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Optical Theorem Formulation and Nuclear Physics Mechanisms for Gamow Factor Cancellation in Low-Energy Nuclear Reactions

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Abstract

Based on the optical theorem formulation of low-energy nuclear reactions, we show that a Gamow factor cancellation can occur for nuclear fusion reactions if the imaginary part of the effective nuclear interaction in the elastic channel has a small component of a finite long-range interaction. It is recently shown that a near cancellation of the Gamow factor at low energies can occur if one of the final-state nuclei has a weakly bound ("halo") excited state. Another mechanism for the Gamow factor cancellation is a continuum-electron shielding of nuclear charge by a dense electron plasma. If the Gamow factor cancellation occurs, it can lead to a large enhancement of reaction rates and probabilities for low-energy nuclear fusion reaction and nuclear fission, and may provide nuclear physics mechanisms for explaining the anomalous effects observed in low-energy nuclear reactions. Several specific cases of the anomalous effects are discussed in terms of nuclear physics mechanisms, including cluster-impact nuclear reactions which may be relevant to the low-energy nuclear transmutation.

1. Introduction

Since the 1989 announcements of "cold fusion" phenomena [1,2] there have been persistent claims of observing the cold fusion phenomena, and hundreds of experimental papers have been published [3-5]. Most of the reported experimental results are not reproducible at a desirable level of 100%. However, there are a few experimental results which appear to be 100% reproducible.

There have been many theoretical models proposed to explain the cold fusion phenomena. Most of those theoretical models claiming to have explained the phenomena appear far from having accomplished their claims [6,7]. Recently, we developed a new alternative theoretical formulation of low-energy nuclear fusion reactions based on the optical theorem [8-10], which is much less model-dependent than previous theoretical approaches, and showed that some of the cold fusion phenomena may be justified theoretically, since a Gamow factor cancellation (GFC) can occur if the imaginary part of the effective nuclear interaction in the elastic channel (ENIEC) has a very weak component with a finite long range (FLR). However, we could not prove nor rule out theoretically the existence of such a FLR component in the imaginary part of ENIEC. In another recent paper [11], we demonstrated (without a rigorous derivation) a possibility of the existence of FLR components if the target nucleus has a weakly bound excited state ("halo" nuclear state). Recently, we have obtained a rigorous derivation [12] of a new type of FLR interaction in the imaginary part of ENIEC for the case in which one of the final-state nuclei has an excited halo nuclear state.

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Another mechanism for GFC is a continuum-electron shielding of nuclear charge [13] by a dense electron plasma such as one observed in ultra-short-time discharge plasma experiments by Shoulders et al. [14,15].

If GFC occurs, theoretical opposition based on the Gamow factor to the cold fusion [3-5] and low-energy nuclear transmutation [16] phenomena may be premature, since it can enhance reaction rate and probabilities for nuclear fusion reaction and nuclear fission and it may provide theoretical explanations of the observed anomalous effects based on nuclear physics mechanisms. Several specific cases of the observed anomalous effects including recent observations of nuclear transmutation [16] are discussed in terms of nuclear physics mechanisms.

2. Uncertainties of Low-Energy Nuclear Reaction Rates

Nuclear reaction rates and cross-section at low energies ($\lesssim$ a few keV) are not well determined, since $\sigma(E)$ at low energies, relevant to the cold fusion phenomena and also relevant to the primordal and stellar nucleosynthesis, cannot be measured in the laboratory. They are extracted from the laboratory measurements of $\sigma(E)$ at higher energies by an extrapolation procedure based on nuclear theory [9,10]. Historically, both experimental and theoretical investigations of low-energy ($\lesssim$ 1keV) nuclear reactions were by-passed and have been neglected by nuclear physics community in favor of investigating nuclear physics phenomena at much higher energies. Therefore, it is important to turn our attention and efforts to investigating these neglected and unexplored new nuclear physics frontiers.

For non-resonance reactions, it is customary to extract the S-factor, S(E), from the experimentally measured $\sigma(E)$ using the following formula,

$$\sigma_G(E) = \frac{S(E)}{E} e^{-2\pi\eta(E)}, \tag{1}$$

where $\eta(E) = Z_i Z_j e^2/\hbar v, e^{-2\pi\eta(E)}$ is the Gamow factor representing the probability of bringing two charged nuclei to zero separation distance, and S(E) is expected to be a slowly varying function of E. The energy dependence of the nuclear reaction cross-section $\sigma(E)$ cannot be obtained rigorously from first principles. Therefore, one must relay on physically reasonable nuclear reaction models, such as Eq. (1), or phenomenological microscopic models, which may not be reliable nor accurate at low energies for some cases. It should be emphasized that Eq. (1) is obtained using a semi-classical approximation. In the following sections 3 and 4, a derivation of $\sigma(E)$ based on the quantum scattering theory is given.

