energy curve this yield can be associated with an average energy of 75 Mev. With further increases of the bombarding energy and of the target thickness we similarly obtain the yield at 85 Mev, 95 Mev etc.

EXPERIMENTAL RESULTS

1. Production of N^{13} by Passage of a Beam of Accelerated N^{14} Ions through Foils of Various Elements

Previously published works report stripping studies for light elements only. It was therefore our first task to determine the possibility of this reaction in other elements. Targets made of Al, Ni, Cu, Ag, Cd, Sn, Pt, Au, and Pb were arranged as shown in Fig. 1a and were bombarded for a few minutes with a 100-Mev N^{14} beam. The target thickness was such that the particle energy after traversing the target did not exceed 70 Mev.

For the first six elements (from Al to Sn) 95 – 98% of all of the activity received by the collectors had a half-life of 10 minutes. By investigating the sign of the beta particles and of their maximum energy (through absorption in aluminum) it was shown that these are positrons with $E_{max} = 1.20 \pm 0.10$ Mev. Thus from our findings concerning the half-life, charge sign, and maximum energy of the beta particles we were able to conclude that when accelerated nitrogen ions interact with nuclei of the six elements mentioned the N^{14} loses a neutron in a highly efficient nuclear reaction and is transformed into N^{13}.

In the case of the heavy elements Pt, Au, and Pb there was no reliable indication of activity with a ten-minute half-life. Most of the activity, judging from the half-lives of 15 min, 70 min, and a few hours clearly belonged to fragments from gold fission.* The causes of the failure to observe the formation of N^{13} in the heavy elements became clear only after a study of the angular distribution and cross section.

A good illustration of the fact that N^{13} is produced by stripping when aluminum is bombarded with nitrogen ions is provided by the distribution of the ten-minute activity according to depth in the lead collector. The arrangement of this experiment is shown in Fig. 1c. The radioactive products of the nuclear reactions emerged from a 7μ aluminum foil which had been bombarded with 74-Mev nitrogen ions and were collected in a stack of lead foils for analysis of the beta decay period. The results are shown in Fig. 2.

The figure shows that all of the ten-minute activity is concentrated in the interior of the lead. This distribution could not be explained easily if it were assumed that the N^{13} results from the decay of a compound nucleus. But the stripping reaction provides a completely reasonable interpretation. When a bombarding N^{14} particle loses a neutron during a peripheral collision it suffers relatively little change of energy, so that the range of the N^{13} is comparable with that of the N^{14}. The short-lived activity

*Similar data will be found in a paper by N. I. Tarantin, Iu. B. Gerlit, L. I. Guseva, B. R. Miasoedov, K. V. Filippov and G. N. Flerov which is being prepared for publication.

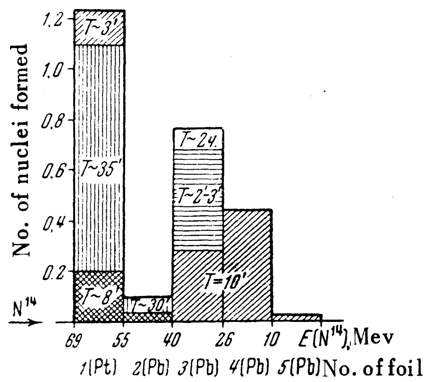

FIG. 2. Distribution of beta-active nuclei in a stack of lead foils. The numerals along the horizontal axis indicate the energy of the bombarding ions upon entering and leaving each foil; T is the half-life.

(2 — 3 min half-life) which is also appreciable in the interior of the lead is most likely due to the capture of protons from aluminum by the N^{14} nuclei. This must result in the formation of an O^{15} nucleus which decays with a 2-minute period. The activity in the platinum foil belongs to radioactive decay products of a compound nucleus.

2. Angular Distribution of N^{13}

The angular distribution of N^{13} was measured for aluminum, nickel, silver, tin and also for the heavy element platinum. Although in the first experiment we did not obtain a reliable separation of N^{13} from the bombardment of heavy elements, the geometry of the experiment for the angular distribution measurement (Fig. 1,b) led us to expect that at large angles it would be possible to separate N^{13} from the fragments. All of the lead strips of the collector except those which were struck directly by the beam showed only a 10-minute activity. The strips which were in the direct path of the beam (two or three out of twelve strips) yielded some additional activity which was due mainly to fission fragments from the shielding foils. The platinum shielding foil was increased to 8μ to stop fission fragments coming from the target.

The angular distribution in the center-of-mass system is shown in Fig. 3. The curves show the statistical errors and the angular spread due to the finite size of the strips. When aluminum was bombarded almost all of the ten-minute activity was concentrated in the two to four central strips. In this instance the angular resolution was inadequate for the plotting of curves such as those of the other elements. Therefore for aluminum Fig. 4 gives only a histogram of the ten-minute activity distribution in the strips compared with a histogram for nickel. From the histogram and the experimental geometry it is possible to determine the most probable N^{13} emission angle for aluminum; at 65 Mev the value is 23° ± 8° in the center-of-mass system.

