Original Research Paper.

METASTABLE NON-NUCLEONIC STATES OF NUCLEAR MATTER: PHENOMENOLOGY

A hypothesis of the existence of metastable states for nuclear matter with a locally shaken-up nucleonic structure of the nucleus, was proposed earlier. Such states are initiated by inelastic scattering of electrons by nuclei along the path of weak nuclear interaction. The relaxation of such nuclei is also determined by weak interactions. The use of the hypothesis makes it possible to physically interpret a rather large group of experimental data on the initiation of low energy nuclear reactions (LENRs) and the acceleration of radioactive α- and β-decays in a low-temperature plasma. The possible mechanisms of LENRs implemented in a Rossi E-CAT reactor are discussed. It is also suggested that the metastable *isu*-states of a different type occur as a result of high-energy collisions of particles, when heavy hadrons (baryons, mesons) are formed in the collisions of protons with characteristic energies higher than 1 TeV. This kind of concept makes it possible to physically interpret the recently recorded anomaly in the angular e^+e^- correlations of positron-electron pairs emitted in the radioactive decays of excited ^8Be nuclei formed by the interaction between protons with kinetic energy ~ 1 MeV and ^7Li nuclei. A recent hypothesis of the existence of yet another, fifth fundamental interaction by Feng et al, in addition to the strong/weak nuclear, electromagnetic, and gravitational interactions, might be introduced to explain this anomaly.

Keywords: metastable non-nucleonic states of nuclear matter; low energy nuclear reactions; heavy hadrons; heavy quarks; inner shake-up state of nuclear matter.

1. INTRODUCTION

Recent studies [1], [2] suggested that there might be a fifth fundamental interaction, in addition to the strong/weak nuclear, electromagnetic, and gravitational ones. They were initiated by the study [3], in which the authors studied the radioactive decays of excited ^8Be nuclei with energies of 17.64 and 18.15 MeV, formed in the interaction of protons with kinetic energy E_p = 1.10 MeV and ^7Li nuclei, using LiF_2 and LiO_2 targets. The above excited states were recorded as resonances at E_p = 0.441 MeV and E_p = 1.03 MeV in the process $^7Li(p,\gamma)^8Be$ under study. The authors [3] studied the formation of a positron-electron pair e^+-e^- resulting from the internal conversion that accompanies the birth of two α-particles in the radioactive decay of the ^8Be nuclei. They expected a sharp drop in the probability of the correlated formation of an e^+-e^- pair as the opening angle Θ between positrons and electrons in the laboratory frame of reference increases. However, they recorded an "anomalous" increase in the angular function within an angular range of Θ ~ 130-140^0, considering this anomaly as a result of the formation of the e^+e^- pair in the decay of a hypothetical neutral isoscalar boson formed in the above process, with a rest mass equal to 16.7 MeV/c^2, where c is the speed of light in vacuum. In this decay, the opening angle would be 180^0 in the system of the center of mass of the e^+e^- pair. It was suggested that the introduced isoscalar boson, with its expected lifetime of ~ 10^{-14} s, might be a good candidate for the relatively light gauge boson performing the role of the mediator in the secluded WIMP dark matter scenario. However, the later analysis [1], [2] showed that the ^8Be anomaly, which is consistent with all existing experimental constraints, can be adequately interpreted only when one puts forward a hypothesis of existence of another type of boson, a protophobic gauge vector boson *X*, which is produced in the decay of the excited state of $^{8}Be^{*}$ down to the ground state, $^{8}Be^{*} \rightarrow {}^{8}Be^{*}X$, and then decays as $X \rightarrow e^{+}e^{-}$. It is the boson that could be related to the elusive dark matter in the Universe. According to [1, 2], this gauge boson, with a mass of about 17 MeV/c^2, is the mediator of the weak force. The boson has milli-charged couplings to up and down quarks and electrons, but with relatively suppressed (and possible vanishing) couplings to protons (and neutrinos) relative to neutrons, i.e. it interacts with neutrons but is “protophobic” and ignores protons. The latter allows one to explain why the X boson might have avoided earlier detection. It was shown that the Standard Model can be easily extended to accommodate a light gauge boson with protophobic quark couplings [2]. As a result, the postulated boson was associated with a new, fifth, fundamental interaction, which should be introduced into the physical science [1], [2].

It will be shown below that the recorded anomalies in the angular $e^{+}e^{-}$ correlations in the radioactive decay of excited ^{8}Be nuclei can be qualitatively interpreted on the basis of a new concept rather than the fundamental hypotheses made in [1], [2]. We assume that metastable states can occur in the nuclear matter when the mass of the nucleus is insufficient to bind a part of the quarks into nucleons, which gives rise to local shake-ups in the nucleonic structure of the nucleus. For these anomalous excited states, the relaxation dynamics of the nuclei crucially depends on the weak nuclear interaction. Earlier, this assumption made it possible to physically interpret a rather large set of experimental data on the initiation of LENRs and acceleration of radioactive α- и β-decays in a low-temperature plasma. It will be shown that such states of the nuclear matter with a shaken-up nucleonic structure can occur in the high-energy collisions of nuclei too, such as protons in the colliding beams with characteristic energies higher than 1 TeV. The concept to be introduced will allow one to understand why the decay of highly excited hadrons (baryons, mesons) formed in these collisions is effectuated by the weak nuclear interaction.

2. ELECTRON FACTOR IN INITIATING NUCLEAR PROCESSES

Phenomenological approach [4]-[7] implies that the dynamic interrelation between the electron and nuclear subsystems of an atom, which is mediated by the electromagnetic component of the physical vacuum (EM vacuum), is the key factor in initiating LENRs [8]-[12] and the radioactive decay of nuclei [5], [8], [13]. This interrelation manifests itself in experimentally recorded facts that the occurrence of radioactive decay of nuclei is accounted for by the positive difference between the total mass of the initial atom subsystems, electron and nuclear (whole atom rather than the nucleus alone), and the total mass of its decay products [14], [15]. When the mechanisms of LENRs and the decay of atomic nucleus ${}_{Z}^{A}N$ (Z and A are the atomic and mass numbers of the nucleus N, respectively) are considered, the nuclear matter is usually represented in the form of interacting nucleons. In the *K*-capture, however, when the electron of the inner shells of an atom interacts with the surface of the nucleus, giving rise to a new daughter nucleus, the nucleonic structure of the nuclear matter is unchanged. At the initial irreversible stage of this process, the electron interacting with the nucleus surface emits a neutrino ν. The resulting virtual vector W^{-}-boson, integrated into the nuclear matter, interacts with the *u*-quark of one of the protons and is converted to a *d*-quark. As a result, this proton is converted to a neutron, and a nucleus ${}_{Z\text{-}1}^{A}M$ is formed. However, the situation can drastically change when the *K*-capture is energetically forbidden, which are the cases under consideration below, and the electron can acquire a rather high (on chemical scales) kinetic energy E_e ~ 3-5 eV, which can occur in a low-temperature plasma. In this case, when the electron shells are not yet ionized by these electrons, the scattering of electrons with the above kinetic energy (de Broglie wavelength $\lambda \approx 0.5$ nm) by atoms and ions initiates the oscillation of the electron subsystems of the atoms and ions, increasing the probability of interaction between the electrons of the inner subshells of the atoms and ions and their respective nuclei.

The first, irreversible stage of this interaction is characterized by the emission of a neutrino ν and the integration of a vector W^--boson into the nuclear matter of the initial nucleus ${}_Z^A N$:

$$ {}_Z^A N + e_{he}^- \rightarrow {}_{Z-1}^{\;\;A} M_{isu} + \nu . \qquad (1) $$

As a result, the nucleonic structure of the formed nucleus ${}_{Z-1}^{\;\;A} M_{isu}$, with a charge less by one than that of the initial nucleus, is locally shaken up. Indeed, the interaction between the vector W^--boson and the *u*-quark of one of the protons of the nucleus ${}_Z^A N$ can only produce a virtual *d*-quark followed by a chain of virtual conversions of quarks involving vector W-bosons. At the same time, the deficit of the total mass of this nucleus prevents from the formation of a neutron. The resulting state of local anomaly in the nuclear matter with a shaken-up nucleonic structure is characterized as a metastable inner-shake-up state, or *isu*-state. The latter is indicated by the subscript on the right of the nucleus symbol in the right-hand side of (1). The subscript in the electron symbol in the left-hand side of (1) indicates that this stage of the process is activated. The initiated chain of virtual conversions of quarks in which the vector *W*-bosons are involved must be interrupted by the irreversible decay of the virtual W^--boson producing the initial nucleus, electron, and antineutrino $\tilde{\nu}$:

$$ {}_{Z\text{-}1}^{\;\;A} M_{isu} \rightarrow {}_Z^A N + e^- + \tilde{\nu} . \qquad (2) $$

Consequently, the overall process can be represented as an inelastic scattering of an electron by the initial nucleus:

$$ {}_Z^A N + e_{he}^- \rightarrow {}_Z^A N + e^- + \nu + \tilde{\nu} . \qquad (3) $$

The nuclei in which the nuclear matter is in a metastable *isu*-state will be called "β-nuclei". The threshold energy for this process producing a $\nu\tilde{\nu}$ pair, which is accounted for by the neutrino-antineutrino rest masses, is about 0.3 eV [16].

It is common knowledge that the nucleus is a system of nucleons bound into a whole by exchange interactions in which the quarks are exchanged using pions. Therefore, the formation of three quarks not bound into a nucleon in a nucleus, which in this case can be regarded as "markers" of new degrees of freedom, in fact, means that the mass of the nucleus is insufficient to provide the traditional proton-neutron arrangement of the nuclear matter in the system under consideration. The subsequent relaxation of the locally formed *isu*-state, which can be transferred by the mediating pions to other nucleons of the nucleus, is initiated only by the weak nuclear interactions, which are effectuated by the mediating quarks in the formation and absorption of gauge vector neutral Z^0 and charged $W^\pm$-bosons. In the case under consideration, this relaxation terminates with the decay of the virtual vector W^--boson followed by the formation of the initial nucleus in the emission of an electron and antineutrino. The lifetime of the formed β-nuclei found in the metastable *isu*-state can be rather long, from tens of minutes to several years, and the nuclei in this state can be directly involved in various nuclear processes [4], [5].

It should be noted that the relaxation rearrangement of the nuclear matter when the products of these nuclear conversions are formed is effectuated primarily by forming a purely nucleonic structure of the nucleus, obeying the principle of least action. While the relaxation processes of de-excitation in nuclei with a proton-neutron (nucleonic) structure can go via the excited states of the nucleus and include γ-quanta emission steps, this type of relaxation in β-nuclei is virtually impossible. Therefore, if the atomic nuclei in which the nuclear matter is in a partial “non-nucleonic” state are involved in the processes, the mechanism of relaxation of the formed products is always accompanied by energy loss due to the emission of neutrino-antineutrino pairs, or due to the URCA process [17], rather than the emission of *γ*-quanta by excited nuclei, as in the relaxation of nuclear products characterized by the proton-neutron arrangement of the nuclear matter. It is for this reason that the corresponding nuclear processes are safe for the environment.

Of special interest are the cases in which the formation of *isu*-states in the nuclear matter is initiated in initially radioactive nuclei because the relaxation process with a vector W^--boson decay can initiate a general radioactive decay of the *isu*-state nucleus that results in the formation of daughter products of the decay of the initial radioactive nucleus. According to [5], [18], the general stability of the nuclear matter in a metastable *isu*-state can be lost by changing the boundary conditions for the components of the electric field intensity vector of the EM vacuum at the surface of the nucleus in whose volume the nucleonic matter shake-up occurred. The index characterizing the ${}^{A}_{Z\text{-}1}M_{isu}$ nucleus instability that occurs in the process (1) is the absolute value of the structural energy deficit ΔQ (ΔQ < 0) of this metastable *isu*-state nucleus, which is defined as $\Delta Q = (m_{{}^{A}_{Z}N} - m_{{}^{A}_{Z\text{-}1}M})c^2$. In this case, the mass of the ${}^{A}_{Z\text{-}1}M_{isu}$ nucleus is taken as $m_{{}^{A}_{Z-1}M_{isu}} = m_{{}^{A}_{Z}N} + m_e$, where $m_{{}^{A}_{Z}N}$ is the mass of the ${}^{A}_{Z}N$ nucleus and m_e is the rest mass of the electron.