3. Optical Theorem Formulation

The conventional optical theorem first introduced by Feenberg [17] is given by

$$\sigma_t = \frac{4\pi}{k} Im f(0) \tag{2}$$

where σ_t is the total cross-section and f(0) is the elastic scattering amplitude in forward direction ($\theta = 0$).

To avoid complications associated with the singularity of the forward Coulomb scattering amplitude when we use the conventional optical theorem, given by Eq. (2), for scattering of two charged nuclei, we describe a different formulation based on "partial-wave" optical theorem involving angle-integrated and/or angle-independent quantities in the following [8-10].

For the elastic scattering involving the Coulomb interaction and nuclear potential, the scattering amplitude can be written as a sum of two amplitudes:

$$f(\theta = f^c(\theta) + \tilde{f}(\theta), \tag{3}$$

where $f^c(\theta)$ is the Coulomb amplitude and $\tilde{f}(\theta)$ is the remainder. $\tilde{f}(\theta)$ can be expanded in partial waves [18] as

$$\tilde{f}(\theta) = \sum_\ell (2\ell+1) e^{2i\delta_\ell^c} f_\ell^{N(e\ell)} P_\ell(cos\phi), \tag{4}$$

where δ_ℓ^c is the Coulomb phase shift, $f_\ell^{N(e\ell)} = (S_\ell^N - 1)/2ik$, and S_ℓ^N is the ℓ-th partial wave S-matrix for the nuclear part. Using Eq. (3) and Eq. (4), the integrated elastic cross section $\sigma^{e\ell}(e)$ can be written as

$$\sigma^{e\ell}(E) = \sigma^c + \sigma^{int} + \sigma^{N(el)}, \tag{5}$$

where σ^c is the pure Coulomb cross section (Rutherford scattering), σ^{int} is the interference term, and $\sigma^{N(e\ell)}$ is the nuclear elastic cross section. The partial wave expansion of $\sigma^{N(e\ell)}$ is given by $\sigma^{N(e\ell)} = \sum_\ell (2\ell+1)\sigma_\ell^{N(e\ell)}$ with $\sigma_\ell^{N(e\ell)} = \frac{\pi}{k^2}|S_\ell^N - 1|^2$.

For the reaction cross section $\sigma^{(r)}$, the partial wave expansion is given by $\sigma^{(r)} = \sum_\ell (2\ell+1)\sigma_\ell^{(r)}$ where $\sigma_\ell^{(r)} = \pi(1-|S_\ell^N|^2)/k^2$. Using the expressions of $\sigma_\ell^{(r)}$ and $\sigma_\ell^{N(e\ell)}$ derived above, we can write $\sigma_\ell^{(r)} + \sigma_\ell^{N(e\ell)} = 2\pi(1 - ReS_\ell^N)/k^2$. Combining this with $Imf_\ell^{N(e\ell)} = (1 - ReS_\ell^N)/2k$, we obtain the partial wave optical theorem for two-potential scattering case as

$$Imf_\ell^{N(e\ell)} = \frac{k}{4\pi}(\sigma_\ell^{(r)} + \sigma_\ell^{N(e\ell)}) \tag{6}$$

which is a rigorous result.

For low energies, $f_\ell^{N(e\ell)} \propto e^{-2\pi\eta}/k$ and hence $\sigma_\ell^{N(e\ell)} = 4\pi|f_\ell^{N(e\ell)}|^2 \propto e^{-4\pi\eta}/k^2$. Since $\sigma_\ell^{(r)} \propto e^{-2\pi\eta}/k^2$, we have $\sigma_\ell^{(r)} >> \sigma_\ell^{N(e\ell)}$ at low energies and hence we can write Eq. (6) as

$$Imf_\ell^{N(e\ell)} \approx \frac{4}{4\pi}\sigma_\ell^{(r)} \tag{7}$$

which is still a rigorous result at low-energies. We note that Eqs. (6) and (7) are non-radiative nuclear reactions and need to be modified for radiative nuclear reactions.

