TWO-NEUTRON TRANSFER DURING N^{15} ION BOMBARDMENT OF SEPARATED $Zr^{90,92,94}$ ISOTOPES

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Targets consisting of separated Zr^{90}, Zr^{92}, and Zr^{94} isotopes were irradiated with N^{15} ions accelerated in the internal beam of the Joint Institute heavy-ion cyclotron. The aim of the experiment was to investigate the effect of nuclear structure on the probability of two-neutron transfer. The effective cross sections of the reactions were measured on the basis of delayed neutron activity of N^{17} nuclei. The measurements were carried out for N^{15} energies between 70 and 120 MeV (lab. system). The ratios of the cross sections for two-neutron transfer as a result of irradiation of Zr^{94}, Zr^{92}, and Zr^{90} targets change from 17 : 6 : 1 for 60-MeV ions (in the c.m.s.) to 6 : 4 : 1 at 100 MeV.

INTRODUCTION

In physics of heavy ions, great interest is attached to a study of the nucleon transfer reactions, occurring in grazing collisions between two nuclei. The experimental data on the angular distribution [1,2] and some theoretical estimates [3,4] show that the transfer reaction occurs in a relatively thin layer near the surface of the nucleus. One can therefore think that their study will yield useful information on the structure of the surface of the nucleus and on the states and correlations of the peripheral nucleons. The greatest change occurs in the structure of the surface of the nucleus on going from a nucleus with closed shell to nuclei in which the largest number of nucleons is present in excess of the shell, so that the study of the transfer reactions near the magic numbers is of particular interest.

In the present investigation we studied the transfer of two neutrons from the target nucleus to an incoming nucleus in the region of the closed neutron shell with magic number 50. The separated zirconium isotopes $_{40}Zr^{90}$, $_{40}Zr^{92}$, and $_{40}Zr^{94}$ (the first has a closed neutron shell and the others have two and four neutrons in addition) were bombarded by accelerated N^{15} ions. The effective cross section of the reaction was measured in the ion energy interval 70—120 MeV (in the laboratory frame, l.s.).

The pickup of the two neutrons by the incoming nucleus was observed first in thick targets in [5,6]. We have measured the effective cross sections of this reaction for aluminum, copper, and tantalum bombarded with N^{15} ions over a wide energy interval [7].

2. EXPERIMENTAL PROCEDURE

The experiments were carried out in the internal beam of the Joint Institute heavy-ion cyclotron. As in our earlier investigations [7-9], we used a procedure in which the N^{17} nuclei were registered as the end product of the reaction and served as emitters of delayed neutrons ($T_{1/2}$ = 4.15 sec). Registration of the N^{17} nuclei makes it possible to reliably eliminate the background produced by other reaction products. Some improvements were made in the previously described apparatus [7]. The sensitivity of the neutron detector was increased by increasing the number of counters with enriched boron, monitoring of the ion energy was introduced, and a better time analyzer was installed.

The neutron detector (Fig. 1) was a Plexiglas moderator block containing 16 proportional counters with enriched boron. The block measured 140 × 250 × 440 mm and was placed in a copper water-cooled jacket. Since all the counters had identical counting characteristics, they were connected in parallel to a single high-voltage source. The high voltage and the electronic amplification coefficient were chosen in such a way as to exclude the possibility of registering γ quanta and the radio noise.

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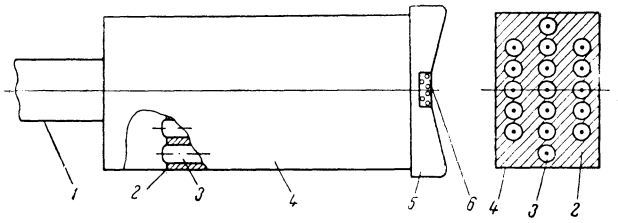

FIG. 1. Neutron detector: 1 – probe rod; 2 – Plexiglas moderator; 3 – boron counters; 4 – copper jacket; 5 – graphite diaphragm; 6 – target.

