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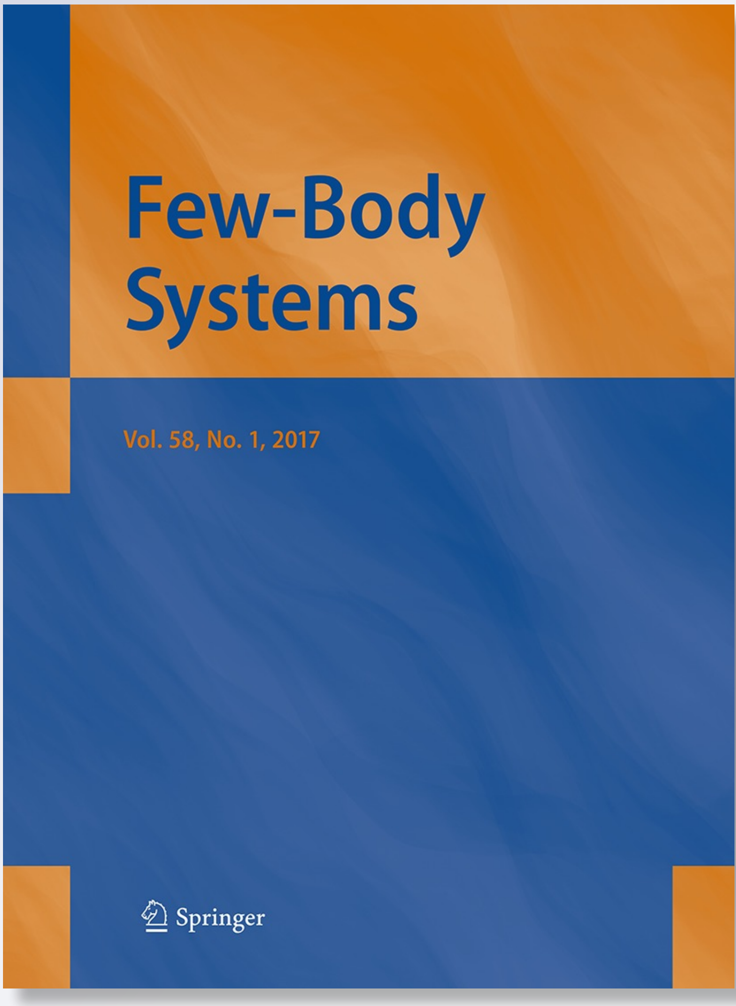

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Abstract Neutron resonances in systems of few nuclei, electron capture reactions with formation of excited nuclei, and density oscillation in the neutron star envelopes are investigated. These results allow to propose the special experiments to verify the neutron resonances in the few-body systems and understand the origin of some processes that are going in the neutron star crusts.

1 Introduction

Processes, reactions and few-body effects that take place in the overdense crystalline structures of neutron star crusts are considered. In the region of matter density from 10^6 to 10^{13} g/cm^3, the lattice is formed by bare nuclei which plunged in the degenerate electron Fermi liquid, so the matter remains neutral [1,2]. However, this unique structure stimulates the appearance and development of interrelated reactions, nonlinear phenomena and new resonance states.

So, the reactions of electron capture by nucleus in the neutron star envelopes lead to appearance of new types of excited nuclei, free protons are transformed into neutrons, the neutrons interact with subsystems of two and more nuclei. Neutron-nuclei resonances change the balance of forces inside of the crust layers and lead to induced specific oscillations and density waves.

The processes taking place in the envelopes impact the surface phenomena and radiation, which are the important sources of information about physical characteristics of neutron stars. To the outside observer, the main sources of information about a neutron star are the characteristics of radiation from the surface and the near surroundings: periodic impulses of pulsars, their spectra and micro-structures, strong magnetic fields and accreting matter, etc.

It is noticeable that describing the processes in the neutron star crusts, one can use the quantum theory for the quasi-particles supplemented with the methods provided by the theory of nonlinear phenomena, and the quantum theory of few-body systems, taking into account resonance states that appear owing to the free neutron component of matter in this area. The important feature of reactions in a superdense lattice is the appearance of the neutron resonances in the few-body system. These resonances appear due to rescattering of free neutrons on a subsystem of neighboring nuclei.

We consider the Faddeev equations where the two-body t-matrices for neutron-nucleus subsystems are taken in the form of the Breit–Wigner resonances. Then, the Faddeev equations give the solutions also in the resonant form which allow to perform exact analyses and estimations.