In terms of the partial wave T-matrix, T_ℓ, the elastic nuclear scattering amplitude, $f_\ell^{N(e\ell)} = (S_\ell^N - 1)/2ik$, can be written as

$$f_\ell^{Ne\ell)}(E) = -\frac{2\mu}{\hbar^2 k^2}\langle\psi_\ell^c|T|\psi_\ell^c\rangle \tag{8}$$

where ψ_ℓ^c is the ℓ-th partial wave regular Coulomb function nd μ is the reduced mass. Using the low-energy optical theorem Eq. (7) with Eq. (8), we obtain the ℓ-th partial-wave reaction cross section $\sigma_\ell(E)(= \sigma_\ell^{(r)}(E))$ as

$$\sigma_\ell(E) \approx \frac{4\pi}{kE}\int_0^\infty \psi_\ell^c(r)U_\ell(r,r')\psi_\ell^c(r)drdr' \tag{9}$$

where $E = \hbar^2k^2/2\mu$ and $U_\ell(r,r') = -Im\langle r|T_\ell|r'\rangle$ with T_ℓ representing the ℓ-th partial wave contribution of the T-mtrix operator. The total reaction cross-section $\sigma(E)$ is given by $\sigma_\ell(E) = \sum_\ell(2\ell+1)\sigma_\ell(E)$.

4. Reaction Cross Section Formula

It is recently shown [8,10] that $Im\langle r|T_\ell|r'\rangle(= -U_\ell(r,r'))$ is separable for the $\ell = 0$ two-channel case, and hence $U_0(r,r')$ in Eq. (9) is also separable for the case of two-channels (elastic and fusion). Therefore, to estimate the S-wave cross section $\sigma_0(E)$ for the two-channel case, we can parameterize $U_0(r,r')$ in Eq. (9) by two parameters λ (strength/length) and β^{-1} (range) in a separable form as

$$U_0(r,r') = \lambda g(r)g(r') \tag{10}$$

where β^{-1} is a potential range parameter for g(r) and $\lambda = V_0\beta(V_0 > 0)$. λ is expected to be a slowly varying function of energy for the non-resonance case. (For the case of resonance reactions, the energy dependence of λ can be parameterized by the Breit-Wigner expression).

For $\ell = 0$ case, the Coulomb wave function $\psi_0^c(r)$ is given by

$$\psi_0^c(r) = C_0(\eta)M_{i\eta,\frac{1}{2}}(2ikr)/2i \tag{11}$$

where $C_0^2(\eta) = 2\pi\eta/(e^{2\pi\eta}-1)$ and $M_{i\eta,\frac{1}{2}}(2ikr)$ is the Whittaker function. The reaction cross section given by Eq. (9), in the case of $g(r) = e^{-\beta r}/r$, can be written as

$$\sigma_0(E) = \frac{4\pi\lambda}{kE}|\int_0^\infty \psi_0^c(r)\frac{e^{-\beta r}}{r}\,dr|^2 = \frac{\pi\lambda}{kE}C_0^2(\eta)|\frac{1}{i}\int_0^\infty M_{i\eta,\frac{1}{2}}(2ikr)\frac{e^{-\beta r}}{r}\,dr|^2 \tag{12}$$

The integral in Eq. (12) can be evaluated exactly

$$\sigma_0(E) = \frac{4\pi\lambda}{kE}[\int_0^\infty dr\psi_0^c(r)e^{-\beta r}/r]^2 \;\; = \frac{4\lambda\pi^2}{E}\,R_B\,\frac{(e^{-2\phi\eta}-1)^2}{(e^{2\pi\eta}-1)}e^{4\phi\eta} \tag{13}$$

with

$$e^{4\phi\eta} = exp[4\alpha\frac{\mu c^2}{\hbar c}(\frac{Z_aZ_b}{k})tan^{-1}(\frac{k}{\beta})] \tag{14}$$

where $\phi = tan^{-1}(k/\beta)$ and $R_B = \hbar^2/(2\mu Z_aZ_be^2)$. The energy dependence of λ is expected to be weak.

