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THE RESONANCE-LIKE FEATURE OF THE TWO NEUTRON TRANSFER CROSS-SECTION NEAR THE COULOMB BARRIER IN THE $^{209}Bi+^{22}Ne$ REACTION

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Description of the experiments and results

The experiments were performed using a ^{22}Ne projectile beam from the U-400 cyclotron of the Laboratory of Nuclear Reactions of the JINR, Dubna. A schematic view of the experimental set-up is shown in fig.1. A rotating target made of metallic bismuth, (0.55±0.05) mg/cm^2 thick, vacuum evaporated onto a backing of (1.6±0.1) mg/cm^2 Al was used. The ^{22}Ne ion energies were varied using Al and Ti degraders and also by the proper choice of the external beam orbit. The energy of the beam, after passing through the degraders, was measured by a Si(Au) detector, registering the ions, scattered by an Au foil (scattering angle being 30°, foil thickness 0.2 mg/cm^2). To measure the beam intensity after passing through the target a Faraday cup was used. The FWHM value of the beam energy distribution was not worse than ±1 MeV. The duty cycle of the cyclotron consisted of 2.7 ms beam time and a 4.0 ms pause. The separation of reaction products from the projectile beam was

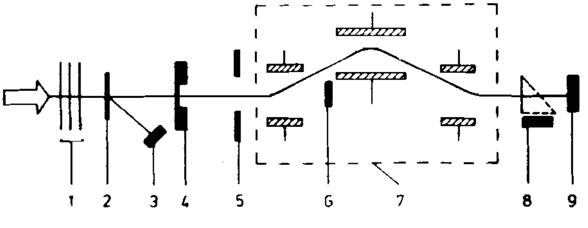

Fig.1. A schematic view of the experimental set-up. 1 - degraders, 2 - Au-scatterer, 3 - detector designed to determine the beam energy, 4 - rotating target, 5 - input diaphragm, 6 - Faraday cup, 7 - separator "VASSILISSA", 8 - time-of-flight detectors, Si(Au)-detector.

performed using the "VASSILISSA" kinematic separator [1,2]. The reaction products, recoiling from the target at 0° with respect to the projectile beam axis, were focused at a distance of 12 m by two triplets of magnetic quadrupole lenses and separated according to their electric rigidity by three high-voltage deflectors placed between the focusing lenses. The angular acceptance of the separator, determined by its input diaphragm, was chosen to be ±3° with respect to the projectile beam axis. To normalize the charge distribution of the reaction products, a thin carbon foil (20-30 $\mu g/cm^2$), situated a few cm from the target was used. To register the evaporation residues and their α-decay products, having passed through the separator, a detector system was used, consisting of two secondary electron transmission detectors and a surface barrier detector (50 mm in diameter, 40 keV FWHM) placed in the focal plane of the separator. To calibrate the Si(Au) detector, the α-lines of $^{213-216}Ac$ and $^{209,210}Fr$ isotopes from the $^{197}Au+^{22}Ne$ reaction were used.

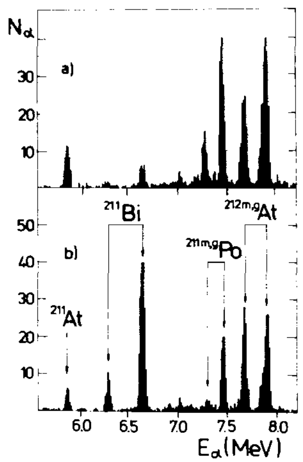

Fig.2. The α-spectrum of the $^{209}Bi+^{22}Ne$ reaction products in the separator's focal plane: a) E_{Ne} = 104.5 MeV,; b) E_{Ne} = 99 MeV.