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Table 1 Samples of the electron capture reactions and electron threshold energies

Main reaction	Threshold energy (MeV)	Daughter reaction	Threshold energy (MeV)
${}^{56}_{26}\mathrm{Fe} + \mathrm{e}^- \rightarrow {}^{56}_{25}\mathrm{Mn}^{3+} + \nu_\mathrm{e}$	$Q = 3.7$	${}^{56}_{25}\mathrm{Mn} + \mathrm{e}^- \rightarrow {}^{56}_{24}\mathrm{Cr}^{0+} + \nu_\mathrm{e}$	$Q = 1.63$
${}^{48}_{22}\mathrm{Ti} + \mathrm{e}^- \rightarrow {}^{48}_{21}\mathrm{Sc}^{6+} + \nu_\mathrm{e}$	$Q = 3.9$	${}^{48}_{21}\mathrm{Sc} + \mathrm{e}^- \rightarrow {}^{48}_{20}\mathrm{Ca}^{0+} + \nu_\mathrm{e}$	$Q = 0.3$
${}^{45}_{21}\mathrm{Sc} + \mathrm{e}^- \rightarrow {}^{45}_{20}\mathrm{Ca} + \nu_\mathrm{e}$	$Q = 0.256$	${}^{45}_{20}\mathrm{Ca} + \mathrm{e}^- \rightarrow {}^{45}_{19}\mathrm{K} + \nu_\mathrm{e}$	$Q = 4.203$
${}^{24}_{12}\mathrm{Mg} + \mathrm{e}^- \rightarrow {}^{24}_{11}\mathrm{Na}^{4+} + \nu_\mathrm{e}$	$Q = 5.52$	${}^{24}_{11}\mathrm{Na}^{4+} + \mathrm{e}^- \rightarrow {}^{24}_{10}\mathrm{Ne}^{0+} + \nu_\mathrm{e}$	$Q = 2.47$
${}^{16}_{8}\mathrm{O}^{0+} + \mathrm{e}^- \rightarrow {}^{16}_{7}\mathrm{N}^{2-} + \nu_\mathrm{e}$	$Q = 10.42$	${}^{16}_{7}\mathrm{N}^{2-} + \mathrm{e}^- \rightarrow {}^{16}_{6}\mathrm{C}^{0+} + \nu_\mathrm{e}$	$Q = 8.01$

In order to verify the existence of neutron resonances in the systems of few nuclei in neutron star crusts, we suggest an idea of terrestrial experiments to investigate the neutron resonances at low thermal energies. To verify the dependence of resonance parameters on distances between nuclei, we propose the experiments with the piezoelectric targets and isotopes with lower-energy neutron resonances.

2 Features of the Electron Capture Reactions

Based on differences in the primary chemical composition of neutron stars, we considered the relevant inter-related chain of reactions. It was found that the electron capture reactions have different characteristics for the light and the heavy nuclei. Table 1 shows the succession of the pair reactions.

So, in the cases of even–even main nuclei (e.g. for ${}^{56}_{26}\mathrm{Fe}$ with the daughter reaction for ${}^{56}_{25}\mathrm{Mn}$), the reactions lead to the appearance of the nuclei in excited states. These reactions start at the layers where the density of matter $\rho > \rho_{cr} = 1.144 \times 10^9\,\mathrm{g\,cm^{-3}}$ and lead to:

$$
\begin{aligned}
&{}^{56}_{25}\mathrm{Mn}^{3+} + \mathrm{e}^- \rightarrow {}^{56}_{24}\mathrm{Cr}^{**4+} + \nu_\mathrm{e}, \quad E^{**}_\gamma = 1.832\,\mathrm{MeV},\\
&{}^{56}_{25}\mathrm{Mn}^{3+} + \mathrm{e}^- \rightarrow {}^{56}_{24}\mathrm{Cr}^{*2+} + \nu_\mathrm{e} \quad E^{*}_\gamma = 1.007\,\mathrm{MeV},
\end{aligned}
$$

where E^{**}_γ and E^{*}_γ are the energies of the excited levels of the nuclei Cr^{**4+} and Cr^{*2+}, respectively.

Here, gamma emission can be limited by the distinction between quantum numbers in the initial and the final states. Moreover, the emission of gamma radiation can be “locked” by the overdense crystal if the lattice parameters are less than the half wavelength of such gamma radiation. Then, the induced emission of high energy gamma becomes more effective for the ensemble of the excited nuclei. These gammas can knock-out the nucleons or clusters from the neighboring nuclei. Energy transfer can also be realized via excitation of quasi-particles in a crystalline structure.