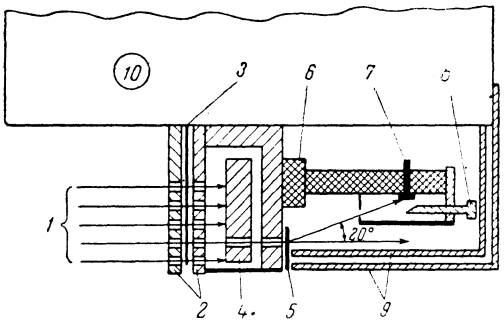

FIG. 2. Over-all view of the target head and of the ion-energy measuring device: 1 – ion beam, 2 – target and grid for passage of the ions to the current collector, 3 – foil for absorption of singly-charged ions, 4 – current collector, 5 – gold foil – ion scatterer, 6 – holder for energy measuring device, 7 – energy measuring device, 8 – bolt with α-particle source, 9 – shield, 10 – housing of neutron detector.

The efficiency of the detector, measured with the aid of a calibrated (Ra-Be) source H-26 [10] placed at the target location, was 0.45%.

The bombarded target was located in the front part of the neutron detector; a current collector and a device for measuring the energy were placed behind the target (Fig. 2).

The energy of the N^{15} ions was measured with the aid of a surface-barrier detector. Part of the ion beam, separated by a special collimator, was incident on a scattering gold foil 7.3 mg/cm^2 thick. The diaphragm ahead of the semiconductor detector, with an opening of 0.5 mm, separated the ions scattered in the gold foil at an angle of 20° to the beam direction. A thin source of ThC′, which emitted 8.78-MeV α particles, was placed near the detector. The ion energy was determined by comparing the amplitudes of the pulses produced in the detector by the ions and by the particles, with account of the energy losses in the gold foil.

The pulse produced in any of the counters was fed to a common cathode follower, located in the neutron-detector block, and further to a linear amplifier and a discriminator. The pulses from the discriminator were fed in parallel to a scaler unit and to a time analyzer. The time analyzer consisted of a time-amplitude converter and a 100-channel pulse-height analyzer. In our experiments we used 30 channels of the analyzer with a channel width of 1 second.

The pulse from the energy meter was fed to the linear amplifier and then to the 100-channel pulse-height analyzer. Simultaneously, calibration pulses were applied to the input of the amplifier from an exact-amplitude generator. It was thus possible to exclude the influence of the nonlinearity of the amplifier and to compare exactly the amplitudes from the α particles and from the N^{15} ions.

The targets were made of zirconium dioxide. Finely ground ZrO_2 powder was precipitated on an aluminum substrate from an aqueous solution of sugar, which was used as a binder. After drying, the targets were roasted, causing the sugar to decompose so that only small amounts of carbon were left in the targets. The zirconium oxide layer was ~ 80 mg/cm^2 thick and 45 × 15 mm in area. Holes were made in the targets permitting part of the ions (10%) to strike the current collector. A carbon foil placed behind the target retained the singly-charged ions. The current collector consisted of a water-cooled copper plate, and a graphite cover which made it possible to decrease the yield of N^{17} nuclei from the collector. Our earlier experiments have shown that the yield of N^{17} from graphite bombarded by N^{15} ions is small. The isotopic composition of the targets is listed in the table. Since the targets contained in addition to zirconium also oxygen and carbon, it was necessary to determine the contribution from these elements. To this end, targets of Al_2O_3, aluminum, and carbon were bombarded with N^{15} ions.

During the time of the experiment, the cyclotron was operated in the pulsed mode. Since the half life of N^{17} is 4.15 sec, the target was bombarded for 30 seconds to attain saturation. The high-frequency voltage was then removed from the dees and the yield of N^{17} was measured for 30 seconds. The pulses from the neutron detector were registered simultaneously by a scaler instrument, to determine the yield, and by a time analyzer to determine the half life. For each value of the ion energy, four cycles of bombardment were performed. The ion energy was varied by moving a probe inside the equipment and setting the target at a different distance from the center of the cy-

Target	Isotope content, %				
	90	91	92	94	96
$Zr^{90}O_2$	96.8	1.4	1.1	0.7	—
$Zr^{92}O_2$	4.4	4.4	88.6	2.4	0.2
$Zr^{94}O_2$	2.9	0.9	1.6	93.8	0.6