For example, in the laser ablation of metal samples in an aqueous solution of uranyl, when a low-temperature plasma is formed in the vapor near the metal surface, the interaction between the plasma electrons and the ${}^{238}U$ nuclei initiates the formation of "*β*-protactinium" nuclei followed by a *β*-decay of the ${}^{238}_{91}Pa_{isu}$ nuclei that produces thorium-234 and helium-4 nuclei as the products of decay of the initial uranium-238 nucleus:

$$ {}^{238}_{92}U + e^-_{he} \rightarrow {}^{238}_{91}Pa_{isu} + \nu \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He + e^- + \nu + \tilde{\nu} + Q(4.27\ MeV). \qquad (4) $$

In this case, the effective rate constant for the initiated decays of ${}^{238}U$ nucleus increases by 9 orders of magnitude, giving rise to a kind of “e^--catalysis” [4]. The deficit ΔQ of structural energy for the formed *β*-protactinium nucleus is $\Delta Q \approx$ –3.46 MeV. An unexpected result was recorded in experiments with a beryllium sample. The beryllium nanoparticles formed in the solution after one-hour laser action showed an anomalously high rate of formation of thorium-234 nuclei for more than 500 days after the laser ablation was completed. The half-life for the nuclei initiated by the laser ablation that produce thorium-234 was 2.5 years. Naturally, this phenomenon could be associated with the accumulation of *β*-protactinium nuclei in beryllium nanoparticles in the laser ablation, which lasted as short as an hour.

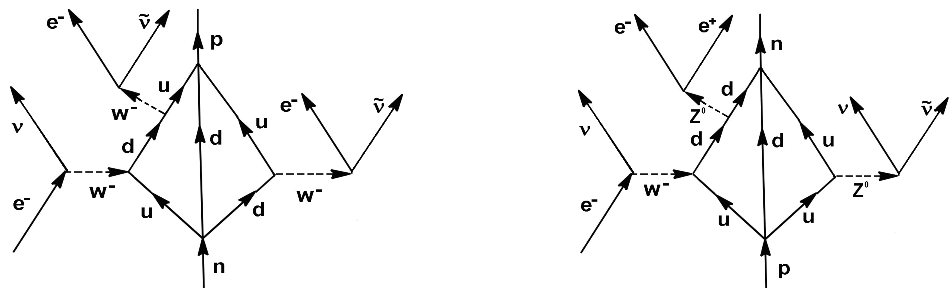
Additional examples are the β^--decay of ${}^{60}_{27}Co$, ${}^{137}_{55}Cs$ and ${}^{140}_{56}Ba$ nuclei initiated by the e^--catalysis mechanism, for which the half-life $T_{½}$ is 1925 days, 30.1 years, and 12.8 days, respectively [4], [7]:

$$ {}^{60}_{27}Co + e^-_{he} \rightarrow {}^{60}_{26}Fe_{isu} + \nu \rightarrow {}^{60}_{28}Ni + 2e^- + \nu + 2\tilde{\nu} + Q(2.82\ MeV), \qquad (5) $$

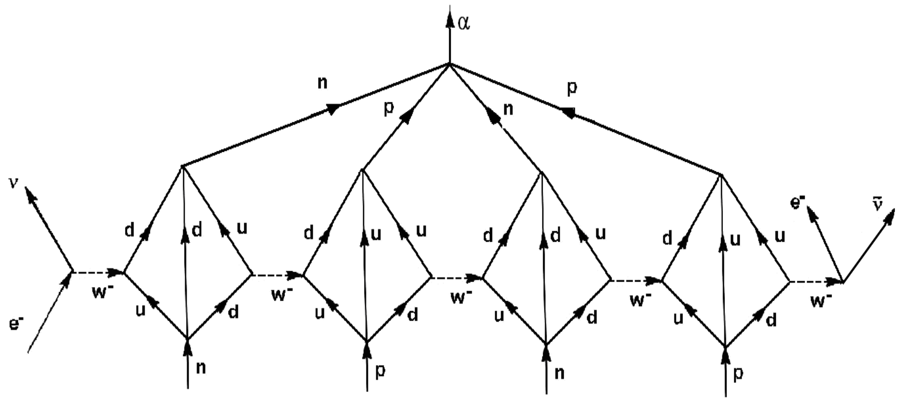
$$ {}^{137}_{55}Cs + e^-_{he} \rightarrow {}^{137}_{54}Xe_{isu} + \nu \rightarrow {}^{137}_{56}Ba + 2e^- + \nu + 2\tilde{\nu} + Q(1.18\ MeV). \qquad (6) $$

$$ {}^{140}_{56}Ba + e^-_{he} \rightarrow {}^{140}_{55}Cs_{isu} + \nu \rightarrow {}^{140}_{57}La + e^- + \nu + 2\tilde{\nu} + Q(1.05\ MeV). \qquad (7) $$

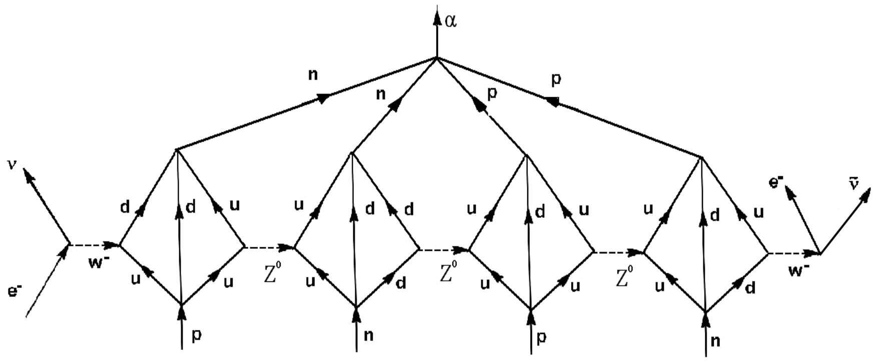
In these examples, the deficits of structural energy ΔQ, which prevent the *isu*-state ${}^{60}_{26}Fe_{isu}$, ${}^{137}_{54}Xe_{isu}$ and ${}^{140}_{55}Cs_{isu}$ nuclei from coming to the stable ground states of the nuclear matter referring to the ${}^{60}_{26}Fe$, ${}^{137}_{54}Xe$, and ${}^{140}_{55}Cs$ nuclei, is -0.237, -4.17, and -6.22 MeV, respectively. It can be expected that the initiation effect of electrons on the β^--decay of nuclei in a low-temperature plasma will be best manifested when the absolute value of structural energy deficit ΔQ for the *isu*-state nuclei to be formed is the highest. This implies that in the above cases the acceleration of radioactive decay would be clearly seen for the ${}^{137}_{55}Cs$ and ${}^{140}_{56}Ba$ nuclei and minimal for the ${}^{60}_{27}Co$ nuclei. The available experimental data [8] on the initiated decays of ${}^{137}_{55}Cs$, ${}^{140}_{56}Ba$, and ${}^{60}_{27}Co$ validate this conclusion: the half-lives of β^--active cesium-137 (30.1 years) and barium-140 nuclei (12.8 days) drop to about 380 and 2.7 days, respectively, whereas the half-life of cobalt-60, equal to 1925 days, remains practically unchanged. The Feynman diagrams for the β^--decays, positron β^+-decays, and α-decays of nuclei initiated by the e^--catalysis mechanism are plotted in Fig. 1.



a *b*



c



d

Fig. 1. Feynman diagrams for initiated (*a*) β^--decays, (*b*) β^+-decays, and (*c*, *d*) α-decay

The unexpected character of the result that the decay of a radioactive nucleus can be affected by external actions consists in the fact that this effect is associated with electrons, which cannot interact with the nucleons of the nucleus as nuclear matter fragments, but can initiate, with the help of vector W^--bosons, local shake-ups in the nucleonic structure of the nucleus. At the same time, the experiments show that the external excitation of a radioactive nucleus as a whole system (for example, by the action of γ-radiation) cannot affect the rate of radioactive decay and, hence, the above initiation of the nucleus instability. In these cases, the nuclear matter manifests itself as a whole system of interacting nucleons with their inherent individual characteristics.

Section 6 will show how the external actions of very high energy can give rise to *isu*-states in the nuclear matter, which account for the decay of nuclei.

3. POSSIBLE MECHANISMS OF NUCLEAR-CHEMICAL REACTIONS

The simplest *β*-nuclei are *β*-neutrons and *β*-dineutrons, which can be formed by the interaction of high-energy electrons with protons p^+ and deuterons d^+, respectively; for example, in the laser ablation of metals in an ordinary or heavy water, as well as in a protium- or deuteron-containing glow-discharge plasma:

$$p^+ + e^-_{he} \rightarrow {}^1n_{isu} + \nu, \qquad (8)$$

$$d^+ + e^-_{he} \to {}^2n_{isu} + \nu . \qquad (9)$$

If the half-lives $T_{1/2}$ of these β-nuclei are sufficiently long, the neutral nuclei ${}^1n_{isu}$ and ${}^2n_{isu}$, which are characterized by the baryon numbers equal to one and two, the rest masses equal to the masses of the hydrogen atom and deuterium, respectively, and by zero lepton charges, can be efficiently involved in various nuclear processes [4]-[7], [13].

Analysis of experimental data on the synthesis of tritium nuclei t^+ in the laser ablation of metals in a heavy water shows that the half-life $T_{1/2}$ of the β-dineutron decay,

$${}^2n_{isu} \to d^+ + e^- + \tilde{\nu} \; , \qquad (10)$$

which produces a deuteron, electron, and antineutrino, is rather long, at least, tens of minutes [13]. It was assumed that the synthesis occurs by the interaction between a tritium nucleus t^+ and nucleus ${}^2n_{isu}$:

$$d^+ + {}^2n_{isu} \to t^+ + n + Q(3.25 MeV) , \qquad (11)$$

where n stands for a neutron. This is accompanied by another process:

$$d^+ + {}^2n_{isu} \to {}^3_2He + n + e^- + \tilde{\nu} + Q(3.27 MeV) , \qquad (12)$$

which is a result of the weak nuclear interaction.

The authors [13] also postulated that the interaction between electrons and a tritium nuclei t^+ may produce a hypothetical β-trineutron ${}^3n_{isu}$:

$$t^+ + e^-_{he} \to {}^3n_{isu} + \nu . \qquad (13)$$

The rest mass of the neutral nucleus ${}^3n_{isu}$ was assumed to be equal to the rest mass of the tritium atom. It is the formation of ${}^3n_{isu}$ that the initiated decay of tritium nuclei in the laser ablation of metals in aqueous media and the synthesis of tritium nuclei can pass through [13]:

$$t^+ + e^-_{he} \to {}^3n_{isu} + \nu \to {}^3_2He + 2e^- + \nu + 2\tilde{\nu} + Q(0.019 MeV) . \qquad (14)$$

It should be noted that the half-life $T_{1/2}$ of ${}^3n_{isu}$ in the e^--catalysis is of the same order of magnitude as that of ${}^2n_{isu}$, which is many orders of magnitude shorter than the half-life of the tritium nucleus ($T_{1/2}$ = 12.3 years) [13].