In fig.2 the α-spectra of the $^{209}Bi+^{22}Ne$ reaction, measured during the "beam out" time intervals of the cyclotron duty cycle at projectile beam energies of 99 MeV and 104.5 MeV (at the target output surface) are shown. The most intensive lines in the α-spectra are due to the decay of the few-nucleon transfer reaction products - $^{211m,g}Po$, $^{212m,g}At$, and ^{211}Bi. The α-line identification was carried out using their energies and relative intensities [3]. In addition, the half-life for the α-transition in ^{211}Bi was measured. The obtained value of (2.3±0.3) min is in good agreement with the tabulated one. The obtained values of the α-decay rates for Ac, Pa, and Np isotopes genetically linked to the α-decay chains leading to $^{211m,g}Po$ $^{212m,g}At$, and ^{211}Bi are more than an order of magnitude smaller and consequently the contribution of the fusion channel to the production of the Bi-At isotopes is small. A supplementary argument for this fact is obtained from the dependence of the α-count rate in the separator's focal plane on the electric rigidity, as shown in fig.3. Following the increasing electric rigidity (Eρ), the count rate, associated with the α-decay of the Bi-At isotopes, grows rapidly, whereas the yield of evaporation residues varies slowly in the same interval of Eρ and even decreases at larger values of

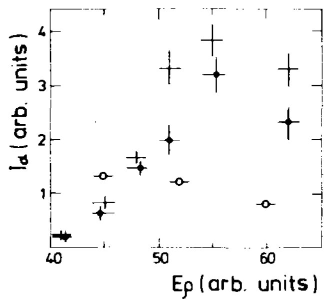

Fig.3. The production rate of the ^{212}At (+), ^{211}Bi (✚),and $^{214,215}Ac$ (o) isotopes as a function of the electric rigidity.

E_ρ given in fig.3. So, there is no doubt that few-nucleon transfer reactions are the basic mechanism of the formation of all above mentioned nuclei.

At the same time we are observing a considerable difference between the production rates of the Po-At and ^{211}Bi isotopes. Indeed, as can be seen in fig.2, the α-decay lines of all nuclei, that is $^{211m,g}Po$, and $^{212m,g}At$ on the one hand and ^{211}Bi on the other, were present in the α-spectrum detected at a projectile energy of 99 MeV. The situation changed at 104.5 MeV when the ^{211}Bi α-decay line practically disappeared whereas the intensities of the Po-At lines remained unchanged or even increased. Fig.4 shows the excitation functions of ^{211}Bi and $^{212m,g}At$, obtained in our experiments. While the behaviour of the $^{212m,g}At$ yield curve is typical for a few-nucleon transfer reaction product, that of ^{211}Bi is an unusual in the sense that it has a narrow pronounced maximum near the Coulomb barrier. Such a peculiar form of the excitation function for ^{211}Bi allows one to assume that two nucleon transfer reactions are governed by a principally new mechanism of two-neutron transfer at small impact parameters, compared with the mechanism of a few-nucleon transfer process in peripheral interactions with large impact parameters. Our attention is attracted to the relatively large maximum of the differential

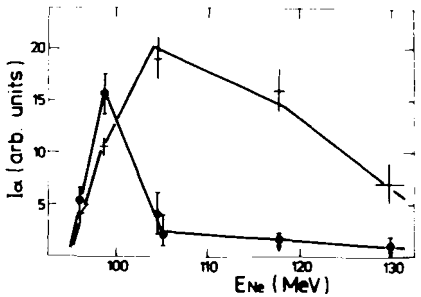

Fig.4. The production rates of the ^{212}At (+) and ^{211}Bi (•)isotopes as a function of the ^{22}Ne projectile energy.

cross-section for ^{211}Bi production (10^{-28}-10^{-27} cm^2/sr) which is comparable with that for ^{212}At. At the same time the differential cross-section for producing of more heavier Bi isotopes with mass numbers 212 and 213, at ^{22}Ne projectile energies of 99 MeV and 104.5 MeV, has a value not exceeding (2-3)% of that for ^{211}Bi. In the control reaction $^{209}Bi+^{20}Ne$ under the same experimental conditions, the α-activities, due to the α-decay of Bi isotopes (including ^{211}Bi) were not observed at a level of <1% of the yield of reaction products such as ^{212}At, ^{213}Rn and $^{213,214}Fr$.

