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Forced reverse reactions in neutron star matter

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Nuclear reactions in neutron star envelopes are considered in the frame of complex interactions stimulated by huge pressures in the overdense crystalline structures in the envelopes. It leads to the inclusion of forced reverse reactions that transform the nuclei to neutron-rich states and the appearance of free neutrons. The free neutrons in the structures cause resonance interactions with nuclei that fixed in nodes of crystal. The neutron re-scattering on subsystem of few nucleus at the energy near the energy of resonance level of the nucleus creates the few-body resonances, which depend on the distances between the nuclei.

Key words: neutron star, nonlinear interactions, neutron resonances with few-nuclei, electron capture reactions.
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1 Introduction

The main reactions and processes that take place in the neutron star envelopes can be described in the frame of modern physical theory and methods [1-6]. In the outer and inner crusts of the envelopes, which surrounding the liquid mantel in deep of neutron star, represent itself the dense crystalline structure. This crystalline structure created by the bare nuclei situated in the lattice nodes is sunk into degenerated fermi-liquid of electrons. This construction is an electrically neutral; the nuclei in nodes of the crystal still have the well-known properties. The distances between the nuclei in the structure are much smaller than the atomic size, but are still much larger than nuclear radius.

However, the behavior of the matter in the region from 10^7 g·cm^{-3} up to 10^{14} g·cm^{-3} is governed not only by the two-body interactions, but also by the few-body forces and some sorts of quasi-particles that act in the crystalline structure [5-8].

Here, we do not consider the effect of external fields, focusing our attention on the impact of close neighbors in the crystalline structure. We take into account the properties of matter at different depths of the structure layers created by the powerful gravitational pressure.

The two-body interactions are undoubtedly important and essential at usual pressures and temperatures, and the applicable even more broadly, but for extremely high densities of matter, the few-body dynamics becomes very important, especially in the ordered structure of matter that appears in the neutron star envelopes.

In next sections, we investigate how the crystalline structure can affect the neutron resonances and create specific additional characteristics. We would also try to consider several intriguing questions.

2 The electron capture reactions

General characteristics of the overdense matter in the envelopes of neutron stars can be estimated employing an assumption that at ultrahigh pressures the structure of matter is simplified by acquiring the most favorable face-centered cubic structure [5].

The nuclear reactions in the neutron star envelopes start from the reactions of electron capture by nuclei. These reactions depend on specific properties of the nuclides. Therefore, the each stable nucleus of original neutron star substance has its own chain of electron capture reactions. Remarkable that most part of even-even nuclei give the two-step electron capture reactions because of after the first (i.e. mother) reaction follows the second (or daughter) reaction which is already open. The resulting daughter nuclei, which decay via the weak link in the terrestrial conditions, would remain stable in the overdense matter in the neutron star envelopes. They cannot emit the captured electrons owing to opposition of the degenerated Fermi electron liquid (see Fig.1).

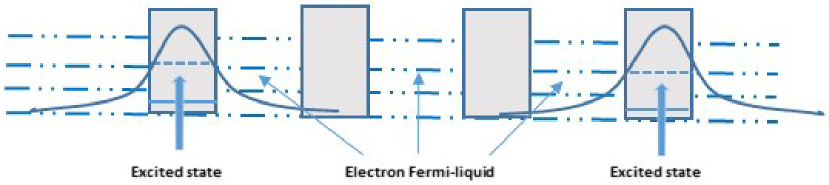

Figure 1– Nuclei in degenerated electron Fermi-liquid

It is remarkable that in many reactions that have the two-step characters the daughter nuclei, which appear in the second reactions, would arise both in the ground and in the excited states. The ban owing to quantum numbers between excited levels of nuclei demonstrates the interesting patterns.

The excited nuclei arise mostly in reactions with the iron group nuclei. The chains of reactions generated by Fermi electrons with the iron group nuclei are given in the Table 1.

Here, the following notations are used: Cr - is the name of a nuclide (chromium in this case), A is the number of nucleons in the nucleus, Z is the number of protons, e^- is an electron and ν_e - electron neutrino; $E_{e;th}$ is the threshold of the electron energy in reactions of the electron capture by a nucleus. The kinetic energy of an electron equals $E_e = E_F - m_e c^2$ and $E_e \geq E_{e;th}$. The estimates of the threshold energies for the electron capture reactions were performed employing the data available in the nuclear databases [9-12].

