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Physics of the transmutation of stable elements at the collision of macro-objects with regard to high speeds

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Abstract. In experiments on the collision of a bismuth bullet (impactor) with a steel target at velocities of about 1 km/s, the transmutation of a stable isotope of bismuth-209 is observed. At the maximum approach of the nucleus (in the structure of macro-objects: the bullet and the target) are at distances much greater than the radius of action of the nuclear forces. In this case, the protons in the nuclei are mutually repelled by Coulomb forces. As a result, the nuclei are deformed. This deformed state can be associated with a specific excitation energy. Excitation is removed by the emission of a particle or nuclear fragments. The decay of bismuth-209 occurs. There is not one nucleus decaying, the process is of a group (collective) nature. Depending on the collision velocity, different decay channels can be realized, including the cluster decay $^{209}\text{Bi} \rightarrow ^{198}\text{Pt} + ^{11}\text{B}$. Two mechanisms of cluster decay are proposed: the formation of a light cluster of quasi-free neutrons and the direct decay of ^{209}Bi into clusters.

1. Introduction. Background

1.1. A task Formatting the title

Is it possible to transmute stable atomic nuclei (for example, bismuth-209) due to acceleration of their radioactive decays by external action, for example, by collision of macro-objects containing these nuclei?

1.2. Forced fission of stable nuclei

The first results of studies of stimulated fission of stable bismuth and lead nuclei by high-energy particles (neutrons, deuterons, helium ions) were published in the late 1940s. [1, 2]. The division of these kernels is symmetrical. The division is preceded by the "evaporation" of 10...12 neutrons by highly excited nuclei. From the evaporated neutrons, new light nuclei are formed [1, 2]. To describe nuclear reactions initiated by particles with energy $\sim 10^2 \dots 10^4$ MeV, in 1947 R. Serber proposed the fundamentals of a cascade-evaporation model [3]. Later the theory of evaporation was developed [4].

1.3. Fragmentation reaction

Fragmentation is understood as the nuclear reaction of the splitting of an atomic nucleus with the formation of several clusters. The mechanism of fragmentation reaction was proposed in 1953–1954 [4]. Nucleons and the light clusters can evaporate from nuclei in a highly excited state [4]. The irradiation of lead with protons of energy 370 MeV and more leads to the realization of the



fragmentation reaction with the formation of ^{18}F , ^{23}Na , ^{24}Na , ^{28}Mg , ^{32}P , and ^{33}P nuclei [4]. The fission of lead by protons with an energy of 450 MeV are researched [4]. The fission of ^{209}Bi by deuterons with an energy of 190 MeV is realized through the formation of a compound nucleus. Against the background of symmetrical bismuth fission, a less probable process was observed, when the fission was preceded by the emission of 12 neutrons and the formation of the ^{199}Po nucleus. Subsequently, the atomic nucleus ^{199}Po decays along the fission channel. Such a process was known earlier and was called the emission fission mechanism.

1.4. Cluster decay of nuclei

The form of radioactivity, occupying an intermediate position between α -decay and spontaneous fission, was predicted in 1980 [5]. In 1984, independent groups of scientists first in the United Kingdom (H. Rose, G. Jones [6]), then in Russia (D. Alexandrov et al. [7]) first observed the spontaneous emission of carbon-14 nuclei by radium nuclei. Later (1987), this phenomenon was called f-radioactivity.

The 25 nuclei from ^{114}Ba to ^{242}Cm were detected experimentally, emitting clusters (^{12}C , ^{14}C , ^{20}O , ^{23}F , ^{24}Ne , ^{25}Ne , ^{26}Ne , ^{28}Mg , ^{29}Mg , ^{30}Mg , ^{32}Si , ^{34}Si) from the main energy states [8–10]. Most of these clusters are radioactive. The ^{28}Mg nucleus can form in the fragmentation of lead [4].