It is shown in [5] that the introduced concept of a β-nuclei with a rather long lifetime formed in the glow discharge in a deuterium-containing gas makes it possible to physically interpret a group of data [9],[10] on the initiated radioactive decay of W nuclei in the surface layers of a tungsten cathode (foil). Note that although 5 isotopes of tungsten (${}^{180}_{74}W$, ${}^{182}_{74}W$, ${}^{183}_{74}W$, ${}^{184}_{74}W$, ${}^{186}_{74}W$) are potentially α-radioactive nuclei,

$${}^A_{74}W \to {}^{A-4}_{72}Hf + {}^4_2He + Q_A , \qquad (15)$$

they are usually considered as stable isotopes because of an anomalously large period of their half-life, $T_{1/2} \approx 10^{17} - 10^{19}$ years, which is many orders of magnitude greater than the lifetime of the Universe. The values of heat release Q_A in the radioactive α-decay of tungsten nuclei with mass numbers A equal to 180, 182, 183, 184, and 186, is 2.52, 1.77, 1.68, 1.66, and 1.12 MeV, respectively. Based on the energy consideration alone, one can admit that there are α-decays producing several α particles for the above stable isotopes of tungsten, including the decay producing nine α particles for the tungsten-180 isotope.

The concept dealing with the formation of metastable *isu*-state nuclei that we are developing distinguishes three mechanisms for initiated nuclear conversions, including radioactive decays of nuclei:

1. *Mechanism of nuclear fusion*. The neutral particles ${}^{A}n_{isu}$ (A = 1, 2, 3) with long enough lifetimes formed in a low-temperature plasma can diffuse along grain boundaries deep into the cathode and interact with the metal (tungsten) nuclei in the cathode surface layers. In this case, the interaction and fusion of ${}^{2}n_{isu}$ nuclei with ${}^{A}_{74}W$ isotopes can give rise to excited ${}^{A+2}_{74}W^{*}$ nuclei at the first process step. In addition to the overall excitation energy, indicated by the asterisk, equal to about 10 MeV relative to the stable ground state of these nuclei, their nuclear matter due to their fusion with ${}^{2}n_{isu}$ can be partially in an unbalanced *isu*-state with a lost stability in the nucleus bulk. All of this causes the resulting conversions accompanied by the emission of α particles and daughter isotopes. Note that in contrast to the nuclear reactions that occur in the collision of reactants in the gaseous phase, the energy factor alone due to the possible effect of the environment is enough to effectuate the above nuclear conversions in the region of grain boundaries of the solid metal phase, with the unmatched spins and parities of the colliding and resulting nuclei.

Experimental works studying the conversions in the glow discharge in a deuterium-containing gas recorded the formation of new elements in the surface layer of the tungsten cathode after it was treated by the plasma for 4 to 7 hours, which include not only stable isotopes of erbium, ytterbium, lutetium and Hafnium, but also radioactive isotopes of ytterbium and hafnium [9], [10]. While the formation of the stable isotopes could be assumed to be related to the diffusion of impurity elements from the cathode bulk to its surface treated by the plasma, the formation of the radioactive isotopes definitely points to the radioactive decay of tungsten isotopes. As all possible reactions for the initiated decay of various tungsten isotopes are already reported [5], only a few examples are given below for illustration:

$${}^{180}_{74}W + {}^{2}n_{isu} \to {}^{169}_{70}Yb + {}^{9}_{4}Be + {}^{4}_{2}He + 2e^{-} + 2\tilde{\nu} + Q\,(10.09\ MeV), \qquad (16)$$

$${}^{182}_{74}W + {}^{2}n_{isu} \to {}^{171m}_{70}Yb + {}^{9}_{4}Be + {}^{4}_{2}He + 2e^{-} + 2\tilde{\nu} + Q\,(10.34\ MeV), \qquad (17)$$

$${}^{182}_{74}W + {}^{2}n_{isu} \to {}^{180m}_{72}Hf + {}^{4}_{2}He + Q\,(10.26\ MeV), \qquad (18)$$

$${}^{184}_{74}W + {}^{2}n_{isu} \to {}^{178}_{70}Yb + 2\,{}^{4}_{2}He + Q\,(12.28\ MeV). \qquad (19)$$

In (16) - (19) it is taken into account that in addition to the major masses 169 to 180, the mass spectra of the products recorded the birth and growth of the peak of mass 9. It should be noted that the absence of the basic mass 4, corresponding to helium nuclei, in the mass spectra recorded in [9], [10] can be attributed to the extremely low solubility of helium in tungsten [19] and the high diffusivity of helium in the zone between the boundaries of foil grains. It is obvious that these transport processes can be accomplished only when the lifetime of ${}^{2}n_{isu}$ is long enough for the diffusive transport of these neutral nuclei along the foil grain boundaries to surface layers. This agrees with the conclusion that this time must be no less than tens of minutes for the synthesis of tritium in the laser ablation of metals in a heavy water [13].

2. *Mechanism of e^{-}-catalysis*.

The above consideration implies that there may be another way of initiating the α-decay of tungsten isotopes in a glow discharge in experimental studies, when electrons with kinetic energy E_e ~ 3-5 eV interact directly with stable isotopes of tungsten in the e^--catalysis. Possible examples of these processes are given below:

$$ {}^{183}_{74}W + e^- \rightarrow {}^{183}_{73}Ta_{isu} + \nu \rightarrow {}^{175}_{71}Lu + 2{}^{4}_{2}He + 2e^- + 2\tilde{\nu} + \nu + Q(3.96 MeV), \quad (20) $$

$$ {}^{186}_{74}W + e^- \rightarrow {}^{186}_{73}Ta_{isu} + \nu \rightarrow {}^{174}_{70}Lu + 3{}^{4}_{2}He + 3e^- + 3\tilde{\nu} + \nu + Q(7.17 MeV). \quad (21) $$

It should be noted that the concept of e^--catalysis can be helpful in understanding the formation of much less than all new isotope products recorded in experiments. Therefore, the processes with ${}^{2}n_{isu}$ nuclei are considered as basic for the initiated decays of *W* stable isotopes.

The above data allow one to state that the nuclear decay of initially non-radioactive tungsten isotopes accompanied by the formation of lighter elements (erbium, lutetium, ytterbium, hafnium), which is initiated in a low-temperature plasma (glow discharge), can be considered as a new type of artificial radioactivity, which is different from the artificially induced radioactivity initiated by nuclear reactions (e.g., by bombardment with alpha particles or neutrons, giving rise to radioisotopes). It should be remembered that the stable isotopes of many nuclei, from neodymium to bismuth, including a tantalum-181 isotope, for which initiated decays similar to those described above are also recorded [9], [10], are potentially *α*-radioactive in the same sense as tungsten isotopes.

3. *Harpoon mechanism.*

The reactions between multi-electron atoms are of highest complexity for understanding the mechanism of low-energy nuclear processes. These processes are usually considered in the study of transformation processes in native systems [20]-[22]. It was recently shown [23], however, that reactions of this type can occur in the initiation of self-propagating high-temperature synthesis (SHS) [24]. The composition of the condensed products of thermite powder mixture (Al + Fe_2O_3) combustion in air was studied [23]. The purity of the initial materials was 99.7 to 99.9 mass %. It was shown that in the combustion of iron-oxide aluminum thermites with a flame temperature higher than 2800 K, 0.55 mass % of stable calcium is formed. The initial thermite powder systems (Al + Fe_2O_3) did not contain any calcium. According to [23], the calcium could be formed in the following nuclear reactions:

$$ {}^{27}_{13}Al + {}^{14}_{7}N \rightarrow {}^{41}_{20}Ca + Q(21.8 MeV), \quad (22) $$

$$ {}^{27}_{13}Al + {}^{14}_{7}N \rightarrow {}^{40}_{20}Ca + n + Q(12.44 MeV). \quad (23) $$

The formation of calcium in the experiments [23] implies that the temperature of electrons in the flame of combustion of iron-oxide aluminum thermites in air can be much higher than the flame temperature estimated using the energy of atoms and ions. It is the case that is typical for the low-temperature plasma in a glow discharge. In this case, the interaction of high-energy electrons with nuclei ${}^{27}_{13}Al$ and ${}^{14}_{7}N$ could produce nuclei ${}^{27}_{13}Mg_{isu}$ and ${}^{14}_{6}C_{isu}$, respectively. Among these nuclei, the nucleus ${}^{27}_{13}Mg_{isu}$ shows the highest activity in the nuclear interactions because the deficit of its energy relative to the nucleus ${}^{27}_{13}Mg$ is ΔQ = - 2.61 *MeV*, whereas the energy deficit for the nucleus ${}^{14}_{6}C_{isu}$ is much less, ΔQ = -0.16 *MeV*.

Following [7], assume that when the nucleus of an atom, or ion is in a pre-decay metastable *isu*-state (supposedly, ${}^{27}_{13}Mg_{isu}$), the lability of its electron subsystem is higher and it is likely that this subsystem can partially overlap the electron subsystems of the neighboring atoms (specifically, the nitrogen atom). It is obvious that the high values of energy release in the overall processes (22) and (23) should act as the factor initiating the spin-spin interaction of the electron subsystems of both atoms and the formation of common "molecular" orbitals with the correcting action of spin electron-nuclear interactions for each atom. The emerging bonds bring both atoms closer to each other, and the formation of common orbitals is more intense as the nuclei are brought closer to each other. This brings about a kind of "harpoon mechanism" in which the atom with an *isu*-state nucleus captures the adjacent atom. The complete integration of the electron subsystems of both atoms initiates the fusion of the nuclear matter of the *isu*-state nucleus (${}^{27}_{13}Mg_{isu}$) and the adjacent nucleus (${}^{14}_{7}N$). In this case, the overall processes can be written as

$$ {}^{27}_{13}Al + {}^{14}_{7}N + e^{-}_{he} \rightarrow {}^{41}_{20}Ca + e^{-} + \nu + \tilde{\nu} + Q(21.8MeV)\,, \qquad (22a)$$

$$ {}^{27}_{13}Al + {}^{14}_{7}N + e^{-}_{he} \rightarrow {}^{40}_{20}Ca + n + e^{-} + \nu + \tilde{\nu} + Q(12.44MeV)\,. \qquad (23a)$$

Earlier, the harpoon mechanism was considered for the nuclear transmutations in native systems [7].

Because weak nuclear interactions are involved in the formation of the nuclear matter in the final nucleus as a set of interacting nucleons, a significant part of the energy can also be released by emitting neutrinos and antineutrinos when the final nucleus can be formed in the ground state, obeying the spin and parity conservation laws. At the same time, when the final nuclei are formed in the excited state, the non-ionizing radiation of neutrinos and antineutrinos will be accompanied by the emission of X-rays or gamma quanta. These X-rays were already reported experimentally [23].

The above phenomenological analysis shows that in order to understand the mechanism of nuclear transformations observed in the burning of thermite mixtures, of great importance is the development of new theoretical approaches to simulating the dynamics of nuclear processes on the basis of quantum-chemical analysis rather than estimating the quantum mechanical probabilities of some processes. This simulation will involve (1) calculations of the electron structure of an atom when *isu*-state nuclei with a shaken-up nucleonic structure are formed; (2) model calculations of the spatial instability of the atom electron subsystem, which is caused by the loss of the nucleus stability; (3) calculations of the overlapping of these "mobile" orbitals with the electron orbitals of the adjacent atoms and formation of molecular orbitals that initiate the approach and fusion of the corresponding nuclei. Analysis of the nuclear radioactive decay may require the discrete Kramers' activation mechanism ("roaming" over energy levels to reach a certain boundary) [25], which is commonly used in the physicochemical kinetics. Here we imply the dynamics of energy accumulation by an unstable *isu*-state nucleus on its "last" bond, the disruption of which leads to the decay of the nucleus along a certain path.

