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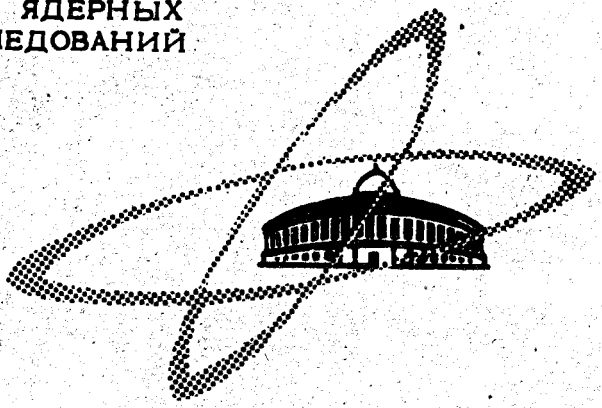

E7 - 4877

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DIFFERENTIAL CROSS SECTIONS OF TWO NEUTRON TRANSFER REACTION (^{15}N, ^{17}N) ON ZIRCONIUM ISOTOPES ^{90}Zr, ^{92}Zr and ^{94}Zr

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Submitted to Nucl. Phys.

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1. Introduction

At present it is generally understood that the transfer reactions with heavy ions are direct type reactions taking place in the grazing collisions of two complex nuclei. The strong absorption in nuclear matter and relatively small de Broglie's wave length of heavy ion allow us to speak about the surface localization of transfer reactions. Thus, it is to be hoped that by investigating such a type of reactions one can obtain information concerning the nuclear surface structure.

The nuclear surface changes mostly in the region of the closed nucleon shells. Therefore it may be expected that the transfer reaction characteristics such as the angular distribution, total cross-section, and the energy spectra of transfer reaction products will change most evidently in the closed shell region. In accordance with this argument we performed experiments on the investigation of the two neutron pick-up reaction (^{15}N, ^{17}N) with separate isotopes of zirconium ^{90}Zr, ^{92}Zr and ^{94}Zr. The first isotope has a closed shell with 50 neutrons while the other two have two and four neutrons above this closed shell, respectively.

The experiments were carried out with the external beam of the 1.5 m heavy ion cyclotron in the Nuclear Reactions Laboratory of J.I.N.R. in Dubna. The differential cross-sections of the reaction (^{15}N, ^{17}N) were measured for two energies of ^{15}N ions. Some information was also obtained about the energy distribution of ^{17}N nuclei - the two neutron transfer reaction products.

2. Method of Measurements

The two neutron transfer reaction (^{15}N, ^{17}N) was studied by the detection method of delayed neutron activity of the ^{17}N nuclei. This method was developed in our Laboratory [1,2] and successfully used for the study of multinucleon transfer reaction [3,4]. The great advantage of this method is that the β and γ background appearing due to the decay of radioactive products of other reactions does not influence the measurements.

Fig. 1 shows a general view of the experimental device. The reaction chamber was a cylinder 200 mm in diameter and 500 mm in length. The collimated ion beam was directed along the axis of the reaction chamber. In the front of the rear parts of the chamber two annular windows covered by 15 μm mylar foil were made through which the reaction products could pass. The target could be moved along the chamber axis by remote control. In this way it is possible to change the emission angle θ , at which the transfer reaction products could reach the product catcher, in the form of an elastic belt, gathered the ^{17}N nuclei and periodically transferred them into the neutron detector. This construction of the reaction chamber allowed about 60% of all reaction products which flowed out in the definite angular interval to be gathered. This

condition is very important because of the rather small efficiency of the fast neutron detectors, which usually amounts to no more that some per cent.

The front and rear annular openings permitted the measurements to be performed in the forward and rear hemispheres over the angular ranges of 14°–80° and 100°–166°, respectively. The measurements at smaller angles, 4°–24°, were performed with the aid of a third annular window, made in a special flange attached to the end surface of the chamber. In this case the activity products catcher was a polyethylene disc which transferred the ^{17}N nuclei from the reaction chamber window to the neutron detector.