The use of a more general form for $g(r) = (e^{-\beta r}/r)\sum_{i=0}^N c_ir^i$ instead of $e^{-\beta r}/r$ in Eq. (10) also leads to the same enhancement factor $e^{4\phi\eta}$. Therefore, the enhancement factor $e^{4\phi\eta}$ is independent of shape of the separable function $g(r)$ used in Eq. (10). For $g(r) = (e^{\beta r}/r)\sum_{i=0}^N c_ir^i$, we obtain for $\sigma_0(E)$ the following result,

$$\sigma_0(E) = \frac{\tilde{S}_0(E)}{E}\,e^{4\phi\eta}e^{-2\pi\eta} \tag{15}$$

where

$$\tilde{S}_0(E) = 4\pi^2\lambda\sum_{ij}c_ic_jF_i^\beta(E)F_j^\beta(E) \tag{16}$$

with $F_0^\beta(E) = R_B(e^{-2\phi\eta}-1), F_1^\beta(E) = R_B^{-1}(\beta^2+k^2)^{-2}, F_2^\beta(E) = R_B^{-3}(2R_B\beta+1)/(\beta^2+k^2)^4$, etc.

The enhancement factor $e^{4\phi\eta}$ is $e^{2/(R_B\beta)}$ at zero energy and decreases as E increases to $e^{\pi/kR_B} = 1$ for large E, and thus can account for the increase of experimentally extracted S(E) toward lower energies. The enhancement factor $e^{4\phi\eta}$ can be applied to both light nuclei reactions (small Z_a and Z_b) but also to heavy ion reactions (larger Z_a and Z_b) such as sub-barrier heavy ion fusion where $e^{4\phi\eta}$ can be very large. The enhancement factor $e^{4\phi\eta}$ is obtained together with the Gamow factor from our quantum mechanical derivation and can be regarded as a modification of the Gamow factor affecting it only at low energies, or as a part of the S-factor if we still wish to keep the semi-classical formula Eq. (1). The new exponential factor is a new quantum effect derived from the quantum scattering theory, and may provide new physical insights for the low-energy behavior of the reaction cross-section.

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5. Effective Long-Range Interaction and Gamow Factor Cancellation

In the limit of $\beta \to 0$ (a long-range limit), we have $\phi = \tan^{-1}(k/\beta) = \pi/2$, and hence $e^{4\phi\eta}$ given by Eqs. (14) approaches to $e^{2\pi\eta}$ which can cancel the Gamow factor $e^{-2\pi\eta}$ in Eq. (15) for $\sigma_o(E)$. Therefore, a Gamow factor cancellation can occur if the interaction range β^{-1} is large (or β is small). If the imaginary part of the effective potential or $g(r)$ in Eq. (10) has a form

$$g(r) = e^{-\beta_1 r}/r + \Lambda e^{-\beta r}/r \tag{17}$$

with $\beta < \beta_1$, the second term could be dominant over the first term even if $\Lambda << 1$. In the limit of $\beta \to 0, \phi = tan^{-1}(k/\beta) = \pi/2$ and $e^{4\phi\eta} = e^{2\pi\eta}$ which can cancel the Gamow factor $e^{-2\pi\eta}$ in Eq. (15). Therefore, it is important to investigate both theoretically and experimentally the possibility of the existence of the finite long range interaction for the imaginary part of the effective potential.

Gamow factor cancellation (GFC) can occur for nuclear fusion reactions if the imaginary part of the effective nuclear interaction in the elastic channel (ENIEC) has a small component of a finite long-range (FLR) interaction. Recently, we have obtained a rigorous derivation of a new type of FLR interaction in the imaginary part of ENIEC for the case in which one of the final-state nuclei has an excited halo nuclear state [12]. The new FLR interaction behaves as $cos(k_0 r - \eta \ell n 2k_0 r + \delta)\psi_n(r)/r^4$ at large distances, where k_0, η, δ, and $\psi_n(r)$ are the final state wave number, the Sommerfeld parameter, the phase shift, and the wave function for the excited p-wave halo nuclear state, respectively. This demonstrates that we cannot rule out theoretically the GFC effect, and that theoretical opposition to the cold fusion [3-5] and low-energy nuclear transmutation [16] phenomena based on Eq. (1) may be premature.

The existence of the FLR interaction in the imaginary part of ENIEC, when one of the final-state nuclei has an halo excited state, leads to a selection rule for final nuclear products: nuclei with halo excited states are most likely observed in the final state, while production of nuclei without halo excited states is suppressed. This selection rule may be applicable to low-energy nuclear fusion reaction [3-5], nuclear fission, and nuclear transmutation [16], induced by a charged nuclei (proton, deuteron, oxygen, etc.). The selection rule should be tested by future experiments.

