NEUTRON EMISSION FROM STRONGLY EXCITED NUCLEI

A. S. KARAMYAN,* G. A. DOROFEEV, and D. S. KLOCHKOV

Submitted to JETP editor October 6, 1960

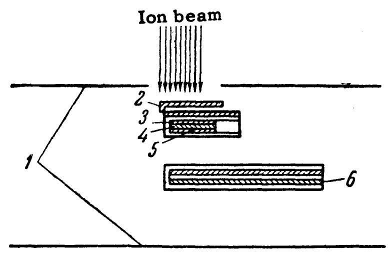
J. Exptl. Theoret. Phys. (U.S.S.R.) 40, 1004-1006 (April, 1961)

The relative intensities and angular distributions of neutrons with effective energies of 10, 15, and 25 Mev produced by multiply charged ions in (C^{12}, xn, xp) and (O^{16}, xn, xp) reactions were investigated. The results are in satisfactory agreement with the predictions of the statistical model of nuclear reactions.

KARAMYAN and Pleve[1] observed that at large excitation energies the cross sections of the reactions (C^{12}, 2n) and (O^{16}, 2n) for vanadium and niobium are quite large. This effect was attributed to the direct interaction of the incident ions with nucleons of the target nucleus. If the main part of the excitation is then taken away by the emitted neutrons, it is natural to assume that the mean energy of these neutrons is approximately equal to half the excitation energy. In the overall energy distribution of neutrons produced as a result of all possible reactions, a group of neutrons in the high-energy region should then be quite distinct. The present work was undertaken to test this hypothesis.

The experimental arrangement is shown in the figure. The target and detectors, which were made of copper, iron, and graphite of natural isotopic composition, were bombarded by the internal beam of a cyclotron. The C^{12} and O^{16} ion current at an orbit radius of 69 cm was ~ 0.5 μa. The maximum energies of the C^{12} and O^{16} ions were then 80 Mev and 108 Mev, respectively. The thickness of the bombarded targets was considerably greater than the range of the ions in them. Therefore the energy spectrum of the ions taking part in the reaction extended from their maximum energy to an energy determined by the Coulomb barrier of the target nuclei.

In the experiment for which the data are shown in the first line of Table I, a uranium plate was placed behind a vanadium target ~ 10 mg/cm^2 thick. Since the ions traveling through the vanadium were of insufficient energy to overcome the Coulomb barrier of the uranium, they stopped in the uranium without evoking nuclear reactions. Hence the energy interval of the ions taking part in the reaction was appreciably reduced.



Experimental arrangement: 1 – dee; 2 – target; 3 – copper; 4 – graphite; 5 – iron; 6 – detector for measurement of the neutron angular distribution.

Table I.

Reaction	$R=A_{Cu}/A_{Fe}$	$\overline{T}_0$, Mev exptl. (c.m.s.)	T_0, Mev theoret.	E_{min}–E_{max}, Mev
V + C^{12}	2,64±0,25	3.5	3,0–3,5	64–79
V + C^{12}	1,84±0,20	3,2	2,4–3,5	35–79
V + O^{16}	2,16±0,20	3,3	2,4–3,6	38–90
Nb + C^{12}	1,36±0,14	2,5	2,2–2,6	52–72
Nb + O^{16}	1,47			
Ta + C^{12}	1,45			
Ta + O^{16}	1,27			
U + O^{16}	1,57			

To record the fast neutrons, we used the reactions Fe^{56}(n, p)Mn^{56}, Cu^{63}(n, 2n)Cu^{62}, and C^{12}(n, 2n)C^{11} with energy thresholds of about 5, 12, and 22 Mev, respectively.[2] The exposure time was 20 min. The absolute β activity of the fast-neutron detectors was measured by a 4π counter. Iron and copper foil cut into four equal strips were used for the measurement of the neutron angular distribution. Their β activity was measured with end-window counters. The detector activity corresponding to the chosen threshold reaction was identified by the half-lives and the absorption curve for

Table II. Neutron Angular Distributions*

Reaction	C.m.s. angle, deg				Effective neutron energy, Mev
	0±12	27±10	45±7	55±5	
V + C^{12}	1	0,93	0,80	0,70	10
V + C^{12}	1	0,82	0,60	0,50	15
Nb + C^{12}	1	0,90	0,80	0,70	10
Nb + C^{12}	1	0,85	0,70	0,65	15
Ta + C^{12}	1	0,93	0,90	0,86	10
Ta + C^{12}	1	0.88	0,85	0,75	15

*The error in the relative values is ≤ ± 3%.