1.5. Acceleration of radioactive decays

The first attempts to influence the half-life of radioactive elements were taken immediately after the discovery of radioactivity [11]. “The influence of temperature, pressure, concentration, age of breed, external fields, chemical state and external environment on the rate of decay was investigated. ...It was pointed out that a change in the chemical composition of an atom could lead to a marked change in the probability of a nuclear transition” [12]. Because of the relative availability of the creation of intense electromagnetic fields, it is simplest to influence these external fields on the rate of β -decays of atomic nuclei. In 2003–2009 the possibility of accelerating β -decay upon changing the state of the electron shell of atoms of radioactive elements was experimentally investigated [13]. Periodic changes in the rate of α - and β -decays due to thermal effects were also studied [13]. The specialists of *JINR* (Dubna, Russia) by 2008 demonstrated experimentally a controlled change in the rate of radioactive decay of atomic nuclei [14]. For example, for ^{212}Po implanted in metallic lead with a natural isotopic composition, an increase in the decay rate of 0.2% was observed compared with the decomposition rate of ^{212}Po in nickel [14]. Thus, attempts to accelerate α and β -decays were successful, but the decrease in the half-life was insignificant.

At the same time, it is known that the half-life with respect to spontaneous fission can be substantially reduced by transferring the nucleus to an excited state. In 1962 G. Flerov, S. Polikanov and their colleagues from *JINR* have discovered delicate isomerism. Uranium nuclei and trans-uranium elements can divide spontaneously with two different half-lives (see [15] and references to this work). For example, for ^{238}U , the half-life $T_{1/2}=5.9\cdot 10^{15}$ years and $0.3\cdot 10^{-6}$ s. The decay comes from two stable states of the system: the main ($T_{1/2}=5.9\cdot 10^{15}$ years) and isomeric ($0.3\cdot 10^{-6}$ s). Divisible isomerism is observed for isotopes of uranium, plutonium, americium, curium and berkelium, which are in an excited state with an excitation energy of about 2...3 MeV.

2. Hypothesis

2.1. Deformation as a factor of destabilization of the nucleus

The deformation of the atomic nucleus, regardless of the causes that caused it, can lead to a change in the spin and its own quadrupole electric moment Q , to the destruction of the shell structure of the nucleus and a change in the arrangement of the energy levels. As a result, the stability of the nuclei decreases [16, 17].

The causes (ways) of deformation of atomic nuclei can be different. Deformations of nuclei can be caused by mechanical collisions of macro-objects (containing a large number of atomic nuclei) at high

velocities. Thus, collisions of macro-objects containing depleted uranium lead to deformation of ^{238}U nuclei and a significant (by orders of magnitude) decrease in the half-life period (including with respect to spontaneous fission [18]).

The transfer of nuclei into an excited energy state leads to a change in the geometric shape that the nucleus has in the ground state [16, 17]. The source of the deformation of the nucleus is not important. It is important that the nucleus is in a deformed state with respect to the basic energy state. In other words, the core "does not remember" about the way of deformation.

2.2. *Overcoming the Coulomb barrier*

In the collision of metallic macro-objects, which have a crystalline structure, at high velocities an inertial metal explosion occurs [19]. The explosion is preceded by the loss of the common electrons of the crystal lattice. At high collision velocities, it is possible to lose all or some of the electrons of the electron shell of ions located at the sites of the crystal lattice. Approximation of positively charged atomic nuclei (or ions) in the absence of electron shells is hampered by the Coulomb barrier. In the collision of two ^{209}Bi nuclei, the barrier height is 1106 MeV, the ^{209}Bi and ^{56}Fe nuclei have a barrier height of 434 MeV.

In the case of overcoming the Coulomb barrier, the particles (nuclei) can enter into a nuclear interaction. In this case, different reaction channels are possible. If the Coulomb barrier is not overcome, then nuclear reactions are possible due to the tunneling effect. The probability of the tunneling effect for large objects (^{209}Bi nuclei) is extremely small.