6. Gamow Factor Cancellation with Continuum-Electron Shielding

Recently, we have suggested a possibility of the GFC due to continuum-electron shielding [13]. For a three-body system (e+p+p) in continuum in which all three particles are mobile, there is a possibility that a solution of the three-body Schroedinger equation may lead to the GFC if the relative velocity v_{ep} between e and p is smaller than the relative velocity ν_{pp} between two protons, i.e. $v_{ep} < v_{pp}$. In general, this condition is $v_{ed} < v_{dA}$ for the case of the $[(e + d) + A]$ system where A is a nucleus such as d or Pd. These conditions may be realized in a localized packet of electrons with nuclei imbedded in the packet such as one produced by K. Shoulders [14, 15]. The continuum-electron shielding may be one possible mechanism for explaining the anomalous results observed by Kamada in his electron-impact experiments [19]. Our formulation of the continuum-electron shielding [13] may provide a theoretical justification of "swimming electron layer" model proposed earlier [20].

Since 1980, K. Shoulders has been investigating dense highly organized micro-size cluster of electrons produced in ultra-short-time discharge plasma experiments [14,15]. The experimental data indicate the existence of a plasma state representing a freely moving, localized packet of eletrons. A short Latin acronym EV (electrum validum or electromagnetic vortex) has been adopted to describe this collective plasma state of tightly bound groups of electrons with extremely high densities. The EV's have been reported to be roughly spherically symmetric with radii on the order of 1.0 μ m, to travel at speeds on the order of 0.1c (corresponding to the electron kinetic energy of $\sim$ 2.7 keV), to tend to move for distances of 1.0 to 10.0 mm in straight lines, to deflect and accelerate with electron characteristics in experiments, and to have high electron densities on the order of 10^{22} to $10^{24} cm^{-3}$ with negligible ion content of $\sim$ one ion per 10^6 electrons.

Shoulders [14] reports the principle requirement for generating these EV structures to be a sudden creation of a very high, uncompensated set of electronic charges in a very small volume of space, i.e., a fast emission process coupled to a fast switching process. He notes the times of creation to be considerably less than 10^{-13} sec. The actual threshold initiation times for the particle packet are believed to be $\tau \sim 10^{-15}$ sec. The packet then travels approximately $10^5 \tau$ before it catastrophically decays.

Ziolkowski and Tippett [21] interpret the EV theoretically as a stable packet of electrons moving collectively through space-time catalyzed by a localized electromagnetic wave, which can be attributed to localized wave (LW) solutions obtained from Klein-Gordon form of Maxwell equations for a joint system of plasma-fluid and electromagnetic field. Beckmann [22] offers a theoretical interpretation based on the oscillating Faraday field surrounding a moving electron.

It has been determined experimentally [15] that the size of EV structure is a function of the high specific energy delivered to the metal. This fact has been recently explained by G. Mesyats in his theoretical analysis [23]. Mechanical storage of energy is though to be the source for the small EVs produced.

The total number of electrons in a 1 μm diameter EV is $\sim 10^{11}$. This allows for inclusion of $\sim 10^5$ ions (or nuclei) which would not be detected in measurements of the charge-to-mass ratio of EV such as time-of-flight measurement, i.e. electrons and nuclei in the EV (NEV) would be collectively accelerated to the velocity of electrons. This would provide a simple nuclear accelerator for accelerating nuclei. Shoulders et al. [15] have proposed this nuclear acceleration mechanism (leading to cluster-impact reactions) as a possible explanation of the anomalous nuclear transmutation effect observed by several groups [16]. Cluster-impact fusion has been previously investigated both experimentally and theoretically with $(D_2 0)_n$ clusters, which is described in the next section 7. For the NEV velocity of $v = 0.1c$, deuterons entrained in the EV would attain kinetic energy of $M_d v^2/2 \approx 9.4$ MeV (or proton kinetic energy of ~ 4.7 MeV or oxygen kinetic energy of ~ 56.3 MeV). Although these higher energy deuterons (or protons) can have large reaction cross-sections, the total reaction rates with the NEV's containing $\sim 10^5$ nuclei per NEV are too small for explaining some of the observed reaction rates, unless a substantially large number of the NEV is produced per unit time and additional mechanisms such as shock-wave heating are invoked.