Table 1 – The chains of reactions generated by Fermi electrons with even-even nuclei of the iron group. The energies are given in MeV.

Main reaction	$E_{e;th}$	Daughter reactions	$E_{e;th}$
${}^{52}_{24}Cr^{0+} + e^- \to {}^{52}_{23}V + \nu_e$	3.97	${}^{52}_{23}V + e^- \to {}^{52}_{22}Ti + \nu_e$	1.977
${}^{54}_{26}Fe^{0+} + e^- \to {}^{54}_{25}Mn^{3+} + \nu_e$	0.697	${}^{54}_{25}Mn + e^- \to {}^{54}_{24}Cr^{0+} + \nu_e$	-1.377
${}^{54}_{24}Cr + e^- \to {}^{54}_{23}V + \nu_e$	7.042	${}^{54}_{23}V + e^- \to {}^{54}_{22}Ti + \nu_e$	4.301
${}^{56}_{26}Fe^{0+} + e^- \to {}^{56}_{25}Mn^{3+} + \nu_e$	3.695	${}^{56}_{25}Mn^{3+} + e^- \to {}^{56}_{24}Cr^{0+} + \nu_e$	1.629
${}^{56}_{24}Cr + e^- \to {}^{56}_{23}V^{3+} + \nu_e$	9.201	${}^{56}_{23}V + e^- \to {}^{56}_{22}Ti + \nu_e$	7.14
${}^{58}_{26}Fe^{0+} + e^- \to {}^{58}_{25}Mn^{3+} + \nu_e$	6.323	${}^{58}_{25}Mn^{3+} + e^- \to {}^{58}_{24}Cr^{0+} + \nu_e$	4.0
${}^{58}_{28}Ni + e^- \to {}^{58}_{27}Co + \nu_e$	0.381	${}^{58}_{27}Co + e^- \to {}^{58}_{26}Fe + \nu_e$	-2.307
${}^{64}_{30}Zn^{0+} + e^- \to {}^{64}_{29}Cu^{1+} + \nu_e$	0.579	${}^{64}_{29}Cu^{1+} + e^- \to {}^{64}_{28}Ni^{0+} + \nu_e$	-1.675

Note that the first reactions of electron capture (the first column in Table 1) have the positive threshold energies (the second column) higher than the threshold for the next (daughter) reactions (the third column). It means that the Fermi-electron energies are sufficient in these reactions to overcome the threshold energy (the fourth column).

As an example, we consider the isotope of ^{56}Fe,

$$\begin{aligned} &{}_{25}Mn^{3+} + e^- \to {}_{24}Cr^{0+} + \nu_e;\ E_{ext} = 2.066\ \text{MeV}; \\ &{}_{25}Mn^{3+} + e^- \to {}_{24}Cr^{*2+} + \nu_e;\ E^* = 1.059\ \text{MeV}; \\ &{}_{25}Mn^{3+} + e^- \to {}_{24}Cr^{**2+} + \nu_e;\ E^{**} = 0.234\ \text{MeV}. \end{aligned} \qquad (1)$$

Here in (1), the two last reactions generate ${}^{56}_{24}Cr$ nuclei that appear in the excited states. It is very important that these excited nuclei cannot emit gammas because the distances between the nuclei are much less than the wavelengths of the gamma radiation. Note that nuclei are fixed in the nodes of the lattice.

For the nuclei with odd mass numbers, the threshold energies of the daughter reactions are higher than the threshold energies of the mother reactions. So that the daughter nuclei in the excited states cannot appear in the electron capture reactions.

3 Nonlinear interactions

3.1 High harmonic generation.

The nuclear reactions and processes that occur in neutron star envelopes were considered in the frame of their mutual influences. Most part of these are stimulated by overdense matter transforming it to exotic states, which cannot appear in ordinary terrestrial conditions or in laboratory experiments.

At large amplitudes of the electromagnetic waves, the total dipole moment depends non-linearly on the amplitude of the incident wave. At higher densities, it leads to the birth of the secondary higher harmonic waves, i.e. the waves of doubled frequency, tripled, and even higher multiplicities.

