SOVIET PHYSICS JETP VOLUME 36(9), NUMBER 2 AUGUST, 1959

DIRECT NEUTRON-EXCHANGE INTERACTION OF COMPLEX NUCLEI

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Submitted to JETP editor July 24, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) 36, 526-528 (February, 1959)

It is shown that it should be possible to observe the process of direct interaction between complex nuclei, in which the nuclei exchange neutrons when located on the external boundary of the Coulomb potential barrier. For large values of neutron moments in the outer shells, this process may result in a large range of the spins of the interacting nuclei and in excitation of all levels, which practically would not be attainable in any other way. The exponent that characterizes the probability of the processes under consideration is estimated.

ACCELERATION of heavy ions makes timely at present the observation of a unique nuclear process, namely the direct (i.e., not involving compound nucleus) exchange of neutrons between complex nuclei. We cite two possible examples of such a process:

$$ {}_8O^{18}_{10} + {}_{10}Ne^{20}_{10} \longrightarrow {}_8O^{18*}_{10} + {}_{10}Ne^{20*}_{10} $$
$$ 0^+ \quad 0^+ \qquad\qquad 0, 2, 4^+ \qquad 0, 2, 4^+ $$

(neutron exchange in the $d_{5/2}$ shell)

$$ {}_{36}Kr^{84}_{48} + {}_{36}Kr^{84}_{48} \longrightarrow {}_{36}Kr^{84*}_{48} + {}_{36}Kr^{84*}_{48} $$
$$ 0^+ \quad 0^+ \qquad\qquad 0, 2, 4, 6, 8^+ \qquad 0, 2, 4, 6, 8^+ . $$

(neutron exchange in the $g_{9/2}$ shell).

It is obvious that at large moments of the neutrons in the outer shells, such an exchange may lead to a very strong change in the spins of the interacting nuclei, i.e., to an excitation of levels which differ greatly from the ground state in the value of the moment, but which are relatively weakly excited ($\lesssim$ Mev). Since the excitation of such levels by any other means is of very low likelihood, it is not excluded that this process, in spite of its uniqueness, may be of interest also for the study of new, still unknown nuclear levels.

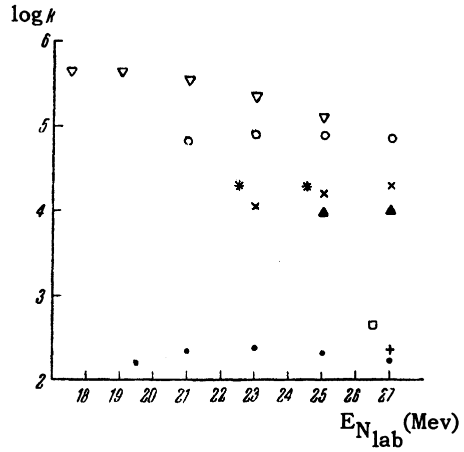
To estimate the probability of this process we can use the general method proposed by Landau[1] to describe transitions in quasi-classical system and applied by E. M. Lifshitz to interactions between deuterons and nuclei[2] and to neutron transfer from one complex nucleus to another.[3] We use Landau's method for the analysis of this case in complete analogy with the method used by Lifshitz, the only difference being that one must consider not one act of neutron transfer from nucleus 1 to nucleus 2, but two such acts (transfer one neutron from 1 to 2 and of another from 2 to 1), the aggregate of which comprises the neutron-exchange interaction.

We used in the calculations the same approximations as in reference 3, namely that the nuclei are considered concentrated in a point, the neutron mass m is assumed small compared with the nuclear masses ($m \ll M_i$, $i = 1, 2$), and the energy of the relative motion E_0 of the nuclei is sufficiently large ($E_0 \gg J_i m/M_i$, where J_1 and J_2 are the binding energies in nucleus 1 or 2). Without dwelling here on the intermediate derivations, we cite only the final result: the sought probability of direct neutron-exchange interaction is proportional to

$$ \Phi = \exp\{-2\sqrt{2}\, Z_1 Z_2 e^2 \sqrt{m}(\sqrt{J_1} + \sqrt{J_2}) / \hbar E_0\}. \quad (1) $$

If the energy J_1' of the detachment of the neutron from nucleus 1, which is the first to join the additional neutron, is less than the energy J_1, or if an analogous relationship ($J_2' < J_2$) is satisfied for nucleus 2, then the most probable process is one in which the neutron first joins nucleon 1 or nucleon 2, and only then does this nucleus emit the neutron that goes into "exchange." Then the term $\sqrt{J_1} + \sqrt{J_2}$ in the final expression for Φ should be replaced by the smaller of the two sums, $\sqrt{J_1'} + \sqrt{J_2}$ or $\sqrt{J_1} + \sqrt{J_2'}$.