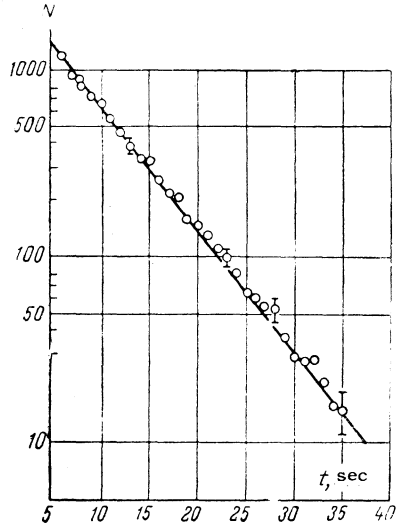

FIG. 3. Curve showing decay of neutron activity in bombardment of $Zr^{94}O_2$ with N^{15} ions (N – number of pulses per channel).

clotron. The energy was measured at each position with accuracy 3—5%. Before and during the experiment, the counting characteristics of the neutron detector were monitored.

The intensity of the N^{15} ion beam, measured with a current integrator, was usually limited to several times 10 microamperes. This resulted in the registration during the zirconium target bombardment cycle of several hundred pulses at low energy to 10,000 pulses at high energy. The neutron detector background was in the mean 20 pulses per minute. The range of variation of the ion energy was determined, on the one hand, by the minimum distance from the center to which the probe could be inserted in the cyclotron, and on the other hand by the maximum radius of acceleration of the N^{15} ions.

3. MEASUREMENT RESULTS

In the irradiation of all three zirconium isotopes, and also of the targets made of aluminum, Al_2O_3, and carbon we observed a delayed neutron activity with only one half life. The value of this half life coincides, within the limits of measurement errors, with the tabulated data for the half life of N^{17}. A typical decay curve for the neutron activity is shown in Fig. 3.

Figure 4 shows the experimental results obtained for the yield of N^{17} in the bombardment of zirconium targets, and of targets made of aluminum, aluminum oxide, and carbon. The effective reaction cross sections were calculated by the usual method of differential yield curves. In our case, however, this calculation was made complicated by the fact that the targets had a complicated chemical composition.

For a single-isotope target, the relations between the effective cross section and the yield or the stopping power of the target material has the form

$$\sigma = \frac{dY}{dE}\frac{1}{dn/dE}, \qquad (1)$$

where σ —cross section of the reaction (in cm^2), Y(E) —yield of the reaction from a thick target per bombarding particle, n(E) —range of N^{15} nuclei in the target material, expressed in atoms per cm^2, and E —energy of N^{15} in the laboratory system. For our zirconium targets, which had a chemical composition $ZrO_2C_{1.7}$, this relation goes over into

$$\sigma(\mathrm{Zr}) + 2\sigma(O^{16}) + 1.7\sigma(C^{12}) = \frac{dY^*}{dE}\frac{1}{dn^*/dE}, \qquad (2)$$

where $\sigma(Zr)$, $\sigma(O^{16})$, and $\sigma(C^{12})$ are the cross sections for the production of N^{17} for Zr, O^{16}, and C^{12}, respectively; Y*(A) is the yield of the reaction for the target of our composition and n*(E) is the range of N^{15} in the target material, expressed in molecules per square centimeter.

Thus, to calculate the cross section of the reaction on zirconium it was necessary to know not only Y* and n* but also the N^{17} production cross section for oxygen and carbon. These cross sections were calculated from the experimental N^{17} yield curves for aluminum, Al_2O_3, and carbon. The stopping power of the targets was calculated from the data on the atomic stopping power of zirconium, oxygen, and carbon calculated with the formula given by Northcliffe [11].

The effective c.m.s. cross sections for the pickup of two neutrons in the interaction between N^{15} with Zr^{90}, Zr^{92}, and Zr^{94} are shown in Fig. 5.