The reaction chamber was equipped with a Faraday cage for the measurements of ion beam intensity, and with an arrangement for the ion energy control. (Thin gold foil as a scattered and semiconductor silicon detector of elastically scattered ions).

The angular resolution of this arrangement varied with the angle, and was 0.5° at 15° and 9° at 80°.

The neutron detector was an axially symmetric system consisting of 24 proportional counters filled with enriched BF_3 (87% of ^{10}B). The counters were placed in a paraffin moderator in two ring groups - 12 counters in each group. The central cilindrical channel was used to insert the catcher with ^{17}N nuclei. To reduce the background of the scattered delayed neutrons, the detector was protected by a screen made of paraffin and cadmium.

The detector efficiency was determined with the aid of a calibrated photo-neutron source (^{24}Na + ^{9}Be) of which the neutron energy spectrum is most similar to the delayed neutron spectrum of ^{17}N nuclei[5]. Taking into account the geometrical

extension of the delayed neutron source in the form of the belt transferring the ^{17}N nuclei, the efficiency was found to be 7%. The accuracy of the calibration was 10%.

Details of the experimental equipment are described elsewhere /6/.

The measurements were performed in the pulsed mode. Since the ^{17}N half-life is equal to 4.15 s, the target was bombarded for 30 s so as to achieve saturation, the high-frequency voltage then being removed from the dees and the activated catcher was displaced for 0.5 s to the neutron detector. The ^{17}N yield was measured for 30 s and all the operations were then repeated. Apart from switching on and off the high-frequency voltage on the dees, all the operations were performed automatically. During the background measurements the catcher of the ^{17}N nuclei remained in place. Usually several runs were done for each angle.

To obtain information concerning the energy distribution of ^{17}N nuclei, their energy range in aluminium foils was measured. These measurements were performed at the angle of 20^{o} in the lab. system, that is close to the angular region where the differential cross-section for (^{15}N , ^{17}N) reaction reaches its maximum. In order to account for the energy loss in the target material and absorbers more correctly the energy of elastically scattered ^{15}N ions at the same angle was also measured.

In the experiment thin metallic zirconium targets were used. The thickness and isotope composition of these targets are given in Table 1.

3. Results and Discussion

The measured differential cross-sections of the (^{15}N, ^{17}N) reaction on the isotopes of zirconium ^{90}Zr, ^{92}Zr and ^{94}Zr are shown in fig. 2. The measurements were performed for two energy values of ^{15}N ions: 97.5 MeV and 88.0 MeV in the lab. system. The energy spread of the ^{15}N ion beam measured with a silicon detector, did not exceed 1.5 MeV at E = 97.5 MeV.

In all the measurements the observed half-life of the neutron activity was equal to that of ^{17}N ($T_{1/2}$ = 4.15 sec.) The background during measurements at the angles corresponding to the maximum yield equalled 5% of the effect observed, changing slightly with the variation of the angle. The statistical error of the measurements was 2% - 5%. We estimated that the error in the absolute value of the differential cross-section is about 25%.

The differential cross-section measurements were done for the forward hemisphere only. At larger angles in the angular interval of 100° - 166° the measured effect coincided with the background within the statistical error.

The obtained angular distributions presented in fig. 2, show the specific features of nucleon transfer reactions: there is a maximum at an angle θ_M corresponding to the surface collision of two nuclei and then a monotonous decrease of the cross-section towards large and small angles. It should be noted that we did not obtain an increase of the cross-section for the angles close to 0° as was found in other works [7,8], though our measurements were done up to an angle of 4°. This picture of angular distribution demonstrates the direct character of the two neutron transfer reaction (^{15}N, ^{17}N).

A comparison of the angular distributions of various zirconium isotopes indicates that they do not differ much from each other. In Table 2 are given the positions θ_M and the half-widths $\Delta\theta$ of the obtained maxima, which nearly coincide. The difference does not exceed $1^\circ - 2^\circ$. Only in the case of ^{90}Zr is $\Delta\theta$ larger than for other isotopes. Thus the angular distributions of the transfer reaction are rather insensitive to the structure of the interacting nuclei.