4. NUCLEAR CHEMICAL PROCESSES IN ANDREA ROSSI'S E-CAT REACTOR

The above concept of initiating low-energy nuclear-chemical reactions by the mechanisms of nuclei fusion and e^{-}-catalysis can be used to physically interpret the results of testing A. Rossi's energy E-Cat reactors as well [26]. Let us briefly discuss the results of testing the E-Cat working chamber of the Rossi's reactor, presented by a group of international experts [27]. The working chamber was a hollow ceramic cylinder 2 cm in diameter and 20 cm long, into which the researchers loaded a fuel: about 0.9 g of finely dispersed nickel powder with all stable isotopes present ($^{58}_{28}Ni$, $^{60}_{28}Ni$, $^{61}_{28}Ni$, $^{62}_{28}Ni$, and $^{64}_{28}Ni$ of 67, 26.3, 1.9, 3.9 and 1 %, respectively), and 0.1 g of $LiAlH_4$ powder ($^{6}_{3}Li$ and $^{7}_{3}Li$ isotopes of 8.6 and 91.4%, respectively). The cylinder was sealed and then heated. The tests were carried out for 32 days at chamber heating temperatures up to 1260 ºC (first half of the time) and 1400 ºC (second half of the time). The energy released in the tests was measured using the value of the heat flux produced by the chamber. In the tests, the overall excess energy of 1.5 MWh was produced, corresponding to the chamber efficiency higher than 3.5. The researchers recorded changes in the isotopic composition of the main fuel components (nickel, lithium), for which the initial composition of stable elements was close to the tabulated natural composition. After the tests, the isotopic composition of the recorded components was dramatically changed: almost all nickel powder, more than 98%, was a nickel-62 isotope (about 4% initially); the fraction of lithium-7 dropped to about 8% and lithium-6 jumped to about 92%. The isotope abundances of the initial fuel and final "ash" in the tests are listed in Table 1 [27].

Table 1. Isotope abundances for the initial fuel and final ash in the tests [27]

Ion	Fuel		Ash		Natural abundance [%]
	Counts in peak	Measured abundance [%]	Counts in peak	Measured abundance [%]	
$^{6}Li^{+}$	15804	8.6	569302	92.1	7.5
$^{7}Li^{+}$	168919	91.4	48687	7.9	92.5
$^{58}Ni^{+}$	93392	67	1128	0.8	68.1
$^{60}Ni^{+}$	36690	26.3	635	0.5	26.2
$^{61}Ni^{+}$	2606	1.9	~0	0	1.8
$^{62}Ni^{+}$	5379	3.9	133272	98.7	3.6
$^{64}Ni^{+}$	1331	1	~0	0	0.9

According to the above concept, the recorded change in the isotopic composition of main fuel components, nickel and lithium, in the presence of the hydrogen given off in the decomposition of $LiAlH_4$ at the above temperatures may be caused by the formation of a protium-containing plasma in the reaction volume and the occurrence of neutral metastable nuclei $^{1}n_{isu}$. Like neutrons, these neutral nuclei can interact with the nuclei of elements constituting the fuel, accounting for the changes occurring in its elemental and isotopic composition, which is accompanied by the corresponding energy release:

$$^{7}_{3}Li + ^{1}n_{isu} \rightarrow 2^{4}_{2}He + e^{-} + \tilde{\nu} + \nu\tilde{\nu} + Q(17.35 MeV), \quad (24)$$

$$^{27}_{13}Al + ^{1}n_{isu} \rightarrow ^{4}_{2}He + ^{24}_{12}Mg + e^{-} + \tilde{\nu} + \nu\tilde{\nu} + Q(1.60 MeV), \quad (25)$$

$$^{27}_{13}Al + ^{1}n_{isu} \rightarrow ^{28}_{14}Si + e^{-} + \tilde{\nu} + \nu\tilde{\nu} + Q(11.58 MeV), \quad (26)$$

$$^{58}_{28}Ni + ^{1}n_{isu} \rightarrow ^{4}_{2}He + ^{55}_{25}Mn + e^{+} + \nu + \nu\tilde{\nu} + Q(2.35 MeV), \quad (27)$$

$$^{60}_{28}Ni + ^{1}n_{isu} \rightarrow ^{4}_{2}He + ^{57}_{26}Fe + \nu\tilde{\nu} + Q(0.47 MeV), \quad (28)$$

$$^{61}_{28}Ni + ^{1}n_{isu} \rightarrow ^{4}_{2}He + ^{58}_{26}Fe + \nu\tilde{\nu} + Q(2.80 MeV), \quad (29)$$

$$^{62}_{28}Ni + ^{1}n_{isu} \rightarrow ^{4}_{2}He + ^{59}_{27}Co + e^{-} + \tilde{\nu} + \nu\tilde{\nu} + Q(0.34 MeV), \quad (30)$$

$$^{64}_{28}Ni + ^{1}n_{isu} \rightarrow ^{65}_{29}Cu + e^{-} + \tilde{\nu} + \nu\tilde{\nu} + Q(7.45 MeV), \quad (31)$$

The above list of reactions implies that the specific (per component unit mass) energy release is the highest for the lithium-7 nuclei. At the same time, when the mass fraction of the lithium-7 isotope in the system is low, the total contribution to the heat release of the nuclear reactions of ${}^{1}n_{isu}$ nuclei with all other fuel elements, such as aluminum and nickel isotopes, can become dominating. The almost complete disappearance of isotopes ${}^{7}_{3}Li$ and ${}^{58}_{28}Ni$ in the ashes, which was recorded after the chamber was tested for more than a month, implies that the values of rate constants are rather high not only for the processes (24) and (27), but also for the other nuclear processes in which the new chemical elements are formed.

To understand the specific mechanisms accounting for the major changes in the fuel composition during the E-Cat operation, including the almost complete exhaustion of the lithium-7 isotope and the dominant growth of the nickel-62 isotope in the ash, it is necessary to consider the other nuclear reactions, which can also change the isotopic composition of the initial nickel. In these reactions, the energy carried away by the formed neutrinos and antineutrinos can noticeably reduce their heat releases, as compared to the above reactions:

$$ {}^{58}_{28}Ni + {}^{1}n_{isu} \rightarrow {}^{59}_{28}Ni + \nu\tilde{\nu} + Q(8.22 MeV), \quad T_{1/2}({}^{59}_{28}Ni) = 7.6 \cdot 10^{4}\, yr\,, \tag{32}$$

$$ {}^{60}_{28}Ni + {}^{1}n_{isu} \rightarrow {}^{61}_{28}Ni + \nu\tilde{\nu} + Q(7.04 MeV),, \tag{33}$$

$$ {}^{61}_{28}Ni + {}^{1}n_{isu} \rightarrow {}^{62}_{28}Ni + \nu\tilde{\nu} + Q(9.81 MeV),, \tag{34}$$

$$ {}^{62}_{28}Ni + {}^{1}n_{isu} \rightarrow {}^{63}_{28}Ni + \nu\tilde{\nu} + Q(6.05 MeV), \quad T_{1/2}({}^{63}_{28}Ni) = 100.1 yr\,, \tag{35}$$

$$ {}^{64}_{28}Ni + {}^{1}n_{isu} \rightarrow {}^{65}_{28}Ni + \nu\tilde{\nu} + Q(5.32 MeV), \quad T_{1/2}({}^{65}_{28}Ni) = 2.52 h\,, \tag{36}$$

The long half-life of the ${}^{59}_{28}Ni$ isotope practically excludes the process in which the other nickel isotopes decayed in the tests are “replenished” with the ${}^{58}_{28}Ni$ isotope, whose fraction is twice the fractions of the other nickel isotopes. Therefore, the almost complete absence of the ${}^{60}_{28}Ni$ isotope in the ash should be attributed to the processes (28) and (33). It can also be assumed that the processes (29) and (34) account for the disappearance of the ${}^{61}_{28}Ni$ isotope in the ash; meanwhile, the process (34) brings the isotope ${}^{62}_{28}Ni$ to the ash, providing its prevailing abundance among the other nickel isotopes in the ash. The additional contribution to this prevailing abundance is made by the “low” value of rate constant for the decline of the ${}^{62}_{28}Ni$ isotope in the reaction (30), which describes the formation of cobalt with a low energy release in the process. It is also important to note that the long half-life of the ${}^{63}_{28}Ni$ isotope practically prevents from increasing the abundance of the isotope ${}^{64}_{28}Ni$ in the ash, and the process (31) provides an almost complete conversion of this isotope in the initial nickel to the copper-65 isotope.

Admittedly, the above arguments can only qualitatively explain the ash composition recorded in the test. In this case, of high interest could be a comparative study of the elemental and isotopic composition of the ash and initial fuel by inductively coupled plasma mass spectrometry [28], successfully used before for studying the isotopic composition of impurities in the nickel in the laser ablation of a nickel sample in water. Here, it is important to study the changes in isotope ratios for various elements in the ash and initial fuel, primarily for the base element (nickel), as well as for the elements formed in the processes (24) - (31), such as magnesium, silicon, manganese, iron, cobalt, and copper.

5. TIME VARIATION OF THE $^{234}U/^{238}U$ ACTIVITY RATIO IN GROUND-WATER FLOW SYSTEMS

One of the manifestations of the above-described initiated ^{238}U nucleus decays is the well-known time variation of the basic, close to unity, ratio of the activity levels of uranium-234 and uranium-238 involved in the same decay chain of radioactive transformations (uranium/radium series) in the surface ground waters of seismic and volcanic regions [29]-[31]. The activity η_i, introduced as the decay rate of the *i*-th uranium isotope, is defined as $\eta_i = k_i N_i$, where k_i and N_i are the decay rate constant and the number of *i*-th isotope nuclei to be decayed, respectively. Note that the fraction θ_i of the uranium-234 isotope in natural uranium ores is as low as $\theta_{234} \approx$ 0.0055%, with a half-life $T_{1/2}(^{234}U) \approx$ 2.45·10^5 years. At the same time, the fraction of the uranium-238 isotope is $\theta_{238} \approx$ 99.3%, yielding $\chi \equiv \theta_{234}/\theta_{238} \approx 5.54 \cdot 10^{-5}$, with a much longer half-life $T_{1/2}(^{238}U) \approx$ 4.47·10^9 years. The corresponding decay rate constants are related by the formula $k_{234} = k_{238} \cdot \chi^{-1}$.

It means [30] that in undisturbed minerals older than several million years, the abundances of ^{238}U and its intermediate α-decay product, ^{234}U, reach a state of secular equilibrium. Under these conditions, the activity ratio (AR), $\eta_{234}/\eta_{238} = \dfrac{T_{1/2}(^{238}U)\,\theta_{234}}{T_{1/2}(^{234}U)\,\theta_{238}} \equiv {^{234}U}/{^{238}U}\,\mathrm{AR}$, will equal unity. However, natural waters, especially in seismically active regions, typically are enriched in ^{234}U with $^{234}U/^{238}U\,\mathrm{AR}$ between 1 and 10 [30]. The uranium concentrations and $^{234}U/^{238}U\,\mathrm{AR}$ ratios in saturated-zone and perched ground waters were used to study the hydrologic flow in the vicinity of Yucca Mountain [30]. The *U* data were obtained by thermal ionization mass spectrometry for more than 280 samples from the Death Valley regional flow system. Wide variations in both U concentrations (commonly 0.6–10 μg l^{-1}) and $^{234}U/^{238}U\,\mathrm{AR}$ (commonly 1.5–6) were observed on both local and regional scales. The ground water beneath the central part of Yucca Mountain had intermediate U concentrations but a distinctive $^{234}U/^{238}U\,\mathrm{AR}$ of about 7–8. It is necessary to add that about 600 seismic events have occurred near the site in the last 20 years alone, with a 5.6-magnitude earthquake that happened as recently as 1992. There is also an evidence of relatively recent volcanic activity in the area.