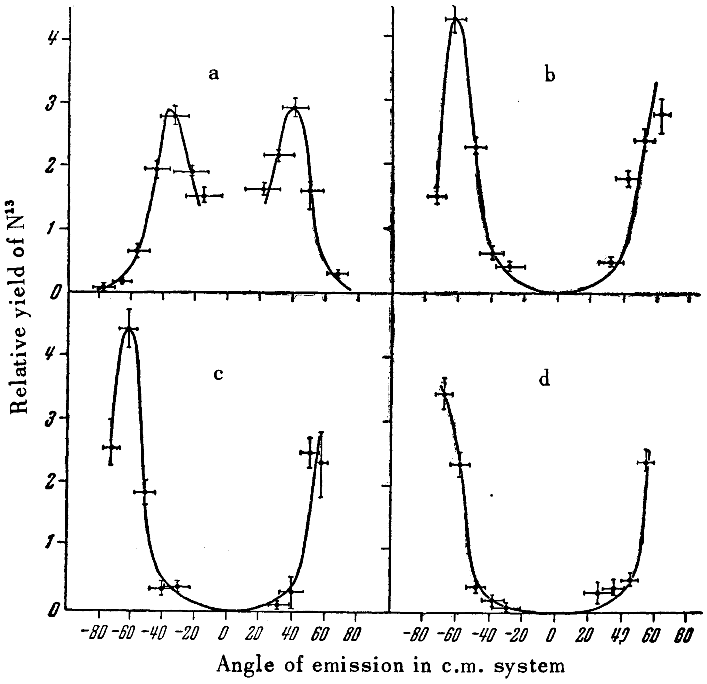

FIG. 3. Angular distribution of N^{13}: a — Ni, $E(N^{14}) = 61 \pm 6$ Mev; b — Ag, $E(N^{14}) = 72 \pm 8$ Mev; c — Sn, $E(N^{14}) = 68 \pm 7$ Mev; d — Pt, $E(N^{14}) = 91 \pm 7$ Mev.

3. Measurement of the Stripping Cross Section for Al and Ni

The stripping cross section was measured in the 28 — 105 Mev range for aluminum and in the 31 — 107 Mev range for nickel. The number of N^{13} nuclei produced by the reaction was determined by separation of the ten-minute activity in the lead collectors. The efficiency of the beta particle detection was determined by means of a radioactive source of known intensity. Since the N^{13} nuclei were stopped at some depth in the collector it was necessary to take into account the scattering

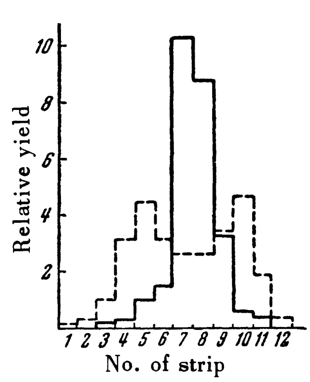

FIG. 4. Distribution of N^{13} in lead collector from nitrogen-bombarded Al and Ni. Solid line — Al, $E(N^{14}) = 62 \pm 6$ Mev; dashed line — Ni, $E(N^{14}) = 61 \pm 6$ Mev.

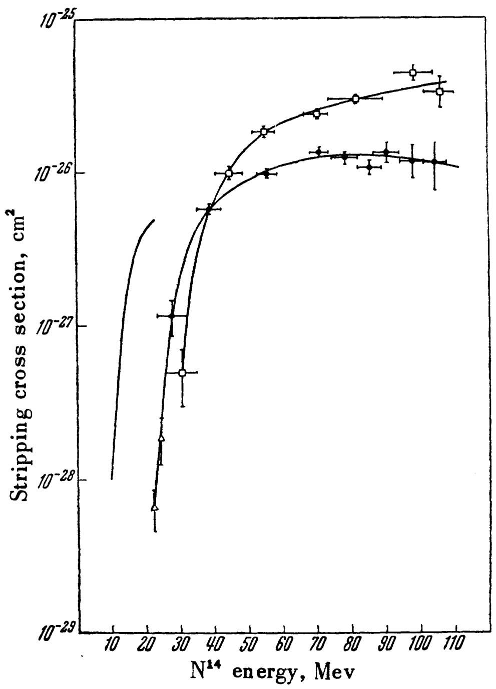

FIG. 5. Cross sections for N^{13} formation in Al and Ni. ● — our data for Al; □ — our data for Ni; Δ — data from Ref. 5 for Al; solid curve — data from Ref. 3 for N.

and absorption of the beta particles in lead. The appropriate corrections of 10 — 20% were determined experimentally. A source containing Na^{24}, whose beta spectrum is similar to that of N^{13}, was placed at different depths within the stack of lead foils of 50μ total thickness, and a relation was obtained between the count and position of the source. The number of bombarding particles passing through the target was computed from the collector current. We know that charge exchange causes variation of the average charge of an ion during its passage through matter. In our experiments, because of the high energies, the N^{14} ions lost all of their electrons while passing through the target, so that their average charge was seven. A small correction of 3 — 10% had to be introduced for only the very lowest energies.[8,9]

The results are shown in Fig. 5, where the data of Refs. 3 and 4 are given for comparison. The curves show the error of the relative measurements as well as the energy spread due to the finite target thickness. The error in determining the absolute value of the cross section was 30% and was caused principally by lack of accurate knowledge concerning the efficiency of detection of the beta particles.