In grazing collision of the heavy ion and target nucleus the orbital angular momentum of the projectile reaches ten units of $\hbar$ and in comparison with this, the change of the angular momentum by the transfer of two neutrons is rather small and probably weakly influences the angular distributions of the (^{15}N ,^{17}N) reaction. Thus the shape of the angular distribution is mainly determined by the global properties of the colliding nuclei: the Coulomb interaction and the strong absorption of heavy ions in the nuclear matter.

As can be seen in fig. 2, the cross-section of the (^{15}N ,^{17}N) reaction sharply increases, passing from ^{90}Zr to ^{92}Zr and ^{94}Zr. This sharp increase of the cross-section in the case of ^{92}Zr and ^{94}Zr isotopes shows that the transferred neutrons come mainly from the states lying above the closed neutron shell (N = 50 neutrons).

The energy distributions of ^{17}N nuclei were measured at the maximum energy of ^{15}N ions (77.5 MeV, θ = 20° in the lab. system). The obtained results show that the two neutron transfer reaction on zirconium isotopes is accomplished by the excitation of final nuclei. The measured excitation energies for ^{90}Zr , ^{92}Zr and ^{94}Zr were 7.2 MeV, 11.5 MeV, and 6.9 MeV ,respectively.Since

the binding energy of the last neutron in the ^{17}N equals 5.8 MeV, the residual nuclei of zirconium remain in an excited state. The higher energy of excitation in the case of ^{92}Zr is evidently connected with the fact that the energy levels of ^{90}Zr lie higher than the levels of the neighbouring isotopes[9].

From the angular distribution data of the nucleon transfer reaction products, one can obtain information about the width of the geometrical region in which the nucleon transfer reactions take place. At present, there is a number of published theoretical papers which provide such information[10-14]. In these papers the transfer reactions are usually considered in quasi-classical approximation, which may be satisfactorily fulfilled for single nucleon transfers. However, if we pay attention to the fact that the angular distributions of the two neutron transfer reaction (^{15}N, ^{17}N) on zirconium isotopes are very similar in shape to the angular distributions of single nucleon transfer reactions[15,16], it may be useful to analyse our experimental data according to some of these models.

The experimental results were analysed according to the model developed by Kalinkin-Grabowski[11] and by Strutinski[12]. Because these two models gave similar results, the discussion will be limited to the results obtained according to the Kalinkin-Grabowski model.

For the description of the nucleon transfer process of energies exceeding the Coulomb Barrier, the authors[11] used the quasi-classical DWBA method. The nuclear potential has a Saxon-Woods form, with the parameters determined from the experiments on the elastic scattering of heavy ions. The matrix element connected with the transfer of the nucleon is assumed to be proportional to the function $W(L) = \exp[-\alpha R(L, E)]$ where R is the distance

of the closed approach of the two nuclei at the moment of collision for a fixed value of the energy E and the angular momentum L . The parameter a of the model is determined by the binding energy of the transfer nucleon. The form of the W(L) function is chosen by taking into account the fact that the radial part of the wave functions of a nucleon in the initial and final states decrease exponentially at the periphery of colliding nuclei.

The theoretically obtained data after this model are given in Table 2, where ΔL is the number of the partial waves providing the main contribution in the transfer reaction, and ΔR is the width of the region around the nucleus where the nucleon transfer reactions occur with the greatest probability.

In calculations of angular distributions the following values of the nuclear potential parameters were accepted: $V_0 = -45$ MeV, $r_0 = 1.2$ fm, and $a = 0.65$ fm.

The calculated curves reflect quite well the shape of the angular distributions of the (^{15}N , ^{17}N) reaction for different isotopes of zirconium (see Table 2).

However, there is a difference between the positions of maxima determined experimentally and calculated: the calculated maxima are displaced toward larger angles for $5^\circ - 6^\circ$. This discrepancy could be the result of the fact that the theoretical calculations were done in zero-range approximation. For the considered (^{15}N , ^{17}N) reaction on zirconium isotopes, the change of the reduced mass is 10%.