Similar results were reported elsewhere [31], where the measurements of the $^{234}U/^{238}U\,\mathrm{AR}$ in groundwater samples were used for monitoring the current deformations in the active faults at the Kultuk polygon, West Shore of Lake Baikal, for earthquake prediction. It was observed that the $^{234}U/^{238}U\,\mathrm{AR}$ fluctuated in time, with the duration of cycles and amplitudes of $^{234}U/^{238}U\,\mathrm{AR}$ fluctuations were variable in the range of 1.5-3.3, and the cycles of $^{234}U/^{238}U\,\mathrm{AR}$ in water were synchronized in the lines of the monitoring stations in the sublatitudinal and submeridional direction at the time intervals when seismic shocks occurred at the Kultuk polygon. The U concentrations in the ground-water samples of the Kultuk polygon ranged from 0.0087 to 5 mcg/l. The basic scenario of $^{234}U/^{238}U\,\mathrm{AR}$ variations in groundwater, recorded in the Kultuk polygon during the monitoring session, was examined in connection with the seismogenic activation of the western end of the Obruchev fault.

It is commonly believed that ^{234}U enters solutions preferentially as a result of several mechanisms related to its origin by radioactive decay of ^{238}U [30]. These mechanisms include damage of crystal-lattice sites containing ^{234}U and the preferential release of ^{238}U not bound to the crystal lattice from the defects of minerals, as well as direct ejection of the recoil nucleus into the water near the boundaries of mineral grains.

At the same time, the results of [29]-[31] suggest that the mechanochemical processes in relatively small volumes of uranium ore in ore deposits located in the geologically active, including seismically and volcanically active, zones of the Earth's crust are the important factor that can account for the significant changes of ${}^{234}U/{}^{238}U$ AR under study [31]. These zones can be characterized by the emergence of high mechanical stresses, initiated shifts in the ore, and the formation of cracks and fissures. These processes in the U ore at high local mechanical pressures can not only change the structure of groundwater flows in the zone, but also give rise to high local electric fields and initiate the decomposition of water molecules and the formation of high-energy (on chemical scales) electrons. In this case, the concept developed in this paper allows us to expect that the formation of cracks and fissures in a uranium ore can initiate the radioactive decay of uranium-238 nuclei by the e^--catalytic mechanism, producing *isu*-state β-protactinium nuclei. Note that it is the phenomenon of mechanically activated nuclear processes discovered in the works of Deryagin et al. [32], [33] that can be regarded as the starting point in the new stage of studying LENRs, which is usually attributed to the work of Fleischmann and Pons [34]. For instance, it was experimentally recorded that the destruction of targets made of a heavy (D_2O) ice by a metal striker with an initial velocity of 100–200 m/s produces neutrons, and their number is several times higher than the background level [32]. In contrast, no new neutrons were recorded when the same action was applied to the target made of an ordinary (H_2O) ice.

Assume that when a fissure is formed, a fraction of uranium atoms leaves the fissure surface layer of the uranium ore and is dissolved in the aqueous phase, with each isotope dissolved according to its abundance in the ore. Additionally, assume that a very small fraction ξ (ξ << 1) of N_{238} nuclei of the main uranium-238 isotope that pass to the aqueous medium is activated in the fissure formation by the e^--catalytic mechanism and converted to *isu*-state β-protactinium nuclei. Without this activation, the activity level of N_{238} nuclei of the atoms of uranium-238 isotope in the aqueous medium, $\eta_{238} = k_{238}N_{238}$, was equal to the activity level $\eta_{234} = k_{234}N_{234}$ for the N_{234} nuclei of uranium-234 isotope that passed to the aqueous medium. Section 2 implies that in the initiated radioactive decay, the effective decay rate constant of ${}^{238}U$ nuclei, $\tilde{k}_{238}$, for a relatively small number ξ of N_{238} nuclei in the aqueous medium can dramatically change. It is wise to use the above in considering the simplified decay of uranium-238 and uranium-234 isotopes. In this case, the decay of "intermediate" thorium-234 and protactinium-234*m* isotopes with short lifetimes, which are also involved in the radioactive uranium/radium series, is taken out of consideration. The balance equations for the numbers of N_{238} and N_{234} nuclei at a steady-state concentration of uranium-234 isotope in the aqueous medium can be written as

$$\frac{dN_{238}}{dt} = -k_{238}(1-\xi)N_{238} - \xi\tilde{k}_{238}N_{238} = -k_{238}^{eff}N_{238}, \qquad (37)$$

$$\frac{dN_{234}}{dt} = -k_{234}N_{234} + k_{238}(1-\xi)N_{238} + \xi\tilde{k}_{238}N_{238} = 0. \qquad (38)$$

Here,

$$k_{238}^{eff} = k_{238}\left[1+\xi\left(\frac{\tilde{k}_{238}}{k_{238}}-1\right)\right] \quad (39)$$

is the effective rate constant for the decay of the uranium-238 isotope when the radioactive decay of the fraction ξ of uranium-238 nuclei is initiated by external factors and characterized by the decay rate constant $\tilde{k}_{238}$. Equations (37)-(38) yield the desired formula for the ratio of activity levels of uranium-234 and uranium-238 isotopes in open systems in which the initiated accelerated decay of uranium-238 is effectuated:

$$\eta_{234}/\eta_{238} = \frac{k_{234}\,N_{234}}{k_{238}\,N_{238}} = {}^{234}U/{}^{238}U\ \mathrm{AR} = 1+\xi\left(\frac{\tilde{k}_{238}}{k_{238}}-1\right). \quad (40)$$

In this case, the apparent higher activity level of the uranium-234 isotope cannot be attributed to the fact that the groundwater is directly enriched with ${}^{234}U$ nuclides because its release to the aquatic medium is easier due to the decay of the main ${}^{238}U$ isotope, as is usually assumed [30], [31]. The increased content of ${}^{234}U$ nuclei in the aqueous medium is a result of the decay of ${}^{238}U$ nuclei initiated by the formation of cracks and fissures, which produces β-protactinium nuclei by the e^--catalytic mechanism; their release to the aqueous medium, and their subsequent decay along the chain of the radioactive uranium/radium series. The reference value of $\tilde{k}_{238}/k_{238} \sim 10^9$ estimated in [4], showing a possible increase by 9 orders of magnitude of the decay rate constant for the ${}^{238}U$ nuclei in the laser ablation, implies that for the ratios ${}^{234}U/{}^{238}U$ AR ~ 5-10, characteristic for the system studied in [30], to take place the fraction ξ of activated ${}^{238}_{91}Pa_{isu}$ nuclei relative to ${}^{238}U$ nuclei in the aqueous media must be ~ $(0.5\text{-}1)\cdot 10^{-8}$.

Subsequent experiments can show how, based on the mechanically activated decay processes of uranium-238, new energy technologies can be created with a controlled supply of nuclear “fuel” in the ${}^{238}_{91}Pa_{isu}$ form to a reactor system.

6. NON-BARYONIC STATES OF NUCLEAR MATTER AND “HEAVY” QUARKS

It is well known that quarks as subunits of hadrons manifest themselves as free point objects in the energy and momentum transfer in the proton collisions occurring in the colliding beams with characteristic energies of more than 1 TeV for each pair of the colliding nucleons [35], [36]. As a result, the quarks can be associated with the independent degrees of freedom of nuclear matter. When the decays of excited hadrons that were formed in these high-energy collisions of particles are considered, the quarks are traditionally regarded as *elementary particles* with “point” electric charges of –1/3 *e* or +2/3 *e*, where *e* is the absolute value of the electron charge. It is as such particles that the quarks are involved in the Standard Model of Elementary Particles [36].

In this section, the concept stating that non-nucleonic *isu*-states may occur in the nuclear matter will be used in considering a set of problems arising in the study of decays of the excited baryons and mesons that were formed in the high-energy collisions of protons and characterized by highly excited states of “decay”. Their characteristic half-lives are quite long, ~10^{-13}-10^{-8} s, which implies the dominant role of weak nuclear interactions in these decays. These times are higher than the characteristic nuclear times by 10 or more orders of magnitude. According to the Standard Model [36], [37], in addition to *u*- and *d*-quarks, which are characterized by the so-called current quark masses of 2.3 and 4.8 MeV/c^2, respectively, the excited hadrons contain heavier *s*-, *c*-, and *b*-quarks with current quark masses of 95, 1275, and 4180 MeV/c^2, respectively [37]. When there is, at least, one heavy quark among the three quarks of a baryon, the baryon is called heavy. The mesons formed by a quark-antiquark pair are called heavy when the quark is heavy.

When the decay of heavy hadrons is discussed, an accent is usually made on purely formal aspects related to the classification of quarks in the Standard Model of Elementary Particles [36], which is based on the requirements of symmetry for the wave functions of baryons as fermions and mesons as bosons with regard for the quantum numbers additively introduced for heavy quarks. This allows one to predict possible decay paths for the heavy hadrons to be formed, using a given set of their quantum numbers. However, the nature of the introduced new quantum numbers, defined as *s* (strange), *c* (charmed), and *b* (beauty or bottom), remains unclear. It is not clear what kind of physically interpreted parameters can account for the above differences in the masses of heavy quarks. In addition, it is unclear how each of the heavy quarks is converted to light *u*- or *d*-quarks in the decay of heavy hadrons, because the hadron-products formed in the high-energy collisions of protons or nuclei contain only light *u*- or *d*-quarks. There is no discussion yet about the nature of the confinement of quarks, defined as the impossibility of separating quarks from the nuclear matter and studying them in a free state. Instead, an assumption is made that the force of mutual attraction of quarks rises as the distance between them increases, without any discussion about the nature of this force.

It is suggested in this study that the above problems can be studied in terms of the phenomenological approach (qualitatively rather than quantitatively) if it is assumed that quarks are not elementary particles but kinetic markers, three for baryons and two for mesons, for the large fragments of the nuclear matter, which are bound to each other by the strong nuclear interaction effectuated by the exchange of pions. It is these interactions that account for the confinement of quarks as quasi-particles. In addition, assume that the highly excited hadrons, such as charged baryons p^*, neutral baryons n^*, and mesons m^*, which are formed in the collisions of high-energy particles, lose their stability, which is provided by the exchange of pions, because of the relative high-energy movements of the current quarks, and come to an *isu*-state of decay. The subsequent relaxation of the *isu*-state of such excited hadrons and the formation of decay products, such as nucleons, pions, and leptons, are initiated by the weak nuclear interaction between the quarks found in the hadrons using the formation and absorption of gauge vector bosons.

Let us consider a working hypothesis, assuming that highly excited heavy baryons and mesons are particles with local soliton-like excited states of nuclear matter that can be based only on *u*- and *d*-quarks, the corresponding $\tilde{u}$ - and $\tilde{d}$ -antiquarks, and virtual pions and vector bosons. We will try to understand whether it is possible to hypothetically identify the degrees of freedom, which can be defined as heavy quarks, in the excited system. Here, it is implied that the polarization of the nuclear medium in the vicinity of its quarks could effectively cause an increase in the current masses of the *u*- and *d*-quarks, converting them to heavy quarks.