The phenomena of light frequency multiplications are observed in the processes of which has the abundance in nature 91.754 %, concerning other iron isotopes. The first electron capture reaction starts for this isotope at the kinetic energy of the Fermi-electron E_e = 3.695 MeV. It requires the matter density be $\rho > \rho_{th} \approx 7.155\ 10^9$ g/cm^3. The daughterly reactions (Table 1, coulomb 3) can undergo the following three possible ways (here A = 56):

laser photonic interactions in special devices [13-15].

At that, two or more electromagnetic waves are absorbed and one photon is emitted at a frequency equal to the amount of absorbed waves. It means the nonlinear medium absorbs two waves ω_1, ω_2 with frequency $\omega_3 = \omega_1 + \omega_2$.

High harmonic generation has interesting properties that result in terrestrial experiments as generation of light with frequencies much greater than the original ones (typically 100 to 1,000 times greater). This phenomenon depends on the driving field and generates the harmonics with similar temporal and spatial coherence properties [13, 16, 17]. High harmonics are often generated with pulse durations shorter than those of the driving laser. This is due to the non-linearity of the generation process and the phase matching.

Considering the overdense matter in the envelopes of neutron stars, one should note that the process of high-multiplicity gamma emission stimulated by nuclei depends on the density of these nuclei in the respective layers of the envelopes. Taking into account the diffusion rate of the impurity nuclei in the crystal structure, their grouping and localization, we can talk about their high local density. Accordingly, this should lead to a high probability of a collective emission of gamma rays of high multiplicity with energies of almost an order of magnitude greater than the excitation energy of an individual nucleus.

In our case, we can consider the excited nuclei instead of the pump photons and their virtual emissions as photons, which also play the role of inducing waves. In the overdense crystalline structure, the excited nuclei interact non-linearly between each other and emit together the gamma rays of high multiplicity. The emission of gamma becomes induced in the case of any photons ≥ 1, which are already emitted in this mode.

The excited nuclei can be considered in overdense crystal as the sources of compressed photons. The combined radiations from such sources would create the modes of high multiplicity, i.e. high-energy gammas.

3.2 Tunneling Effects.

Obviously, it is very challenging to consider the complete manifold of the interactions between the stable and excited nuclei in an overdense crystalline structure. However, particular significance in the super-dense crystalline structures acquires tunneling effects because, unlike the dense gas environments, here the tunneling phenomenon has its own ordered pattern. Imagine, for example, the quasi-particle motion inside the nucleus as the motion in the potential well. Let the energy of the quasiparticle excitation energy be equal to E^*, and the height of the well be E_F.

The nuclei are immersed in a degenerate electron Fermi liquid, which prohibits the output of gamma rays that have energies below the Fermi energy of the electrons. Let us also consider two neighboring wells, i.e. two adjacent excited nuclei. The overlap coefficient of the wave functions can be defined in this simplified model employing a simple formula

$$D(d^*) = D_0 /[1+ (k^2 + \kappa^2)^2/4\, k^2 \cdot \kappa^2\, \mathrm{sh}(\kappa \cdot d^*)] \quad (2)$$

where

$$k = [2m^* \cdot E^*]^{1/2} /\hbar \; ; \; \kappa = [2m^* \cdot (E_F - E^*)]^{1/2} /\hbar \quad (3)$$

Here, $D_0 \approx 1$ is the normalized overlap integral of the two identical wave functions of the nuclear excited states taken at $d^* = 0$; m^* is the effective mass of the quasi-particle. In reality $d^* \geq d$, where d is the lattice constant.

Then one can write $d/d^* = (\rho^*/\rho)^{1/3}$.

Summing (2) over all the neighboring excited nuclei, one can obtain the dependence of the overlap integral of the excited nuclei density $\Omega(\rho^*)$ in the lattice as:

$$\Omega(\rho^*) = \Sigma_p D(p \cdot d_{av}) \quad (4)$$

where d_{av} is the average distance between the single excited nuclei p = 1,2,3 … The overlap integrals with highly excited states are to be also included in the sum $\Omega(\rho^*)$ by introducing the wave numbers

$$k_n = [2m^* \cdot E_n^*]^{1/2}/\hbar \ ,$$
$$\kappa_n = [2m^* \cdot (E_F - E_n^*)]^{1/2}/\hbar \quad (5)$$

where E_n^* is the energy of the related states. Equating the sum (4) to unity, one can get the critical value for the density of the excited states of the nuclei in the lattice:

$$\rho^*/\rho = d^3 (k_n \cdot \kappa_n)^{3/2} \quad (6)$$

This shows that at low d and κ_n, the critical values can occur even with low concentrations of excited nuclei.