The relations obtained (like the omitted intermediate derivations) are quite analogous to those obtained by Lifshitz for the transfer of a neutron from one complex nucleus to another. The final result — the quantity Φ — differs in our case from that given in reference 3 only in the presence of two terms $\sqrt{J_i}$ instead of a single one, either $\sqrt{J_1}$ or $\sqrt{J_2}$. To test the applicability of these relations and to estimate the effective values of



● — Be^9, + — C^{12}, □ — O^{16}, × — Na^{23}, o — Mg^{24}, ▽ — Mg^{25}, ▲ — Mg^{26}, ∗ — Al^{27}

the factors in front of the exponents it is necessary to compare the formulas obtained in reference 3 with the large experimental material accumulated recently on the transfer of neutrons from N^{14} nuclei to various bombarded targets.[4-9] For N^{14} we have: $Z_1 = 7$, $J = 10.55$ Mev, $E_0 = \{(14/(14 + M_2)\} E_{N\,lab}$.

The experimental dependence[5-8] of the cross sections for the neutron transfer to various nuclei by the nitrogen nuclei on the energy of the nitrogen nuclei is illustrated in the diagram in the form of the logarithms of the factor in front of the exponent [$\text{Log}\, k = \log \sigma_{(mbn)} + \alpha/2.3\, E_{N\,lab}$] at various values of $E_{N\,lab}$. The diagram shows that, at least for six nuclei (Be^9, Na^{23}, Al^{27} and the three isotopes of Magnesium) the sum $\log \sigma + \alpha/2.3\, E_{N\,lab}$ is actually constant, thus confirming qualitatively the applicability of the discussed relationships.

Data on neutron transfer from N^{14} to B^{10} and N^{14} do not fit into the relation obtained in reference 3, since the cross sections of these reactions increase with energy rather slowly (α_{exp} is less than that cited above), and the values of $\log \sigma + \alpha/2.3\, E_{N\,lab}$ diminish with increasing energy of the nitrogen ions. However, even in these cases the discrepancy between the experimental data and the ordinary formula for the probability of penetrating through the Coulomb barrier is considerably greater.

The values of the factors in front of the exponents, obtainable from the diagram (0.2 to 0.4 barns for Be, C, and O and 10 to 100 barns for Na, Mg, and Al) are naturally too high, since in the derivation of these relations the nuclei were assumed to be concentrated in a point.

Without dwelling in greater detail on the role of the finite dimensions of the nuclei in the exact calculations, we point out only that the region in which the sharp increase in the cross section of neutron transfer by the N^{14} nuclei increases rapidly with energy is shown experimentally to extend to energies somewhat in excess of the usually employed Coulomb potential barrier. However, the exact contribution of the barrier factors to the foregoing effective values of the factors in front of the exponents is immaterial. All that is important is that the true values of the factors in front of the exponents are close in order of magnitude to those proposed for the direct neutron-exchange interaction. In the latter case we can expect only a relatively small reduction in the factor in front of the exponent for the production of each of the final states with different spins, owing to the large number of these possible states. A comparison of the geometrical cross sections with the cross sections of the neutron-transfer processes, together with a comparison of the values of Φ for neutron exchange and for neutron transfer, give therefore grounds for assuming that the direct neutron-exchange cross sections of complex nuclei may reach values on the order of $10^{-30} - 10^{-29}$ cm^2 near the limiting barrier energy and that such an interaction can be thus observed by recording the subsequent γ radiation (in particular, the coincidences between γ quanta from both final nuclei) and in some cases by detecting hitherto-unknown isomer transitions (relative to the long-lived low-energy E2 transitions).

The author expresses sincere gratitude to A. S. Kompaneets and E. M. Lifshitz for valuable advice.

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Translated by J. G. Adashko
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