To date, the researchers have discovered many types of decays of excited baryons, including those producing both neutral and charged particles at intermediate stages, which leads to a wide variety of final neutral and charged particles, such as nucleons, pions, and leptons [36], [37]. Consider several examples of the decay of excited nucleons n^* and p^*, parenthesizing the hyperon (heavy baryon) that decayed to form the products of interest. Let it be hyperons $\Lambda(uds)$, $\Lambda_c^+(udc)$, $\Sigma_c^0(ddc)$ and $\Lambda_b^0(udb)$, containing *s*-, *c*-, и *b*-quarks. These quarks are symbolically shown in the parenthesized quark composition of the hyperons. The processes below show the intermediate and final decay products for these hyperons, with two possible decay paths for the hyperon Λ:

$$n^*(\Lambda) \to p + \pi^- , \tag{41}$$

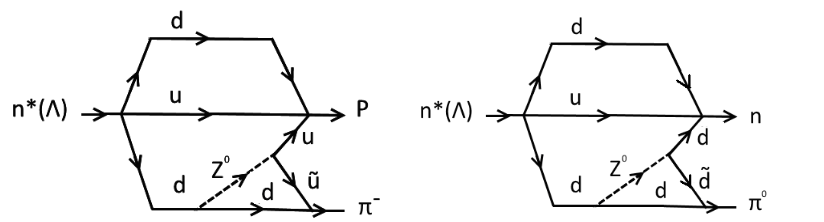
$$n^*(\Lambda) \to n + \pi^0 , \tag{42}$$

$$p^*(\Lambda_c^+) \to p + K^- + \pi^+ \to p + \mu^- + \tilde{\nu}_\mu + \pi^+ , \tag{43}$$

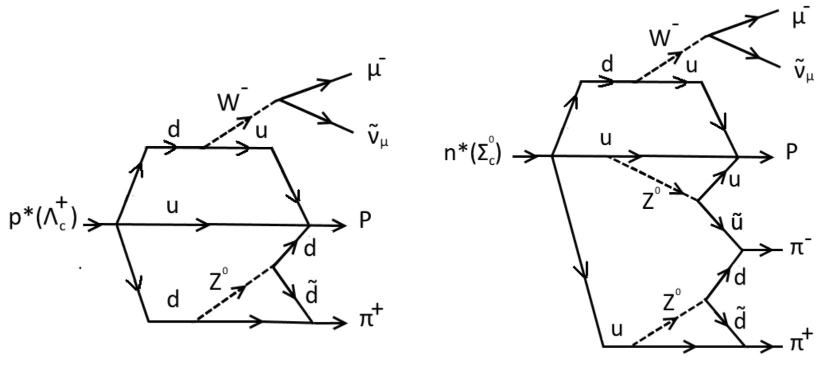
$$n^*(\Sigma_c^0) \to \Lambda_c^+ + \pi^- \to p + \mu^- + \tilde{\nu}_\mu + \pi^+ + \pi^- , \tag{44}$$

$$n^*(\Lambda_b^0) \to \Lambda_c^+ + \pi^+ + \pi^- + \pi^- \to p + \mu^- + \tilde{\nu}_\mu + \pi^+ + \pi^+ + \pi^- + \pi^- . \tag{45}$$

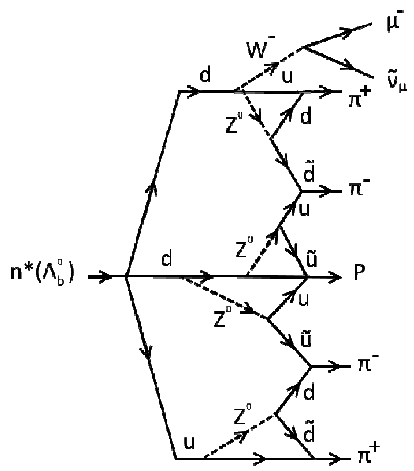
Feynman diagrams representing the above processes, which present the complicated dynamics of *u*- and *d*-quark conversions in the formation and decay of charged and neutral virtual vector bosons, are plotted in Fig. 2.



a *b*



c *d*



e

Fig. 2. Feynman diagrams for the decay of hyperons that contain (*a*, *b*) *s*-quark, (*c*, *d*) *c*-quark, and (*e*) *b*-quark

It is obvious that the number of pions and muons formed along with a nucleon in the decay of an excited baryon depends on the total excitation energy of the baryon. As the birth of, at least, one virtual vector boson is needed for one pion or muon to be formed in the final state (Fig. 2 *a*, *b*, *c*), one could expect that the processes in which the number of formed pions and muons in the final state increases would be strongly suppressed because the dimensionless constant α_F of weak nuclear interaction is low. Note, however, that when the processes in Fig. 2 are analyzed quantitatively, it should be taken into account that the weak nuclear interactions are not as weak as it is often assumed. The value of the corresponding dimensionless constant α_F is almost an order of magnitude greater than the value of fine-structure constant α_e [18], [38]. Indeed, if the dimensionless constant of strong nuclear interaction is taken to be $\alpha_s = \sqrt{2}$ [18] and the value of squared elementary charge of weak nuclear interaction is estimated by $q_F^2 \equiv G_F / a_Z^2$ [36], where $a_Z = 2^{1/2}\hbar / m_Z c \approx 3.3\ 10^{-16}$ cm is the characteristic radius related to the mass of the intermediate Z^0 vector boson m_Z = 91.2 GeV/c^2 = 1.62 10^{-22} *g* and $G_F = 1.17 \cdot 10^{-5} (\hbar c)^3 / (GeV)^2$ is the Fermi constant of four-fermion interaction, we obtain $\alpha_F = \frac{q_F^2}{\hbar c} \approx 4.9\ 10^{-2}$ and, hence, $\alpha_F / \alpha_s \approx 3.45\ 10^{-2}$. In this case, $\alpha_e = 1/137 \approx 0.73 \cdot 10^{-2}$ and, hence, $\alpha_e / \alpha_s \approx 5.2\ 10^{-3}$ and $\alpha_F / \alpha_e = 6.7$.

Unfortunately, the proton mass is often used in the literature [35] as the normalizing mass in estimating the dimensionless constant of weak nuclear interaction, though it is almost 100 times smaller than the mass of a Z^0 vector boson [36]. As a result, the value of constant α_F is underestimated by almost 4 orders of magnitude. According to our above estimates, the correct value of this constant is only 35 times, rather than 5 orders of magnitude, less than the value for the dimensionless constant of strong nuclear interaction. It is this correct value that accounts for the existence of reliable experimental data on the decays of highly excited heavy baryons that produce five or more pions and a muon [39].

As noted above, *u*- and *d*-quarks can be regarded as kinetic markers for the subunits of nuclear matter. The diagrams plotted in Fig. 2 imply that every decay process given above is a complicated process with respect to the *u* and *d* dynamic variables, in which the nonlinear interrelations with respect to these variables represent the processes of energy redistribution in the transfer of charged and neutral vector bosons and account for the emergence of pions as decay products.

The diagrams demonstrate both the variety of possible baryon decays for the same excited state (Fig. 2 *a*, *b*) and the fact that it is *impossible to introduce*, in addition to *u* and *d*, new types of degrees of freedom − heavy quarks as effective dynamical variables for describing the entire diversity of complicated decay dynamics of excited baryons p^* and n^*. The latter follows from the comparison of Figs. 2 *c* and Figs. 2 *d* showing the decays of $\Lambda_c^+(udc)$ and $\Sigma_c^0(ddc)$ hyperons, respectively, which contain, as supposed, the same heavy *c*-quark, but are accomplished by different mechanisms with 2 and 3 virtual vector bosons formed, respectively.

The number of examples of this kind that illustrate different decay mechanisms for hadrons, which according to the modern theory [35], [36] contain light quarks together with one of the heavy quarks (*s*, *c* or *b*), could be larger if we consider the decays of heavy baryons and mesons. It will be wise, however, to use the general phenomenological approach when only *u*- и *d*-quarks are considered as the current degrees of freedom, which are related to certain fragments of nuclear matter and change their electric charge in the absorption and emission of charged vector bosons.

Concluding this section, it should be noted that, proton-proton collisions with an energy of 7-8 TeV produce particles with a four-quark [40] and five-quark arrangement of nuclear matter [41]. The lifetimes of these particles are ~ 10^{-24}-10^{-23} s, which is typical for the resonances. This means that the nuclear exchange forces in the excited systems of 4 and 5 quarks are too weak to keep these systems so long as it is necessary for their relaxation to be accounted for by the weak nuclear interaction, which is true for the systems of 2 and 3 quarks. Experiments of this kind could not record the formation of a weakly decaying strange heavy dibaryon either [42], in contrast to the low-energy experiments, which produce a β-dineutron.

7. METASTABLE NON-NUCLEONIC STATES OF NUCLEAR MATTER IN DOUBLE BETA-DECAYS

The double β-decays of some even-even nuclei [43]-[46] could be a future candidate for one of the manifestations of the initiation of metastable states in the nuclear matter, in which the mass of the nucleus is insufficient (or the nuclear forces are not strong enough) to bind a part of the quarks into stable nucleons and the nucleonic structure in the nucleus is locally shaken up. All cases in which this type of decay is reliably recorded are characterized by half-lives longer than 10^{18} years, which is several orders of magnitude greater than the existence time of the Universe. The main difficulties to overcome in studying the double β-decay are represented by its low probability and the long-run experiments needed to minimize background events as possible, as well as by close and thorough analysis of experimental results. So far, these decays are experimentally recorded in 10 out of more than 30 pairs of even-even isotopes that can be bound by the double β^--decay. At the same time, in about the same number of pairs of even-even isotopes that can be bound by the double β^+-decay, no decays of this type have not been recorded yet. The latter can be a result of a noticeable difference in the probabilities of β^-- and β^+-decay. The double e^--capture was recorded for only one nucleus: ^{130}Ba isotope.

The above phenomenological concept of the radioactive decay of nuclei initiated by the e^--catalysis mechanism [5], [7] allows us not only to understand the possible reason for the difference in the probabilities β^-- and β^+-decay, but also open new opportunities in studying double β^-- and β^+-decays because their rates dramatically rise when the processes are initiated using low-energy excitations. The latter is implied not only by the general result of [5], [7] regarding the loss of stability of *isu*-state nuclei in the nuclear matter, but also by the experimental data recorded in a group of studies, for example, [9], [10], dealing with the α-decay of all so-called stable tungsten isotopes (half-lives ~ 10^{17}-10^{19} years) initiated in the glow discharge.

As a future experiment idea, it is of interest to compare the characteristic parameters Q and $|\Delta Q|$ for already and not yet recorded double β^--decays of different isotopes, including those of the same element:

$$^{48}_{20}Ca + e^-_{he} \to {}^{48}_{19}K_{isu} + \nu \to {}^{48}_{22}Ti + 3e^- + 2\tilde{\nu} + \nu + Q(4.27 MeV), \quad \Delta Q = -12.09 MeV, \qquad (46)$$

$$ {}^{46}_{20}Ca + e^-_{he} \rightarrow {}^{46}_{19}K_{isu} + \nu \rightarrow {}^{46}_{22}Ti + 3e^- + 2\tilde{\nu} + \nu + Q(0.98 MeV), \quad \Delta Q = -7.72 MeV, \tag{47} $$

$$ {}^{82}_{34}Se + e^-_{he} \rightarrow {}^{82}_{33}As_{isu} + \nu \rightarrow {}^{82}_{36}Kr + 3e^- + 2\tilde{\nu} + \nu + Q(3.01 MeV), \quad \Delta Q = -7.27 MeV, \tag{48} $$

$$ {}^{80}_{34}Se + e^-_{he} \rightarrow {}^{80}_{33}As_{isu} + \nu \rightarrow {}^{80}_{36}Kr + 3e^- + 2\tilde{\nu} + \nu + Q(0.136 MeV), \quad \Delta Q = -5.64 MeV, \tag{49} $$

$$ {}^{116}_{48}Cd + e^-_{he} \rightarrow {}^{116}_{47}Ag_{isu} + \nu \rightarrow {}^{116}_{50}Sn + 3e^- + 2\tilde{\nu} + \nu + Q(2.81 MeV), \quad \Delta Q = -6.15 MeV, \tag{50} $$

$$ {}^{114}_{48}Cd + e^-_{he} \rightarrow {}^{114}_{47}Ag_{isu} + \nu \rightarrow {}^{114}_{50}Sn + 3e^- + 2\tilde{\nu} + \nu + Q(0.54 MeV), \quad \Delta Q = -5.08 MeV, \tag{51} $$

$$ {}^{186}_{74}W + e^-_{he} \rightarrow {}^{186}_{73}Ta_{isu} + \nu \rightarrow {}^{186}_{76}Os + 3e^- + 2\tilde{\nu} + \nu + Q(0.49 MeV), \quad \Delta Q = -3.9 MeV. \tag{52} $$

The value of released energy Q accounts for the phase volume of the reaction products to be formed because the process probability is proportional to this factor, whereas the value of deficit $|\Delta Q|$ for the structural energy of the *isu*-state nucleus accounts for the extent to which the stability of the nucleus is lost.