This peculiarity does not appear in the case of odd main nuclei (e.g. for ${}^{45}_{21}\mathrm{Sc}$) because the following electron capture reactions have more higher energy thresholds than the previous one.

For the neutron stars consisting of light elements, the accumulation of neutron-rich nuclei happens almost without the formation of excited states. And destruction of the crystalline structure starts already in high layers of the envelopes.

3 Neutron Resonances in Few-Body Systems

It is known that the neutron-nucleus scattering amplitude has a lot of resonances in the keV-energy region up to 1 MeV [3]. At low energies, the two-body resonances can be considered as single peaks situated far enough from each other. The t-matrix can be written in this case in the Breit–Wigner form $t(E) = -(2\pi\rho)^{-1}\Gamma_2/(E - E_{R,2} + i\Gamma_2/2)$, where $E = k^2/2m$ is the neutron energy, $\pi\rho = 2mk/4\pi$, $E_{R,2} = k_2^2/2m$ and Γ_2 are the energy and the width of the resonance, respectively. $t(E)$ can be written in form $t(E) = \bar{\nu}_2 \cdot \eta_2(E) \cdot \nu_2$, where $\eta_2(E) = \Gamma_2/(E - E_{R,2} + i\Gamma_2/2)$. Here, the index 2 denotes the two-body values, and we take $\hbar = 1$.

In the case of three-body system consisted of a free neutron and two nuclei fixed in the neighboring nodes of the crystalline lattice, we consider the three-body amplitude. This amplitude corresponds to the re-scattering of the neutron on these two nuclei. Taking into account the Breit–Wigner form of the two-body amplitudes, we can obtain the solutions for the new resonances of three-body type also in the analytical form. Then, we come to the important results: (a) new neutron resonances depend both on the energy of neutron, and on r—the distance between nuclei; (b) the new resonances can appear at the energies higher or below the energy of the selected two-body resonance. Omitting the details of the calculations [4], we present the results for simple neutron resonances of the three-body type:

$$E_{R,3} = E_{R,2} \pm \Gamma_2 \cos(k_3 \cdot r)/(2 \cdot k_3 \cdot r), \quad \Gamma_3 = \Gamma_2 \cdot (1 \pm \sin(k_3 \cdot r)/(k_3 \cdot r)). \tag{1}$$

Here, the index 3 corresponds to the three-body quantities such as $E_{R,3} = k_3^2/2m$. Note that all resonances are situated at the second Riemann sheet of the complex energy. The dependence on the distance between the nuclei is clearly shown. It means that only special layers of crystalline structure of a neutron star can contain and support the resonances of the few-body type.

Then, one can introduce the effective interaction between two nuclei in the form $\xi_n \cdot V^{ef}$, where ξ_n is the density states of free neutrons in the local layer of the crystalline structure. Following the well-known Hellmann–Feynman relationship $dE_n^{ef}/d\xi_n = \langle\chi_n|V^{ef}|\chi_n\rangle/\langle\chi_n|\chi_n\rangle$, where the wave function of the neutron χ_n can be taken as that for a particle in a potential well, one can write the expression of the effective energy as $E_n^{ef} \approx \xi_n\langle\chi_n|V^{ef}|\chi_n\rangle/\langle\chi_n|\chi_n\rangle$ for a small value of ξ_n in an adiabatic approximation. Note that in this approximation $E_n^{ef} = E_{R,2} - i\Gamma_2/2 \pm J(d/2)$, where $J(r) = \Gamma_2 exp(ikr)/(2rk_{R,2})$ contains the main dependence on the distance between the nuclei. Here, d is the lattice parameter.

Enhancement of this specific interaction leads to changing of the balance of forces in the corresponding layers of the overdense crystal and causes local oscillations in these layers. Pressure can be determined from the general expression [2]: $P = \tau^2\partial(E_{tot}/\tau)/\partial\tau$, where τ^{-1} is the volume per one baryon, $E_{tot} \approx E^{ef} \cdot \overline{n}/2$ is the total energy density of the respective forces, $\overline{n}$ is the average number of the resonant pairs of nuclei. Note that P_{res}^{ef} is almost zero everywhere, but increases significantly only near the $d \approx d_{res}$. The net action of the forces leads to a new equilibrium value of $d_0 \neq d_{res}$, which may not have a monotonic behavior and there may be local density oscillations [4].