The scatter in the experimental points on the N^{17} yield curves is connected principally with the fluctuations of the beam intensity during the bombardment cycles. The error in the relative measurements, which is significant when the cross sections are compared for different zirconium isotopes, is 10%. The errors in the determination of the absolute value of the cross sections reach 40% according to our estimates. They are governed by the accuracy with which the sensitivity of the neutron detector is determined. In estimating the effective cross sections, no account was taken of the isotopic composition of the target (see the table).

4. DISCUSSION OF THE RESULTS

The comparison of the cross sections for the pickup of two neutrons in the case of Zr^{90}, which

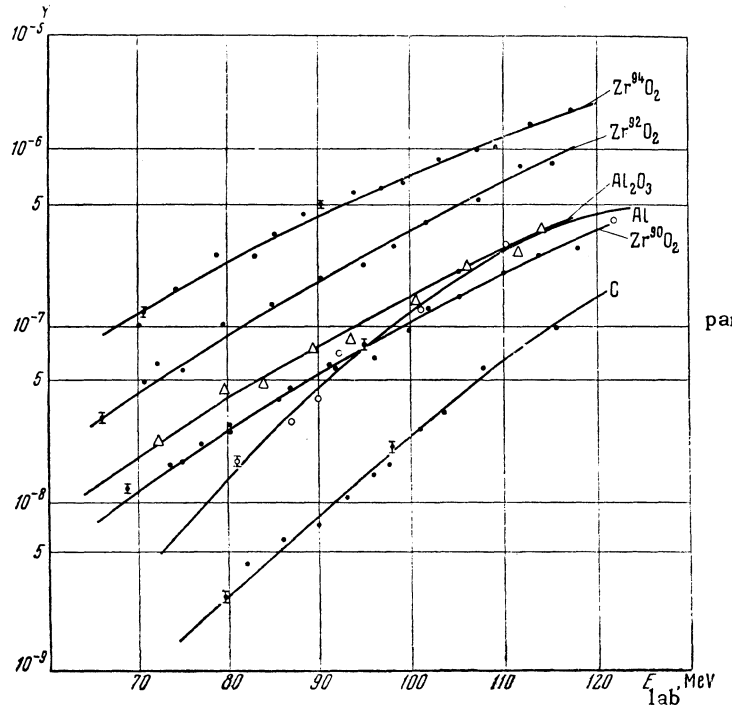

FIG. 4. Yield of N^{17} nuclei from thick targets (per incident particle) as functions of the energy of the N^{15} ions.

has a closed neutron shell, with the cross sections for Zr^{92} and Zr^{94}, indicates that the pickup probability increases greatly for the neutrons in excess of the closed shell. Indeed, the addition of two or four neutrons to the Zr^{90} changes the number of neutrons in the nucleus little, whereas the cross section of the reaction increases by many times. This may point to the fact that the neutrons in excess of the closed shell spend a considerable part of the time in the surface layer of the nucleus.

Another striking fact is the large cross section for the transfer of two neutrons, reaching several times 10 millibarns in the case of Zr^{92} and Zr^{94}. These values are close to, and even exceed, the known cross sections for the transfer of a single nucleon. If we estimate from the angular distribution of the reaction products the geometrical dimensions of the region near the nuclear surface in which the single-nucleon transfer occurs, we obtain a value on the order of 1 barn. This means that the probability of transferring one nucleon is of the order of one hundredth. If two neutrons from Zr^{92} and Zr^{94} were to be picked up by the N^{17} independently of each other, the cross section of the reaction would be several tenths of a millibarn. The value obtained for the cross section indicates a possible transfer of a correlated neutron pair.

The cross section for the reaction on Zr^{94} is approximately double the cross section for Zr^{92}. From the point of view of transfer of a correlated neutron pair, this result is natural, since the second pair of the neutrons in the Zr^{94} is under similar quantum conditions.

For an analysis of the data obtained it is advantageous to construct curves for the ratio of the cross sections for different isotopes as a function of the ion energy. Such curves are shown in Fig. 5. It is clear from Fig. 5 that the difference in the cross section of the reaction for the different isotopes increases with decreasing ion energy. This singularity in the course of the cross sections can perhaps be explained in the following manner. The pickup reactions occur in surface collisions between two nuclei. Outside the nucleus, that is, in the region where no other nuclear particles act on the neutron, the wave function of the neutron contains a factor $e^{-\alpha r}$ [12], with α containing in addition to various constants also the neutron binding energy ($\alpha \sim E_b^{1/2}$).