Comparison of the values of $|\Delta Q|$ and Q for the experimentally studied processes of double β^--decay of calcium-48, selenium-82, and cadmium-116 isotopes with those for the processes not studied yet due to, as we can suggest, their much lower probability gives us a reason to consider the released energy Q as the main parameter accounting for the double β^--decay – the processes with lower energy releases. This suggestion is supported by the data in Table 2 (was compiled on the basis of [43], [44]) which lists the values of Q in the other 7 processes for which the β^--decay was experimentally recorded. Note that the smallest value of parameter Q refers to the double β^--decay of uranium-238 nuclei, and this value, as we can suggest, may account for the highest value of its half-life, which is 3-4 orders of magnitude higher the values for the other 9 nuclei.

Table 2. Isotopes with experimentally recorded double β^--decay

Isotope	Q, MeV	$\lvert\Delta Q\rvert$, MeV	$T_{1/2}$, years
${}^{48}_{20}Ca$	4.27	12.09	$(4.3 \pm 2.3)\times10^{19}$
${}^{76}_{32}Ge$	2.04	7.01	$(1.3 \pm 0.4)\times10^{21}$
${}^{82}_{34}Se$	3.01	7.27	$(9.2 \pm 0.8)\times10^{19}$
${}^{96}_{40}Zr$	3.35	7.1	$(2.0 \pm 0.4)\times10^{19}$
${}^{100}_{42}Mo$	3.03	6.24	$(7.0 \pm 0.4)\times10^{18}$
${}^{116}_{48}Cd$	2.81	6.15	$(3.0 \pm 0.3)\times10^{19}$
${}^{128}_{52}Te$	0.87	4.38	$(3.5 \pm 2.0)\times10^{24}$
${}^{130}_{52}Te$	2.53	4.96	$(6.1 \pm 4.8)\times10^{20}$
${}^{150}_{60}Nd$	3.37	5.69	$(7.9 \pm 0.7)\times10^{18}$
${}^{238}_{92}U$	1.11	3.46	$(2.0 \pm 0.6)\times10^{21}$

Below we list several double β^+-decays of even-even isotopes among which there may be processes with the values of Q commensurate with those at which the double β^--decay is effectuated:

$$ {}^{106}_{48}Cd + e^-_{he} \rightarrow {}^{106}_{47}Ag_{isu} + \nu \rightarrow {}^{106}_{46}Sn + 2e^+ + e^- + 3\nu + Q(2.78MeV), \quad \Delta Q = -0.094MeV , \qquad (53) $$

$$ {}^{108}_{48}Cd + e^-_{he} \rightarrow {}^{108}_{47}Ag_{isu} + \nu \rightarrow {}^{108}_{46}Sn + 2e^+ + e^- + 3\nu + Q(0.27MeV), \quad \Delta Q = -1.65MeV , \qquad (54) $$

$$ {}^{112}_{50}Sn + e^-_{he} \rightarrow {}^{112}_{49}In_{isu} + \nu \rightarrow {}^{112}_{48}Cd + 2e^+ + e^- + 3\nu + Q(1.92MeV), \quad \Delta Q = -0.66MeV , \qquad (55) $$

$$ {}^{152}_{64}Gd + e^-_{he} \rightarrow {}^{152}_{63}Eu_{isu} + \nu \rightarrow {}^{152}_{62}Sm + 2e^+ + e^- + 3\nu + Q(0.058MeV), \quad \Delta Q = -1.82MeV . \qquad (56) $$

In the above processes, the possible candidate isotopes are cadmium-106 and tin-112. At the same time, the comparison between the $2\beta^+$- and $2\beta^-$-decays shows that their values of $|\Delta Q|$ are much different from each other (see the Table 3 compiled on the basis of [43], [45]). It is the low values of $|\Delta Q|$ that may account for the low probabilities of $2\beta^+$-decays, because any radioactive decay of nuclei begins with the initiated (either due to fluctuation or by the action of external factors) interaction of an electron in the inner shells of the radioactive atom with its nucleus ${}^{A}_{Z}N$, which produces an intermediate *isu*-state nucleus ${}_{Z-1}^{\;\;A}M_{isu}$ [5], [7]. As the rates at the stage where the ${}_{Z-1}^{\;\;A}M_{isu}$ nucleus is formed are much higher when the process is initiated in a low-temperature plasma, the possibility of recording $2\beta^+$-decays may be higher for the isotopes characterized by the highest values of $|\Delta Q|$ and Q. Probable candidate nuclei for these decays among all $2\beta^+$-active nuclei are listed in Table 2, where the barium-132, xenon-126, and tellurium-120 isotopes may be expected to become the most promising candidates for experimental studies of $2\beta^+$-decay.

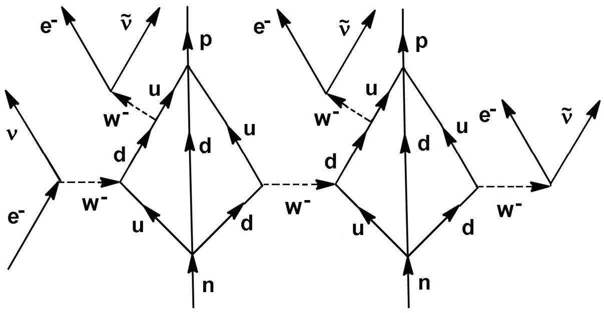
The above difference in the values of $|\Delta Q|$ for the $2\beta^-$- and $2\beta^+$-decays is reasonable to attribute to the initiating role of the electron factor in the radioactive decays of nuclei [5] occurring in our asymmetric Universe, which is characterized by the recorded existence of the matter with atoms composed of elementary particles and the absence of the antimatter with atoms composed of antiparticles. This difference in probability of the $2\beta^-$- and $2\beta^+$-decays can be considered as one of the arguments in favor of the hypothesis of the activating role of electrons in radioactive decays. Indeed, the nature of these differences for radioactive decays cannot be understood in terms of generally accepted approaches.

Table 3. Possible double β^+-decay candidates for even-even isotopes

Isotope	Q, MeV	$\lvert\Delta Q\rvert$, MeV
${}^{96}_{44}$Ru	2.72	0.254
${}^{106}_{48}$Cd	2.78	0.194
${}^{112}_{50}$Sn	1.92	0.664
${}^{120}_{52}$Te	1.70	0.982
${}^{124}_{54}$Xe	3.07	0.295
${}^{126}_{54}$Xe	0.90	1.258
${}^{130}_{56}$Ba	2.58	0.368
${}^{132}_{56}$Ba	0.833	1.28
${}^{138}_{64}$Ce	2.01	0.433
${}^{156}_{58}$Dy	0.708	1.045

$^{162}_{68}$Er	1.85	0.296

We suggest that the above double β-decays must be accompanied by the coupled conversion of quarks of two neutrons in the β^--decays or two protons for the β^+-decays in the emission and absorption of vector bosons. In these processes, the initiating role is played by the quasi-free (within the nucleus) quarks emerged in the formation of the *isu*-state of nuclear matter. The corresponding Feynman diagrams, which schematically represent the dynamics of the interactions effectuated in double β-decays, are plotted in Fig. 3.



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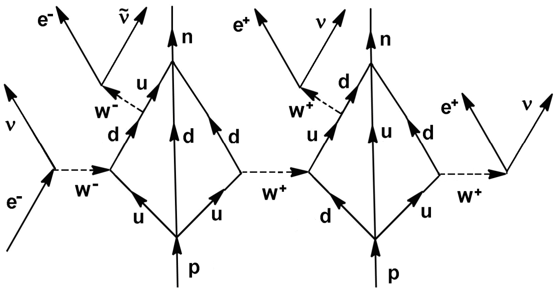

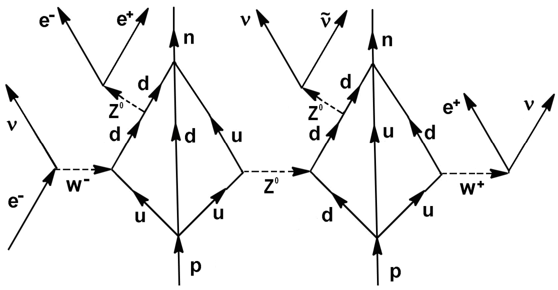

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Fig. 3. Feynman diagrams for initiated (*a*) 2 β^-- and (*b*, *c*) 2 β^+-decays

Note that when double β-decay diagrams are discussed, the dynamics of coupled conversions are taken into account only when the decays without neutrinos, which are possible when the neutrino and antineutrino are the same particle (Majorana neutrino), are considered [46]. As we can expect that the characteristic times of 2 β-decays initiated by low-energy actions will be many orders of magnitude less than the values usually recorded in experiments, there is a hope to see in the future not only new experimental data on double β^--decays, but also the first data on β^+-decays, as well as to get some idea about the extension to which the lepton number conservation law in the 2 β-decays is violated.

8. NATURE OF THE ANOMALY RECORDED IN THE BERYLLIUM-8 DECAY

Let us discuss the anomalies in the angular correlations between the positrons and electrons emitted in the radioactive decays of excited ${}_4^8Be^*$ nuclei [3]. As in [5], we assume that the decay of a ${}_4^8Be^*$ nucleus is preceded by its interaction with one of the electrons in the inner electron shells of the atom, which emits a neutrino ν and produces an excited metastable *isu*-state ${}_3^8Li_{isu}^*$ nucleus:

$$ {}_3^7Li + p \rightarrow {}_4^8Be^*, \quad {}_4^8Be^* + e_{he}^- \rightarrow {}_3^8Li_{isu}^* + \nu \rightarrow 2{}_2^4He + 2e^- + e^+ + \nu + \tilde{\nu} . \qquad (57) $$

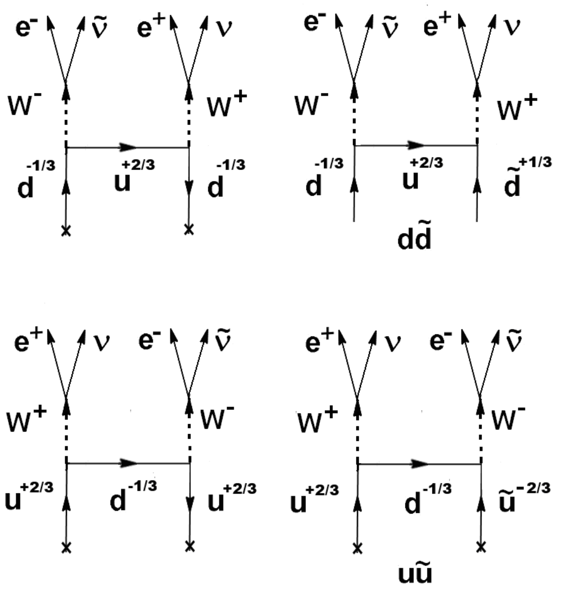
Based on the above decay diagram for the excited ${}_4^8Be^*$ nucleus, we can suggest a new formation mechanism for a correlated e^+e^- pair in the reaction ${}^7Li(p,\gamma){}^8Be$ when two states of the ${}_4^8Be^*$ nucleus, 17.64 MeV and 18.15 MeV, are excited, as in the experiment [3], which is alternative to the one proposed in [1]-[3].