Furthermore, one may note that the effective cross-section ratios of the (^{15}N, ^{17}N) reaction on zirconium isotopes: $\sigma^{94}Zr / \sigma^{90}Zr$, $\sigma^{92}Zr / \sigma^{90}Zr$, and $\sigma^{94}Zr / \sigma^{92}Zr$, calculated after the Kalinkin-Grabowski model, agree well with the values obtained experimentally by the graphical integration method of the differential cross-section given in fig. 2. These data are given in Table 3. For comparison, the analogous ratios obtained in our earlier experiment /17/ are presented.

In the theoretical calculations the exponential character of the radial part of the wave functions of periphery neutrons are taken into account, as well as the fact that the parameter of the model depends on the binding energy of these transferred neutrons. Thus, the length of the exponential tails will increase as the neutron binding energy decreases. This leads to a rise in the integral overlap of the radial parts of the wave functions and consequently to the increase of the effective reaction cross-section for the transfer of less bounded neutrons in the delivering nucleus. Hence, the conclusion may be drawn that the binding energy of transferred neutrons is one of the main factors defining the effective cross-section values for the neutron transfer reactions.

It would be very interesting to compare the total cross-section values of one and two neutron transfer reactions on zirconium isotopes. Such a comparison might give important information on the possibility of two neutron transfer reaction in the form of a binding pair. Unfortunately at present there is a lack of experimental data for one neutron transfer reaction on zirconium isotopes.

To sum up the following conclusions may be drawn:

1. The two neutron transfer reaction (^{15}N, ^{17}N) on zirconium isotopes is a direct type reaction;

2. The geometrical width of the region where the neutron transfer reactions occur is equal on the average to about 1 fm.

3. The angular distributions of the two neutron transfer reactions are rather insensitive to the structure of the interacting nuclei.

4. The close connection between structure and reaction characteristics is more evident in the effective reaction cross-section values, an essential role being played here by the neutron binding energy in the delivering nuclei.

The authors would like to express their gratitude to Professor G.N.Flerov for his interest in this work and for valuable advice.

The authors are also grateful to Dr. V.A.Gareav for his help in theoretical analysis of the experimental data, to Dr. A.A.Rosen for preparing the metallic zirconium targets, to A.V.Pojarski for designing the reaction chamber, to Dr. B.N.Kalinkin and Dr. J.Grabowski for valuable discussions of the results.

We are indebted to the technical staff, led by V.S.Alfeyev, for regular and efficient operation of the heavy ion cyclotron.

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Received by Publishing Department
on December 29, 1969.

Table 1

Isotopic Composition of the zirconium targets (in per cent) and their thickness

Target	Isotopic concentration in per cent					Target thickness mg/cm^2
	^{90}Zr	^{91}Zr	^{92}Zr	^{94}Zr	^{96}Zr	
^{90}Zr	96.8	1.4	1.1	0.7	-	1.89
^{92}Zr	4.4	4.4	88.6	2.4	0.2	0.60
^{94}Zr	2.9	0.9	1.6	93.8	0.6	1.74

Table 2

Comparison of the expreimental and theoretically calculated data of angular distributions of the two neutron transfer reaction (^{15}N,^{17}N) on zirconium isotopes

TARGET	Experiment			Theory				
	E c.m. MeV	Θ_M	$\Delta\Theta$	Θ_M	$\Delta\Theta$	ΔL	ΔR fm	α fm^{-1}
^{90}Zr	83.6	27.0°	21°	22.5°	20°	8	1.60	1.1
	75.4	31.5°	22°	37.3°		7	1.60	1.0
^{92}Zr	83.8	25.0°	16°	32.2°	19°	8	1.55	1.1
	75.7	29.0°	20°	37.0°		7	1.55	1.0
^{94}Zr	84.1	26.0°	17°	32.0°	18°	8	1.51	1.1
	75.9	31.0°	17°	36.5°		7	1.51	1.0

Table 3

Ratios of the total cross-sections of the two neutron transfer reaction (^{15}N , ^{17}N) on zirconium isotopes ^{90}Zr, ^{92}Zr and ^{94}Zr, obtained experimentally and theoretically calculated after the Kalinkin-Grabowski model