4 Neutron Resonances of Few-Body Type in the Crystalline Structures

We consider the model of neutron scattering on two fixed centers where the two-body scattering amplitudes have the resonant Breit-Wigner form:

$$t_i = |\nu_i> \frac{\Gamma_i/2}{E - E_{R_i} + i\Gamma_i/2} < \nu_i| \quad (7)$$

The energy and width of the resonance are determined with real and imaginary parts of the resonance wave number:

$$E_{R_i} = (p_R^2 - p_I^2)/2m\,; \quad \Gamma_i = -2p_R p_I/m$$

We can assume that the form-factor ν_i is almost a constant value in a sufficiently wide range around the resonance point $E \approx E_{R_i}$. Note that the two-body scattering amplitude has the pole in the second sheet of complex plane of energy. Moreover, the resonant pole in the two-body system can give the series of poles for the three-body amplitude.

The neutron resonance in the ordered structure becomes the relatively stable state via the resonant re-scattering in the subsystems of two (or more) heavy nuclei. The resonant re-scattering appears and exists in a crystal at specific distances between nuclei and energies of neutron. Both these values depend on the inner property of the nuclei. These values can also be defined in an analytical form [18,19].

If the conditions are suitable for collective emission of high harmonic gammas, it means that nonlinear interactions between nuclei in the overdense crystal can stimulate these processes in deep layers of the neutron star envelopes.

It is very important to take into account the solutions of more complex objects, particularly the four-body systems that consist of three heavy nuclei and one neutron. The solutions of these four-body systems can give us the tendency of resonance influences in the cells of corresponding layers of the crusts. As in the previous case, the problem of neutron scattering on this subsystem can be solved in an analytical form. To simplify this, we can consider that all three nuclei are identical.

The resonant points can appear at larger distances between the nuclei than in the case of the three-body system above (see Fig. 1 and Fig. 2). The resonance picture in the neutron star envelopes can be more complicated and wealthy than in the frame of the two-body point of view.

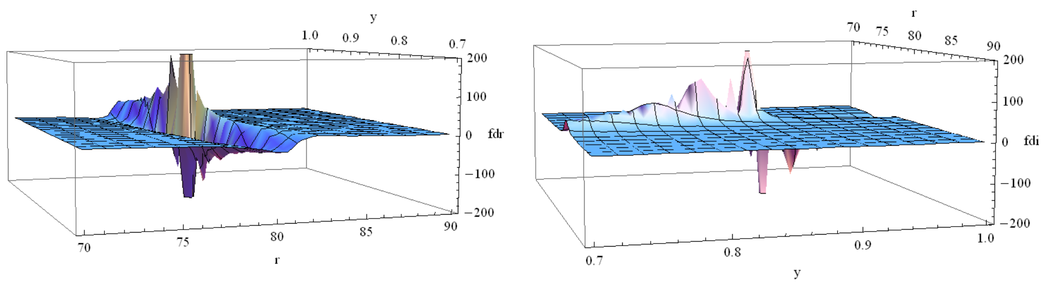

Figure 2 – Real and imaginary part of K in the case of (n + ^{55}Mn + ^{55}Mn) system

There are some difficulties in determination of the characteristics for neutron scattering on unstable neutron-excess nuclei. Firstly, it is the absence of data on neutron resonances for such nuclei. Secondly, it is the determination of nonlinear interactions and their manifestations that play important role at the lower layers of the neutron star envelopes. Therefore, in order to underline the role of the neutron resonances and related processes, we considered several simple examples of the neutron resonances with the iron group nuclei involved. These nuclei may not be preserved at considered depths, because they would be transformed in the electron capture reactions. Our aim is to show how the new processes can emerge in the deep layers of the neutron stars envelopes and how they can manifest themselves in the analysis of data, obtained by the external observer. Therefore, in order to underline the role of the neutron resonances and related processes, we considered several simple examples of the neutron resonances with the iron group nuclei involved. These nuclei may not be preserved at considered depths, because they would be transformed in the electron capture reactions. Our aim is to show how the new processes can emerge in the deep layers of the neutron stars envelopes and how they can manifest themselves in the analysis of data, obtained by the external observer.