Acceleration process of positive ions to higher energies due to electron plasma was observed in 1960 [24] in experiments involving a rapid expansion of plasma in a vacuum spark discharge [25,26]. Plyutto et al. obtained protons with kinetic energies of 4-5 MeV and carbon ions with kinetic energies of 15-20 MeV, when pulsed voltages of only 200-300 kV were used for spark discharge. The average number of $10^{11} - 10^{12}$ per pulse was achieved for accelerated protons or deuterons [27].

If the number of nuclei (deuterons, protons, oxygens, or others) imbedded in the EV is of the same order as that of electrons (10^{11} electrons in μm diameter size) in the EV, kinetic energies of electrons and nuclei in the NEV become much smaller. However, a Gamow factor cancellation due to the continuum electron shielding can occur if the relative velocities between electrons and nuclei in the NEV are much smaller than the velocity of the NEV. If such a GFC condition and a high production rate of the NEV are achieved, most of the observed anomalous effects [3-5,16] can be explained by nuclear physics mechanism.

Once the GFC is achieved in the entrance channel, nuclear reactions can proceed either via the direct reaction mechanism (i.e. fusion) or via the compound nucleus mechanism (de-excitation by γ-ray or neutron emission, or by fission). The compound nucleus mechanism leading to fission may be consistent with some of observations of the anomalous nuclear transmutation [16].

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For most of the electrolysis experiments, applied voltages were much smaller ($\sim 10V$) than the voltage $\sim$ 2.7 kV Shoulders used to generate the EV from his discharge experiments. However, some mechanisms such as the fractoemission may generate the EV at lower applied voltages $\sim$ 10 V. Generation of the EV has been observed with applied voltages as low as $\sim$ 50 V [14, 15]. If a sufficiently large number of smaller size ($< 1\mu m$) EV with lower velocities corresponding to the electron kinetic energy of $\gtrsim$ 10 eV can be produced at the surface of the cathode and/or inside microcavities and cracks of the cathode metal, the GFC due to the continuum electron shielding may offer a consistent explanation for most of the anomalous effects observed in electrolysis experiments, based on nuclear physics mechanisms (fusion, fission, etc.). Therefore it is important to verify the results of Shoulders independently by other experimentalists.

7. Cluster-Impact Nuclear Reaction (CINR)

Previous investigations of the cluster-impact nuclear reaction were carried out for heavy-water molecule-clusters $(D_2O)_n$. Unliked electrons in the NEV, electrons in $(D_2O)_n$ are bound electrons and not continuum electrons, and hence the GFC due to the continuum electron shielding is not applicable. The original claims [28-31] of the anomalous enhancement of $(D_2O)_n$ cluster-impact fusion cross-section were later found to be incorrect and attributed to contaminants. Nevertheless, most of theoretical formulations and models [32-39] developed to describe the cluster-impact fusion phenomena are still applicable to the cluster-impact nuclear reactions with the NEV (CINR/NEV). CINR/NEV is a way of coupling first the input energy into the electronic system and then into the target nuclei, as the laser induced fusion does. However, CINR/NEV may turn out to be more efficient than the laser induced fusion.

Shock-wave mechanisms for the cluster-impact fusion are theoretically investigated in references [34-39] such as pinch instability heating due to magnetic confinement [36-40] and shock wave heating [34-39].

8. Conclusions

It is shown that a near cancellation of the Gamow factor can occur under certain conditions. If one of the final-state nuclei has an excited halo nuclear state, it can lead to a GFC. Another mechanism for obtaining the GFC is due to the continuum electron shielding which can be achieved by creating high density cluster of mobile electrons and nuclei such as the NEV, in which the relative velocity between electron and incident nucleus in the NEV are much smaller than the NEV velocity between the NEV and the target nucleus. Therefore, theoretical opposition based on the Gamow factor to the anomalous low-energy nuclear reactions may be premature.

Once the GFC is achieved in the entrance channel, it can lead to the exit channel of nuclear fusion reaction (the direction reaction mechanism) or decay via emission of γ-rays or neutrons or via spontaneous fission (the compound nucleus mechanism). These nuclear physics mechanisms may offer a consistent explanation for many of the anomalous effects observed in low-energy nuclear reaction experiments including the nuclear transmutation.

The cluster-impact nuclear reaction with the NEV (CINR/NEV) may turn out to be a more efficient way of coupling first the input energy into the electronic system and then into the target nuclei, as compared with the laser induced fusion. Furthermore, CINR/NEV may offer other advantages such as possibilities of aneutronic reactions. Therefore, it is important to verify the EV phenomena by independent experiments.

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