Total crpss-section ratios	Energy of ^{15}N ions in c.m.	Experimentally obtained		Theoretically calculated
		present paper	paper[17]	
$\frac{\sigma_{2n}{}^{94}Zr}{\sigma_{2n}{}^{90}Zr}$	76 MeV	8.0	10.0	11.1
$\frac{\sigma_{2n}{}^{92}Zr}{\sigma_{2n}{}^{90}Zr}$	76 MeV	5.0	5.1	7.2
$\frac{\sigma_{2n}{}^{94}Zr}{\sigma_{2n}{}^{92}Zr}$	76 MeV	1.6	1.7	1.5
$\frac{\sigma_{2n}{}^{94}Zr}{\sigma_{2n}{}^{90}Zr}$	84 MeV	7.2	7.6	8.2
$\frac{\sigma_{2n}{}^{92}Zr}{\sigma_{2n}{}^{90}Zr}$	84 MeV	4.3	4.5	5.5
$\frac{\sigma_{2n}{}^{94}Zr}{\sigma_{2n}{}^{92}Zr}$	84 MeV	1.7	1.6	1.5

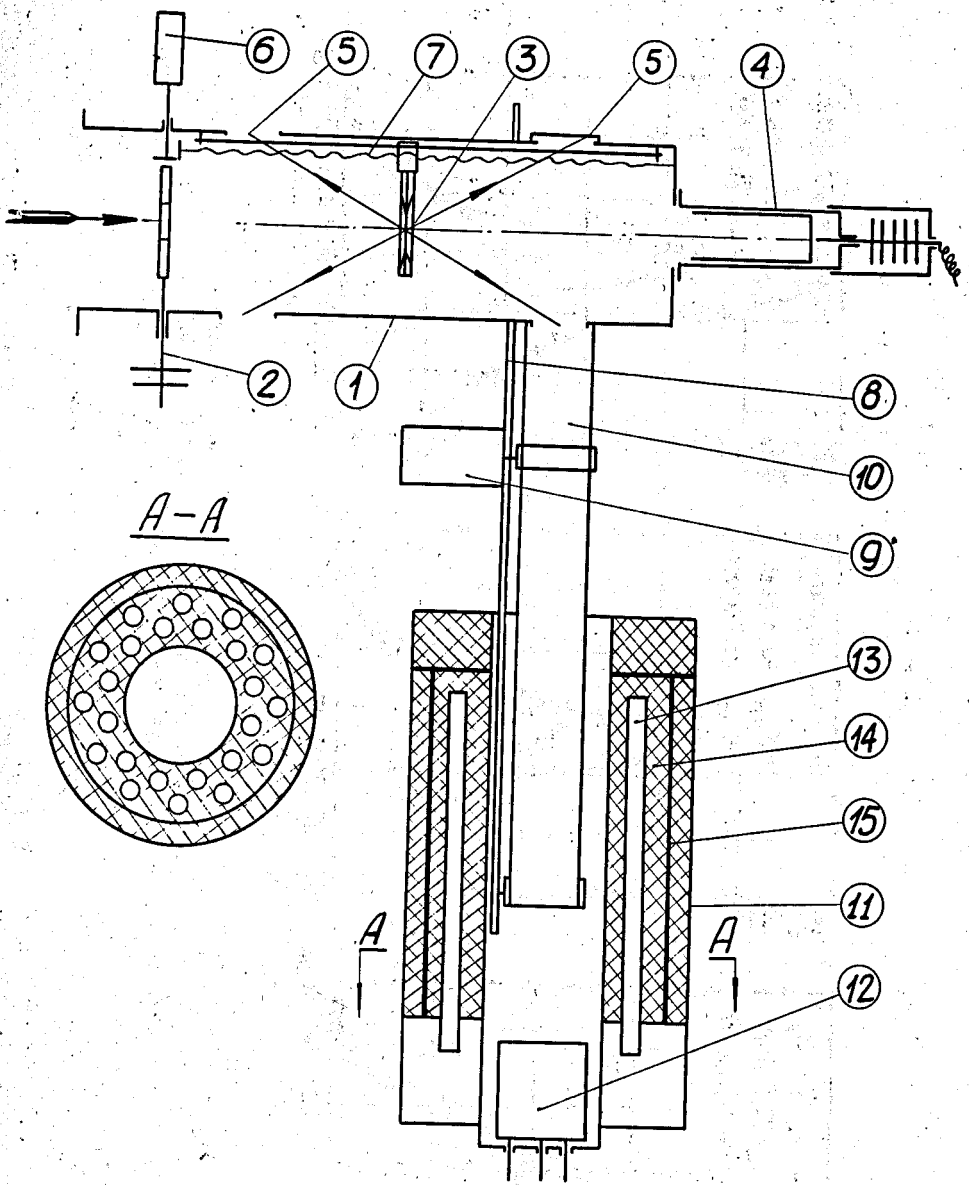