EVALUATION OF RESULTS

As can be seen from Fig. 2, the character of the angular distribution of N^{13} is very different from the usual picture for the decay products of a compound nucleus. The distinguishing feature of this distribution is the fact that the particles are emitted in a relatively narrow angular range. The angle of maximum intensity increases with Z. This features of the angular distribution clearly show that N^{13} is actually formed as a result of stripping. For large impact parameters the probability of neutron loss by N^{14} is small; in nearly central collisions the two particles are fused to form a compound nucleus. Thus there exists an optimum impact parameter for which neutron loss is most probable. From the position and width of the maximum it is possible to obtain an approximate value for the closest approach of N^{14} to the target-nucleus and for the width of the geometric region around the nucleus within which stripping is most probable. Such estimates, without taking account of nuclear interactions, show that when the energy of the nitrogen ions exceeds the height of the Coulomb barrier the region in which stripping occurs corresponds to the distance between the colliding particles which is approximately equal to the sum of the radii of N^{14} and the target-nucleus.

The character of the relation between the angular distribution and Z enables us to understand why we could not distinguish a ten-minute activity from nitrogen-bombarded heavy elements. In such cases the angle of emission of the N^{13} particles is so much larger that they do not reach the collector but are stopped in the shielding foil or in the target itself.

We turn now to the energy dependence of the cross section. When a radioactive isotope is formed due to the decay of a compound nucleus the energy dependence of the cross section for its formation is a bell-shaped curve of ~ 10 Mev width.[10-13] In our case, as is seen in Fig. 5, this dependence is characterized by slight energy dependence of the cross section for N^{13} formation for energies considerably above the Coulomb barrier. At first glance it might seem that with increasing energy the cross section should decrease because the N^{14} is in the vicinity of the nucleus for a shorter time. But it must be remembered that the probability of neutron loss by N^{14} can be affected by other factors in addition to the transit time. For example, it may be expected that with variation of the acceleraged ion energy there will also be a variation of the neutron sticking probability as well as of the geometric region within which the reaction takes place.

The results contained in Refs. 2 — 5 show that a fast N^{14} ion which passes close to a nucleus may not only lose a neutron but is also able to capture a proton, neutron or even alpha particle. It was not our special purpose here to study other stripping reactions, but our results enable us to estimate the cross sections of other reactions. It will be useful to present such estimates here. In the experiment with a lead foil stack (Fig. 3) it was found that nuclei with a half-life of 2 — 3 minutes have a long range, as well as the N^{13}. The two-minute activity was also distinguished during measurements of the cross section for N^{13} formation in Al and Ni, and the ratio of the two-minute activity yield to the N^{13} activity yield did not vary with energy. This indicates that the cross sections for the formation of both products have the same energy dependence. We believe that this two-minute activity can be assigned to O^{15}, which is formed when N^{14} captures a proton from the target nucleus, according to the scheme

$$A_Z(N^{14},\ O^{15})\,A-1_{Z-1}.$$

The cross section of this reaction is estimated to be for Al 40 ± 10% and for Ni 17 ± 5% of the cross section for loss of a neutron.

In conclusion we consider it our pleasant duty to thank Academician I. V. Kurchatov for several useful comments during discussions of this work. We also thank the cyclotron crew, directed by Iu. M. Pustovoit, for their excellent work and V. M. Strutinskii for theoretical calculations of several observed effects.

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PRODUCTION OF NEGATIVE π MESONS BY 660-Mev PROTONS ON NUCLEI OF VARIOUS ELEMENTS

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The energy spectra and cross sections $d\sigma^-/d\Omega$ for π^--meson production have been measured at an angle of 45° with respect to the proton beam for Li, Be, Al and Cu. The differential cross sections $d^2\sigma^-/d\Omega dE$ for 157 Mev π^--mesons were measured for Ag and Pb. A conclusion is reached concerning the dependence of the cross section for π^--meson production on atomic weight for elements lying between Li and Pb. A comparison is made with similar results obtained for π^0 and π^+ mesons in other works.

THE dependence of π-meson yield on the number of nucleons in the nucleus has been investigated at various angles for neutral π mesons[1,2] and at an angle of 45° for positive π mesons,[3] the π mesons being produced by 660-Mev protons on nuclei of various elements. In the present work, carried out at the