2.3. *Interactions without overcoming the Coulomb barrier*

Suppose the Coulomb barrier is not overcome. The nuclei are at a distance exceeding the radius of action of nuclear forces. The transmutation of nuclei in the composition of macro-objects is possible due to the forces of electromagnetic interaction between protons of colliding nuclei. The range of electromagnetic interaction forces is infinite. These forces deform the nuclei. First of all, the proton radius (more precisely, the proton size of the initially non-spherical core) are changes. The probability of this event is relatively large because of the large number of protons in stable heavy colliding nuclei. With the external similarity of the processes under consideration to the fission, fragmentation, and cluster decay reactions, the mechanisms of interaction can differ from those proposed more than half a century ago (see [1-4, 20] and references to these papers).

2.4. *Mechanisms of cluster decay of nuclei in collisions of macro-objects*

It is possible to propose two mechanisms of cluster decay of nuclei in the collision of macro-objects. One of them assumes the formation of a light cluster of quasi-free neutrons. The other assumes a direct decay of the nucleus into clusters.

The ^{209}Bi core is characterized by the magic number of neutrons $N=126$, therefore $Q(N)=0$. The number of protons is $Z=83$ (not magical), $Q(Z)\neq 0$. Neutron matter in the ^{209}Bi nucleus "tends" to form a sphere, proton matter tends to deform this sphere. As a result of the action of nuclear forces of mutual attraction of nucleons, the nucleus, which is even in the ground state of energy, is deformed, and the neutron and proton radius (or rather, the dimensions, since the shape of the nucleus is not spherical) are different [16].

What happens when the macro-objects (one of which contains bismuth-209) converge and subsequently collide? At distances exceeding the radius of action of nuclear forces, electromagnetic interaction is manifested. Compared with protons, neutrons have no electric charge and are less involved in electromagnetic interaction. For this reason, nuclear matter containing protons is deformed to a much greater degree. In the nucleus ^{209}Bi , the number of neutrons is $N-Z=43$. In the central part of the nucleus, $N\approx Z$ is usually. The peripheral part of the nucleus is overloaded with neutrons. As a result, the proton and neutron radius (size) of the nucleus are different [16]. The mutual Coulomb repulsion of protons of neighboring nuclei as they approach each other leads to deformation of these nuclei. The process is of a collective (group) nature: many nuclei participate in the interaction at once. At a

mechanical collision of macro-objects due to electromagnetic interaction, the proton radius (size) of the nucleus is deformed to a much greater extent. As a result, in a deformed nucleus (especially if this deformation leads to an even greater deviation from the spherical shape), a neutron "cloud" is formed near the surface, a region (or regions), where $N/Z > 1$. This increases the probability that the remaining atomic electrons approach the protons of the nucleus. As a result, the probability of capture of an atomic electron by the proton of the nucleus increases (β -conversion). Neutrons of this region are connected with each other and the central part of the nucleus by forces of nuclear attraction, but smaller than in the central part of the nucleus.

At the time preceding the departure of quasi-free neutrons from the nucleus, the neutron cloud forms an unstable neutron nucleus, a quasi-nucleus (which can't exist in the free-state). A quasi-nucleus is a group of neutrons held by the forces of the mutual nuclear attraction of a neutron "cloud" and a heavy fragment remaining from ^{209}Bi . For the existence of such a quasi-nucleus in the free-state, i.e., for transmutation of it into a normal atomic nucleus, it is necessary and energetically beneficial to transfer a part of the neutrons into protons. This is due to a change in the projection of the isotopic spin of one of the d -quarks in the composition of several neutrons. The process is realized due to the nuclear symmetry energy: the tendencies to the stability of nuclei with the same number of neutrons and protons [16, 17]. In the forced fission of lead and bismuth, the authors of [1, 2] speak of the evaporation of 10...12 neutrons. If the number of quasi-free neutrons is 11, then the transmutation of five neutrons into protons corresponds to the formation of the ^{11}B nucleus. The transmutation of six neutrons corresponds to the formation of the ^{12}C nucleus (which immediately decays in ^{11}B) near the heavy fragment remaining from ^{209}Bi . (Since among quasi-free neutrons there can be several protons in a quasi-nucleus, such transitions can be less than five.) The heavy cluster (^{198}Bi) remaining from the ^{209}Bi nucleus decays by a weak interaction at ^{198}Pt . Finally, we obtain: $^{209}\text{Bi} \rightarrow ^{198}\text{Pt} + ^{11}\text{B}$. The initial nucleus and its decay products are stable. It is possible that the nucleus emits quasi-free neutrons. These neutrons can initiate nuclear reactions.