Fig. 1. General view of the experimental arrangement. 1. Body of the reaction chamber. 2. Support of the ion beam collimator. 3. Target support. 4. Faraday cage. 5. Annular windows covered by mylar foil. 6. Electric engine for target displacement. 8. Belt conveyor of reaction products. 9. Electric engine of conveyor. 10. Elastic belt - reaction products catcher. 11. Neutron detector system. 12. Preamplifier. 13. BF_3 neutron counters. 14. Paraffin. 15. Cadmium coat.

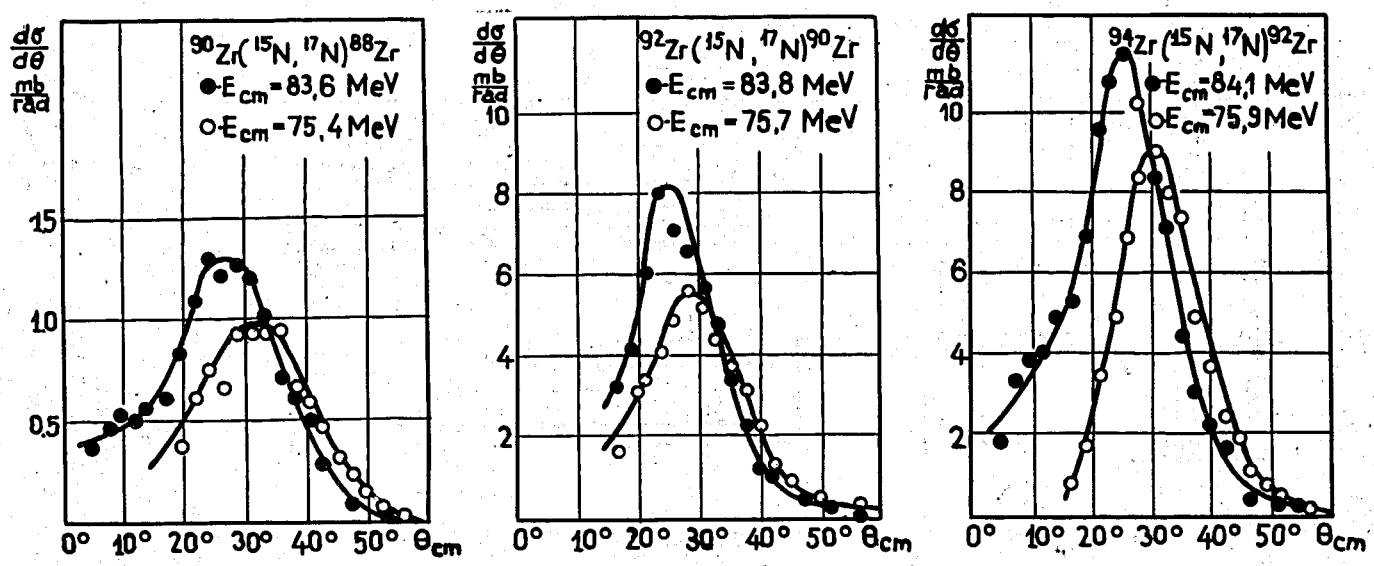

Fig. 2. Differential cross-section of the two neutron transfer reaction (^{15}N, ^{17}N) on separated isotopes of zirconium ^{90}Zr, ^{92}Zr and ^{94}Zr for two energy values of ^{15}N ions.