We present below data on the binding energies of two neutrons in the bombarded zirconium isotopes:

	Zr^{90}	Zr^{92}	Zr^{94}
E_b MeV:	23,3	15,8	14,9
Q, MeV:	—15,0	—7,5	—6,5

We see that these energies differ greatly for the neutrons in the closed shell and those outside the shell. On the other hand, the lower the energy of the incoming ion, the larger the distance at which it should pass from the target nucleus in order not to be captured to form a compound nucleus. As a result, as the ion energy decreases, the transfer of two neutrons will occur in more and more remote regions of the nuclear surface, where the

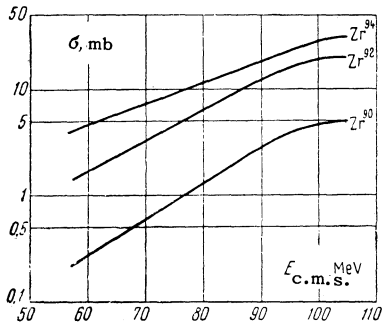

FIG. 5. Effective cross sections of the pickup of two neutrons from zirconium isotopes as functions of the energy of the N^{15} ions.

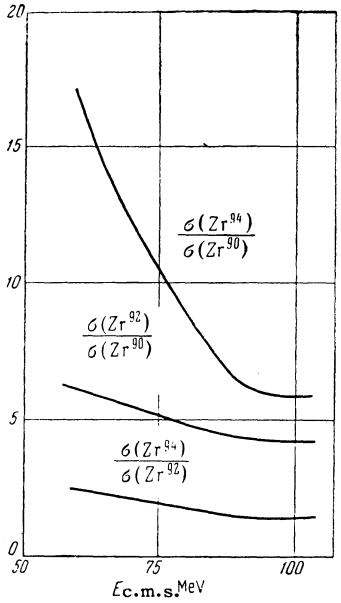

FIG. 6. Ratios of the effective cross sections as functions of the energy of the N^{15} ions.

probability of finding strongly bound neutrons decreases sharply.

In conclusion, we consider it our pleasant duty to express deep gratitude to corresponding member of the USSR Academy of Sciences G. N. Flerov for continuous interest in the work, for valuable advice, and for friendly help. We are also grateful to the cyclotron crew for uninterrupted operation of the accelerator.

[1] R. Kaufmann and R. Wolfgang, Phys. Rev. **121**, 192 (1961).

[2] G. Kumpf and E. D. Donets, Preprint Joint Inst. Nuc. Res. No. 1071, 1962.

[3] T. Kammuri, Progr. Theor. Phys. **28**, 934 (1962).

[4] V. N. Kalinkin and Ya. Grabovskiĭ, Preprint, Joint Inst. Nuc. Res. 1963.

[5] Alkhazov, Gangrskiĭ, and Lemberg, JETP **33**, 1160 (1957), Soviet Phys. JETP **6**, 892 (1958).

[6] Karnaukhov, Ter-Akop'yan, and Khalizev, JETP 36, 748 (1959), Soviet Phys. JETP **9**, 525 (1959).

[7] Volkov, Pomorski, Tys, and Flerov, JETP **43**, 865 (1962), Soviet Phys. JETP **16**, 613 (1963).

[8] Flerov, Volkov, Pomorski, and Tys, JETP **41**, 1365 (1961), Soviet Phys. JETP **14**, 973 (1962).

[9] Volkov, Pomorski, Tys, and Flerov, Preprint, Joint Inst. Nuc. Res. No. 1192, 1963.

[10] Dorofeev, Kutikov, and Kuche, Atomn. énerg. **3**, 328 (1957).

[11] L. C. Northcliffe, Phys. Rev. **120**, 1744 (1960).

[12] Breit, Hull, and Gluckstern, Phys. Rev. **87**, 74 (1952).

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