*Deseased.

β particles. The investigated reactions and ratio R of the activity induced in the copper (A_{Cu}) and iron (A_{Fe}) detectors are given in Table I, and the angular distributions of the neutrons produced by the C^{12} ions are given in Table II.

The results were compared with the predictions of the statistical model of nuclear reactions. According to this theory, the energy spectrum of the neutrons emitted from excited nuclei is approximately of the form

$$W(\varepsilon) \sim \varepsilon \int_{\varepsilon/T_0}^{\infty} dx e^x/x,$$

where ϵ is the c.m.s. neutron energy, $T_0 = \sqrt{10E^*/A}$ is the initial temperature of the compound nucleus at an excitation energy of E^*.[3]

To calculate the values of R theoretically, this spectrum was transformed into the laboratory system spectrum. Then, for different values of T_0 we took the numerical product of the functions representing the neutron spectrum in the laboratory system and the dependence of the effective cross section of the threshold reaction on the neutron energy for Fe^{56}, Cu^{63}, and C^{12}. The effective energy of the neutrons recorded by the detectors was determined by the maximum of this product and turned out to be ~ 10, 15, and 25 Mev, respectively; the value was almost the same for all reactions. In the calculation of the values of R, we took into account the weight of the targets and their isotopic composition. The final value of R also contained a correction taking into account the self-absorption of β particles in the detectors. This correction, no greater than 10%, was determined experimentally.

Table I gives the values of $\overline{T}_0$ at which the theoretical value of R is the same as the experimental value. The averaging signifies that ions of energy varying over a wide range of values take part in the reactions.

As seen from Table I, the values of $\overline{T}_0$ are in satisfactory agreement with the theoretical values of T_0. The reason for the closeness of the values of T_0 to the maximum values of T_0 is that the reaction cross section increases with increasing energy of the incident ions. We note that for the $V + C^{12}$ and $V + O^{16}$ reactions the intensity of neutrons of energy greater than 22 Mev (in the case of a graphite detector) also corresponds to the above-mentioned shape of the neutron spectrum. It should be kept in mind, however, that the angular momenta of the compound nucleus are not taken into account in the theoretical calculation of the spectrum.

The data of Table II on the neutron angular distributions have two interesting characteristics: a) neutrons of high energy have a more peaked angular distribution; b) as the mass of the target nucleus increases, the anisotropy in the angular distributions becomes less marked. However, for a detailed comparison with the theory, it would be desirable to measure the angular distribution of neutrons emitted in the forward and backward directions in reactions produced by monoenergetic ions. Unfortunately, since we worked with the internal beam of the cyclotron, we were not able to do this.

Nevertheless, since our results are not in contradiction with Strutinskii's calculations[4] based on the statistical model of nuclear reactions, it can be concluded qualitatively that the neutrons are emitted by a compound nucleus.

In conclusion, we consider it our duty to thank G. N. Flerov for his interest in the work and for his day-to-day guidance, and also V. M. Strutinskii for helpful discussions on the problem under study.

[1] A. S. Karamyan and A. A. Pleve, JETP **37**, 654 (1959), Soviet Phys. JETP **10**, 467 (1960).

[2] D. Hughes, Neutron Cross Sections, Pergamon Press, London, 1957.

[3] Yu. V. Adamchuk and V. M. Strutinskii, (Theory of Nuclear Level Density and Radiation Widths), Preprint, Inst. Atom. Energy U.S.S.R. Acad. Sci., 1960.

[4] V. M. Strutinskii, Труды Всесоюзной конференциих по ядерным реакциям при малых и средних энергиях, (Proceedings of the All-Union Conference on Nuclear Reactions at Low and Medium Energies, November, 1957), U.S.S.R. Acad. Sci., 1958, p. 576.

Translated by E. Marquit
165