As is known, stable nuclei are characterized by the condition of equilibrium of forces characterizing weak, strong and electromagnetic interactions. For stable nuclei, a certain N/Z ratio (we call it optimal) is typical, obtained empirically from the Weizsacker formula (in the drop model of the nucleus) [16, 17]:

$$N/Z = 0.98 + 0.015 \cdot A^{2/3}.$$

Here A is the mass number, $A = N + Z$. The relation is satisfied up to parity of N and Z in the nucleus, that is, does not take into account the effect of the pairing of neutrons (protons).

In fragmentation reactions, light clusters are usually stable. Heavy clusters are either radioactive due to neutron overload, or are stable [4]. When a light stable cluster is formed with the optimal N/Z ratio, the heavy cluster will also be characterized by an N/Z ratio close to the optimal one. Hence, in contrast to natural cluster radioactivity, in the case of mechanical collisions of macro-objects, the appearance of light clusters with a small mass number is more likely. The determining factor is the rate of convergence of macro-objects.

At higher macro-object collision rates, it is possible to expect the subsequent decay of a heavy ^{198}Pt or ^{198}Bi cluster, which is in an excited state, that is, the transition of cluster decay to nuclear fission.

Another mechanism assumes a direct decay of the nucleus into clusters: $^{209}\text{Bi} \rightarrow ^{198}\text{Pt} + ^{11}\text{B}$. The process should be realized at lower collision rates of macro-objects than the decay of $^{209}\text{Bi} \rightarrow ^{198}\text{Bi} + 11^1_0n$ with the subsequent transmutation of $5^1_0n \rightarrow 5^1_1p$ and the formation of ^{11}B . The mechanism of direct decay of bismuth into clusters is analogous to the natural cluster radioactivity described in the framework of the drop model of the nucleus. (The nucleus-drop of a pear-shaped form splits into two parts, very different in mass.) The implementation of this mechanism requires lower collision rates of macro-objects, the decay products are stable, there are practically no free neutrons in the system capable of initiating nuclear reactions.

The mechanisms of fission, α -decay, decays of ^{209}Bi into other clusters during mechanical collisions of macro-objects are similar.

3. Experimental confirmation of the hypothesis

The hypothesis has been experimentally confirmed. Direct shock experiments were conducted on the collision of a bismuth striker with a steel target.

The preliminary results of these experiments are presented in [21-26]. Of greatest interest are 4 series of experiments with different ranges of velocities of bullets containing bismuth: series *A* (speed is about 791 m/s), *B* (1224 m/s), *C* (1095 m/s) and *D* (956 m/s). In all series, the cluster decay of a stable isotope of bismuth into two stable nuclides was registered: $^{209}\text{Bi} \rightarrow ^{198}\text{Pt} + ^{11}\text{B}$. Experiments are characterized by repeatability. The process of disintegration is of a massive nature. In series *B*, α -particles with an energy of about 8 MeV, emitted by metallic dust formed directly at the interaction site of the bullet and steel, are recorded [21, 22]. The most probable source of delayed high-energy α -particles can be the ^{198}Bi nuclei formed along the $^{209}\text{Bi} \rightarrow ^{198}\text{Bi} + 11^1_0\text{n}$ channel. This process is facilitated by a relatively high speed bullet.

The lightest cluster is obtained from all known cases of cluster radioactivity. It is lighter than carbon-12. As expected, depending on the speed of the bullet, the observed decay is either cluster decay in explicit form $^{209}\text{Bi} \rightarrow ^{198}\text{Pt} + ^{11}\text{B}$ (at lower collision rates of macro-objects), or $^{209}\text{Bi} \rightarrow ^{198}\text{Bi} + 11^1_0\text{n}$, followed by β^+ -conversion of ^{198}Bi to ^{198}Pt , transmutation five quasi-free neutrons into protons and the formation of ^{11}B . The process is an incomplete (incomplete) division, when a heavy cluster (^{198}Pt) does not break up into fragments.