From the analysis of the data obtained in the $^{209}Bi+^{22}Ne$ reaction, in the "beam on target" time periods, it was possible to detect another α-line of which the intensity was decreased by a factor of (6.5±2.5) as the ^{22}Ne projectile energy was increased from 99 MeV to 104.5 MeV. This line is due to α-decay with E_α=8030±20 keV and $T_{1/2}$<0.2 ms. At the ^{22}Ne projectile energy of 99 MeV the production rate of this α-activity is (15±3)% of that for ^{211}Bi. Taking into consideration the given energy and half-life it is quite possible to attribute this α-activity to the decay of ^{215}At. We were unable to measure the production rate of ^{215}At in the given reaction at higher projectile energies. On the other hand the fact itself of the qualitative agreement in the behaviour of the ^{211}Bi and ^{215}At production rates at 99 MeV and 104.5 MeV is essential for the interpretation of the effect observed.

Discussion and conclusions

The obtained experimental results give an evidence that in the $^{209}Bi+^{22}Ne$ reaction the differential cross-section of the transfer of two neutrons or a cluster of ^6He (2n+α) to the target nucleus, followed by the emission of the product nucleus at 0^o with respect to the projectile beam axis, has a narrow maximum at energies around the Coulomb barrier. At the same time, in the transfer reactions leading to the formation of $^{212m,g}At$ and $^{211m,g}Po$ such a maximum in the differential cross-section has not been observed. The result, in our opinion, is unexpected because no production maxima have been observed before neither in the integral cross-sections of few-nucleon transfer reactions, nor in the differential cross-sections obtained in detecting light projectile-like transfer products, scattered quasi-elastically from medium-mass and heavy target nuclei at different angles.

The experimental data presented here do not allow one to give an unambiguous explanation of the nature of the effect observed. Nevertheless it is possible to advance some assumptions. It is evident that at ^{22}Ne bombarding energies close to the Coulomb barrier the most frequent products of few-nucleon transfer processes occurring at 0^{o} are target-like nuclei having small impact parameters. At energies above the Coulomb barrier interactions characterized by small values of the impact parameter lead, with a high probability, to the formation of a compound nucleus and do not contribute to the cross-sections of the transfer reaction products. Nevertheless, in the energy region of the Coulomb barrier, especially for nuclei with large Z, there may exist a definite interval of impact parameters in which the repulsive Coulomb forces are equal or comparable with the attractive nuclear forces. The small momentum values and the longest possible interaction time for direct processes provide, in our view, optimal conditions for a Josephson-type quantum effect in nuclear interactions [4,5,6] and this effect will manifest itself in this interval of impact parameters. There are, of course, some other possible quantum effects, such as the formation of the real structure of the outer states of the nucleons in the two-body nuclear potential, or a significant growth of the overlap of the single particle levels of the interacting nuclei in the Fermi surface region in the transition from the spherical to the two-body nuclear potential. It seems clear, that such quantum effects in the interaction of two nuclei have to manifest themselves mostly in the yields and angular distributions of nuclei produced in a few-nucleon transfer channel, the channel which lies nearest to the quasi-elastic one and leads to the minimum excitation energy of the two-body nuclear system. An increase in the projectile beam energy will lead to an increase in the excitation energies of the nucleons in the nuclei, to an increase in the nuclear forces and to a sharp rise of the probability for the two-body nuclear system to evolve into the fusion channel. This, apparently, may give us at least a qualitative explanation of the fact why the cross-sections of ^{211}Bi and ^{215}At production decrease so sharply with increasing ^{22}Ne projectile energy.

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