The non-linear relations, oscillatory processes can appear in form of the beats of the wave packets, formations of solitons and other phenomena inside the envelopes contributing to the important properties of gamma emissions from a neutron star [5]. Neutrons and neutron resonances play a noticeable role in such processes.

4 Experiments at Low Thermal Energies to Detect the New Neutron Resonances

We propose to set up the experiments on scattering of neutrons at low thermal energies on a target with piezoelectric features. The ^{113}Cd isotope seems to be the most suitable because other cadmium isotopes, for example ^{114}Cd and ^{115}Cd, have no neutron resonances in the low thermal energy range [6]. In this study, we calculated the new resonances of the few-body type on the targets with different Cd isotopes (see Fig. 1) and found that ^{113}Cd is more convenient for such experiments. Note, that all these crystals demonstrate piezoelectric features that allow changing of the spatial parameters of the crystal.

The lowest neutron resonance in the two-body system n+^{113}Cd has the neutron energy 2.77 meV, and the wavelength (in Angström) is 5.44 Å[6]. The next resonance level has the energy 7 eV, the wavelength is 0.178 Å [3]. Meanwhile, the lowest neutron resonance in the two-body system n+^{114}Cd is at the energy 56.4 eV. Therefore, the influence of this resonance level is too small to distort the action of the neutron lower resonance in the three-body system $n +^{113}$ Cd $+^{113}$ Cd or $n +^{113}$ Cd $+^{114}$ Cd in the low thermal region.

The theoretical results demonstrate the facts of appearance and disappearance of the three-body resonances in the crystal with Cd at alteration of the crystalline parameters.

The relationship between the three-body and the two-body amplitudes can be written as

$$F(k_0; \mathbf{r}) = \left| \sum_{i,j} J_{i,j}(k_0; \mathbf{r})(1 + \eta_j J_{j,i}(k_0; \mathbf{r}))/(1 - J_{i,j}(k_0; \mathbf{r})\eta_j J_{j,i}(k_0; \mathbf{r})\eta_i) \right|^2. \tag{2}$$

We can change the distance between the nuclei in the target using the piezoelectric effect. In Fig. 1 (the left diagram) the blue, red and yellow curves correspond to $k_0 = 1.28$ Å^{-1}, $k_0 = 1.15$ Å^{-1} and $k_0 = 0.99$ Å^{-1}. Note that the two-body system n + Cd^{113} has the resonance at $k_{res} = 1.157$ Å^{-1}.

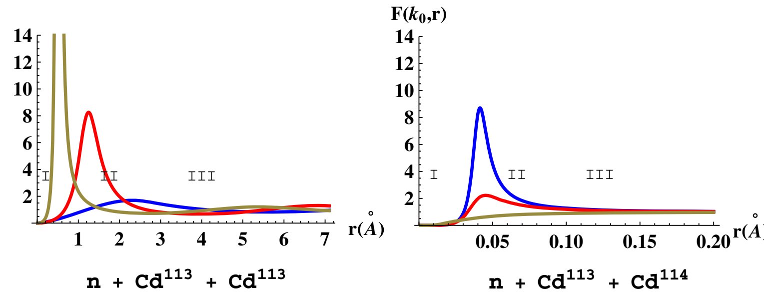

Fig. 1 Neutron resonances on a two nucleus subsystem: left "$n + A + A$"-system, where the resonance energy and the width of the $(n + A)$-subsystem are $E_R = 2.77$ meV, $\Gamma = 0.5$ meV, $A \equiv \text{Cd}^{113}$; on the right "$n + A + B$"-system, where the resonance energy and the width of the $(n + B)$-subsystem are $E_R = 56.4$ eV, $\Gamma = 0.08$ eV, $B \equiv \text{Cd}^{114}$

5 Conclusion

It has been shown that in the crystalline layers, each system consisted of two (or more) nuclei and a neutron 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. Influence of the new resonances would increase and becomes very important.

A particular role of the non-linear interactions has also been discussed: on a macro scale, such interactions can generate the beats in the corresponding layers of the neutron star crusts and define the micro-structure of the profile surface of the pulses coming to the Earth from pulsars.

The opportunities for further laboratory experiments in terrestrial conditions were also discussed. It is proposed to set up the experiments with a beam of thermal neutrons and the certain targets such as special CdS and CdSe piezo-crystals containing selected isotopes. Our calculations confirmed this supposition and the possibility to find the new resonance effects and the dependence on distances between nuclei in the different crystalline structures. The positive result of the experiments would confirm neutron resonances at suitable layers in neutron star crusts.

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