The output channel of the decay contains α -particles. With a high probability, decay of ^{198}Bi (especially from an excited energy state) is possible with the emission of high-energy delayed (with respect to cluster decay) α -particles. In this case, one can speak of an incomplete division of ^{209}Bi initiated by an external action. Only the first stage of division is realized: $^{209}\text{Bi} \rightarrow ^{198}\text{Bi} + 11^1_0\text{n}$, accompanied by α -decay, rather than by fission of ^{198}Bi .

4. Analysis of results and Conclusion

The decay of stable atomic nuclei can be significantly accelerated by external influences. Mechanical collisions of macro-objects can significantly facilitate the study of highly unlikely processes in the natural environment of cluster radioactivity, including stable nuclei.

The characteristics of the decays of different atomic nuclei depend differently on external influences (pressure, temperature, etc.). Deformation of the nucleus can lead not only to the destruction of its shell structure, but also to the reduction of all other stabilization factors, including those not related to the filling of nuclear envelopes [16, 17]. At the same time, the significance of different factors can vary in different ways for different atomic nuclei. The abnormally high pressure created by mechanical collisions of macro-objects can significantly reduce the half-life of bismuth with respect to cluster radioactivity with an insignificant increase in the rate of α -decay and fission.

When a bullet containing bismuth collides with a steel target at a speed of up to 1 km/s, the decay of $^{209}\text{Bi} \rightarrow ^{198}\text{Pt} + ^{11}\text{B}$ is realized. With an increase in the speed of the drummer to 1.2 km/s, the process $^{209}\text{Bi} \rightarrow ^{198}\text{Bi} + 11^1_0\text{n}$ is most likely. Subsequently, out of 11 neutrons, due to the symmetry energy, about a half (five) weakly bound neutrons by the ^{209}Bi nucleus become protons. As a result, the nucleus ^{11}B is formed. The ^{198}Bi nucleus either undergoes β^+ -transformations (electron capture, with the final product is ^{198}Pt), or emits a high-energy retarded ($T_{1/2}=1.7$ min) α -particle. At still high velocities of the drummer, a symmetrical fission of ^{198}Bi (or ^{198}Pt) should be expected.

Various external influences (for example, different velocities of the bullet) can lead to a different probability of the realization of a particular decay channel. In the processes of natural radioactivity (in the absence of external influences), each decay channel is characterized by a definite value of the half-life. In decays initiated by external influences, the average lifetime with respect to a particular decay can vary depending on these effects. In other words

$$T_{1/2,i}(A, Z) = f(A, Z, k, \delta\rho).$$

Here, A is the mass number, Z is the number of protons in the nucleus, k is the decay channel, and $\delta\rho$ is the external perturbation that initiated the decay (temperature, pressure, etc., as well as various

combinations of these perturbations). As a result, the half-life in different channels for different nuclei depends on external influences in different ways. For this reason, the rate of cluster decays with certain effects on certain nuclides can significantly increase in comparison with other types of decay.

In essence, the observed phenomena are similar (one might say equivalent) to radioactive decays from highly excited energy states. The deformation of nuclei in the collision of macro-objects is so great that cluster radioactivity becomes noticeable and even predominant on the background of α -decays. The nucleus is energetically more profitable to immediately get rid of a heavy cluster. At high velocities of the bullet, we can expect the fission of a heavy cluster (^{198}Pt or ^{198}Bi), that is, a formal overgrowth of cluster decay into fission. The nuclei that form in these processes can be radioactive. Decay products can cause nuclear reactions.

Practical application of research results can be expected in fundamental studies on the study of cluster decays, in the possibility of obtaining energy on a limited scale using stable nuclides as a nuclear fuel, in transmutation of base metals into noble metals.

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