As noted above, the nature of the excitation of ${}_4^8Be$ nuclei initiated by the collisions with nucleons, when the entire nucleonic subsystem of the nucleus is excited, is substantially different from the nature of the local metastable *isu*-excitation caused by a shake-up in the nucleonic structure of ${}_3^8Li_{isu}$ nucleus and the loss of the overall stability of these β-nuclei. The latter depends on the absolute value of structural energy deficit $\Delta Q = (m_{{}_4^8Be} - m_{{}_3^8Li})c^2$ and the difference in the masses of ${}_4^8Be$ and ${}_3^8Li$ nuclei in the ground state. Therefore, we can assume that the excitation energy of the nucleonic subsystem of the ${}_4^8Be^*$ nucleus can be almost completely kept in the nucleonic subsystem of the ${}_3^8Li_{isu}^*$ nucleus if the latter has the corresponding excited state. In this case, it becomes obvious that the efficiency of the decay of the excited ${}_3^8Li_{isu}^*$ nucleus that emits two alpha particles and a correlated e^+e^- pair will depend on how close one of the excited states of the ${}_3^8Li$ nucleus approximates the excited state of the ${}_4^8Be$ nucleus [47].

Here we must take into account that the probability of emitting γ quanta by excited nuclei, which depends on the width of the corresponding excited state, and the probability of emitting photons in the transition of a single atom from the excited state to the ground state are initiated by the zero-point oscillations of the EM vacuum [48]. Virtually, the main factor is the average of squared fluctuating values of the electric field intensity for the EM vacuum. As noted above, when a metastable *isu*-state with a local shake-up in the nucleonic structure is initiated in the nuclear matter, the irreversible loss of the nucleus stability is likewise accounted for by the EM vacuum as a result of changes in the boundary conditions at the nucleus surface [5], [18]. However, these two emissions are independent of each other.

As the ground-state energy for the ${}_3^8Li$ nucleus is 16.005 MeV higher than that for the ${}_4^8Be$ nucleus [47], the excited states of 1.635 and 2.145 MeV for the ${}_3^8Li$ nucleus could formally correspond to the excited states of 17.64 and 18.15 MeV for the ${}_4^8Be$ nucleus. For the ${}_3^8Li$ nucleus, the excited states closest to the ground one are 0.891 MeV, which is not high enough for producing an e^-e^+ pair, and 2.255 MeV, which is 0.11 MeV higher than the above value of 2.145 MeV. If the anomaly in angular correlations between positrons and electrons recorded in [3] is effectuated by the above excited states of ${}^{8}_{4}Be$ and ${}^{8}_{3}Li_{isu}$ nuclei, it implies that in this case the width of the 2.255 MeV state for the ${}^{8}_{3}Li_{isu}$ nucleus is larger than 0.11 MeV, and we can speak about a direct correspondence between the 18.15 MeV excited state for the ${}^{8}_{4}Be$ nucleus and the 2.255 MeV excited state for the ${}^{8}_{3}Li_{isu}$ nucleus. Obviously, this correspondence needed for the anomaly recorded in [3] to take place may be achieved by adjusting the kinetic energy E_p of the bombarding protons, though not always.

Assume that the anomaly recorded in [3], which is the formation of correlated e^-e^+ pairs at their opening angles Θ ~ 130-140^0, is mostly due to the exchange of *d*- and *u*-quarks localized in the region of non-nucleonic metastability of the *isu*-state nucleus, which can migrate over the nucleus, and *d*- and *u*-quarks of the superpositions $d\tilde{d}$ and $u\tilde{u}$ among the quark-antiquarks pairs produced in the decay of vector Z^0-mesons in the same *isu*-region of the nuclear matter. Virtually, this exchange is effectuated in the annihilation of these quarks and antiquarks of $d\tilde{d}$ and $u\tilde{u}$ pairs producing a correlated e^-e^+ pair, which is in good agreement with the decay of a neutral boson studied in [1]-[3].



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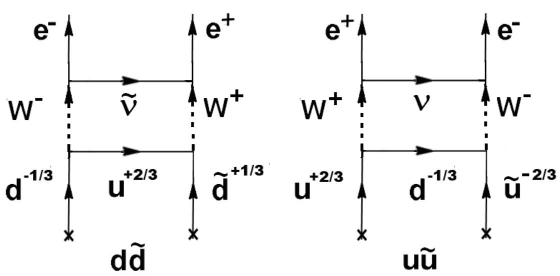

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Fig. 4. Feynman diagrams for the formation of correlated e^-e^+, $e^-\tilde{\nu}$ и $e^+\nu$ pairs initiated by the interaction between a π^0-meson (quark-antiquark superposition $d\tilde{d}$ and $u\tilde{u}$) and the nucleons of the excited ^{8}Be* nucleus

Possible diagrams for the formation of $e^{-}e^{+}$ pairs accompanied by the production of $e^{-}\tilde{\nu}$ and $e^{+}\nu$ pairs are plotted in Fig. 4. In contrast to the decays of bosons as particles with a certain set of quantum characteristics analyzed in [1]-[3], the quark pairs to be annihilated in these diagrams can have different relative orbital moments, as in [49], which does not impose any substantial restrictions on the sets of quantum numbers for the excited states of the nuclei; specifically, ${}^{8}_{4}Be^{*}$ and ${}^{8}_{3}Li^{*}_{isu}$. For this reason, the results of [3] were discussed above without referring to the quantum numbers for the excited states of these nuclei.

The developed concept stating the existence of the metastable states of the nuclear matter with a local shake-up of its nucleonic structure makes it possible to qualitatively interpret the formation of correlated $e^{-}e^{+}$ pairs in the experiment under discussion [3] without involving the hypothesis of afifth fundamental interaction into the physical science. Admittedly, it is possible so far to speak only about a qualitative understanding of the correlation of $e^{-}e^{+}$ pairs in the above process because the exchanges of quarks in the region of nucleus non-nucleonic metastability have not been studied yet.

An additional clarity in discussing the above alternative could be brought by the new experiments proposed in [2] to record the anomalies in the angular correlations between positrons and electrons, like those in [3], that are emitted in the radioactive decay of other excited nuclei. The study [2] deals with the reactions ${}^{7}Li({}^{3}He,\gamma){}^{10}B^{*}(19.3MeV)$ [50] and ${}^{7}Li(t,\gamma){}^{10}Be^{*}(17.79MeV)$ [51] and assumes that the decay of these excited states of the daughter nuclei can produce $e^{+}e^{-}$-pairs with the same type of opening-angle anomaly as in [3].

The developed concept of the radioactive decays of the excited nuclei producing the ${}^{10}B^{*}(19.3MeV)$ nucleus implies that, in the first of the above reactions, the ${}^{10}_{4}Be^{*}_{isu}$ nucleus rather than the ${}^{10}_{5}B^{*}$ nucleus would decay, producing the final products ${}^{7}Li$, ${}^{3}He$, and an $e^{+}e^{-}$-pair. In the second reaction, the final products ${}^{7}Li$, ${}^{3}H$, and an $e^{+}e^{-}$-pair are formed in the decay of the ${}^{10}_{3}Li^{*}_{isu}$ nucleus rather than the ${}^{10}_{4}Be^{*}$ nucleus. The above differences are significant due to the high difference in the ground-state energies of the nuclei to be decayed when these energies are referred to the unified energy scale. It is this kind of analysis that will enable us to make an unambiguous choice in conducting appropriate experimental studies in favor of the hypothesis of the existence of a fifth fundamental interaction or developed concept of nuclear radioactive decays. The most significant differences are seen for the energy levels of ${}^{10}_{3}Li^{*}_{isu}$ and ${}^{10}_{4}Be^{*}$ nuclei: the ground state for the lithium-10 nucleus is 20.444 MeV higher than the one for the beryllium-10 nucleus. The corresponding difference between the ${}^{10}_{4}Be^{*}_{isu}$ nucleus and ${}^{10}_{5}B^{*}$ nucleus is 0.556 MeV [47].

In view of the above differences, the excited state of 19.3 MeV for the boron-10 nucleus should formally be in correspondence with the excited state of 18.74 MeV for the beryllium-10 nucleus, in which the excited-state energy closest to the latter value is 18.55 MeV. When the width of this state is greater than 0.2 MeV, the above correspondence can be true and the anomaly in the angular correlations between positrons and electrons emitted in the radioactive decays of excited ${}^{10}B*$ nuclei can, in principle, be recorded. The situation is substantially different when we look for these anomalies in the decays of excited ${}^{10}Be*$ nuclei. The excited state of 17.79 MeV for the beryllium-10 nucleus cannot even formally be in correspondence with the ground state for the lithium-10 nucleus because the energy difference between the ground states for the lithium-10 nucleus and beryllium-10 nucleus is higher than the above excited-state energy for the beryllium-10 nucleus. Therefore, the desired correlations in the $^{7}Li(t,\gamma)^{10}Be^{*}$ reaction should be sought at kinetic energies E_t of the tritium nuclei higher than those suggested in [2]. For example, the excited states of 1.4, 2.35, and 2.85 MeV for the lithium nucleus, whose decay into ^{7}Li and ^{3}H may be accompanied by the anomaly in the angular correlations of the recorded $e^{+}e^{-}$-pair can be achieved using the tritium nucleus energies of 21.8, 22.8, and 23.3 MeV, respectively. This experiment can become an *experimentum crucis* in selecting between the discussed nature alternatives for the correlated opening angle of the $e^{+}e^{-}$-pair, as well as in deciding whether it is possible to initiate metastable states with a shaken-up nucleonic structure in the nuclear matter and, hence, validate the new concept of radioactive decays of nuclei.

9. CONCLUSION

This study may be the first attempt to discuss the existence of metastable states in the nuclear matter in which the mass of the nucleus is insufficient (or the nuclear forces are not strong enough) to bind a part of the quarks into stable nucleons, which results in a local nucleonic structure shake-up in the nucleus. With this anomalous excited state of the nuclear matter, called inner shake-up or *isu*-state, the relaxation of the nuclei is initiated by the weak nuclear interaction. Apparently, the most unexpected result of this study is represented by the fact that we discovered the unified physical nature of decays in the nuclear matter under the action of weak nuclear forces. These decays can be initiated by both a low-temperature plasma and the collision of countermoving proton beams with characteristic energies higher than 1 TeV per colliding proton pair. In either way of initiation, the necessary condition for this type of decay – large enough drop in the strong nuclear interaction, is met. In the first way, this is achieved by the “soft force”: by initiating an inelastic interaction between the hot (on chemical scales) electron and the nucleus denying the *K*-trapping, which produces a certain mass deficit in the resulting nucleus. In the second way, it is achieved by a direct high-energy action: by increasing the kinetic energy of the baryon quarks.

It is the above approach that we successfully used before to understand a large enough set of experimental data on the initiation of low energy nuclear reactions and acceleration of radioactive α- and β-decays in a low-temperature plasma. Taking the metastable non-nucleonic states of the nuclear matter into account in the study of the above high-energy collisions made it possible to understand the nature of various recorded decays of highly excited hadrons, which are effectuated by the weak nuclear interaction.

The concept stating the existence of metastable states of the nuclear matter, in which the nucleonic structure is locally shaken up, enabled us to present the arguments substantiating an alternative approach to interpreting the experimental results [1]-[3] and question the need to introduce a fifth fundamental interaction into the physical science, additional to the electromagnetic, nuclear strong/weak, and gravitational interactions, which can relate ordinary matter and hypothetical dark matter.

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