Note that every neutron-nucleus resonance creates own structural resonance levels in the three-body system. Figure 2 and 3 demonstrate the behavior of the neutron amplitude for the re-scattering in the subsystem of two nuclei.

Our choice to consider the crystal structures with isotopes of the iron element is motivated by the fact that these elements are essential in the composition of the neutron star matter and, of course, for the neutron star envelopes. The calculations were carried out for the scattering channel, where every subsystem n + ^{55}Mn has the similar quantum numbers: the total moment J = 3 and the angular moment l = 0. The resonance levels were taken into account: E_{R0} = - 1.615 keV, and E_R = k_R^2 =1.098 keV with Γ = 18 eV [12]. Note that every neutron-nucleus resonance creates own structural resonance levels in the three-body system (see Fig 2 and 3).

One can see that the resonant distances between the nuclei become larger and the dispositions of the resonances are more complicated.

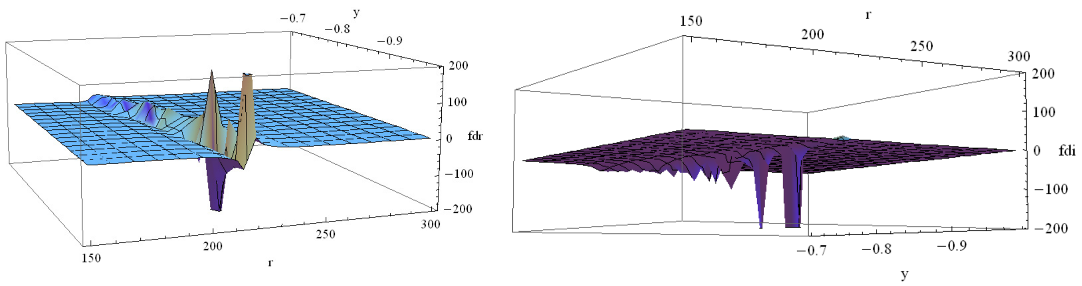

Figure 3 – Real and imaginary part of K in the case of (n + ^{57}Fe + ^{57}Fe)

The calculations demonstrate that the structural neutron resonances mostly appear in a wide energy area around the resonance energy of the neutron-nucleus resonance, and along the narrow trajectory in the space coordinate. Moreover, the two-body resonances with narrower widths produce the larger number of structural neutron resonances, some of them are more powerful and have very narrow peaks.

We also estimated the nuclear jitter effect in the crystal lattice. Fluctuations were considered to be small so far, but they may be considered with selecting an appropriate wave function describing the heavy nucleus state in the lattice node.

5 Conclusion

We consider the forced reverse reactions, which are acting in neutron star envelopes and stimulated by huge pressure that leads to the transformation of matter, closes some reactions of beta decay and neutron-rich of matter.

However, the remarkable distinctions have been also discovered. For example, the cardinal distinctions appear in the reactions and processes between nuclei of Fe group and the group of light elements.

The chemical composition of primordial matter of a neutron star determines the evolution of the neutron star matter and peculiarities of nuclear reactions and processes. The neutron resonances of few-body type that arise in crystalline structure have the selected character and take place only in suitable layers that lead to local oscillations of density. The nonlinear interactions can result to reactions with gammas, which knockout alpha particles from the nuclei. Then the inner crust layers will be enriched with free neutrons and alpha particles also.

The detailed theoretical descriptions of such resonances were based on the few-body model and supported by sample calculations of the new three-body and four-body neutron resonances. The study of the these resonances is focused at scattering of neutrons on a subsystem of two or three isotopes with the distances between these isotopes is considered as a key parameter. It was shown that each nucleus has its own resonance states at corresponding unique energies and lattice parameters. The new neutron resonances are calculated in the energy range close to the conventional neutron-nucleus resonances. In overdense matter like we deal with in neutron stars, the influence of the new resonances would increase and become very important.

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