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Excited nuclei, resonances and reactions in neutron star crusts

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Abstract. The short review of research results concerning the study of reactions and processes that occur in the neutron star crusts is given. The peculiarities of electron capture reactions by a nucleus in overdense crystalline structures have been demonstrated for various nuclei, in particular some even-even nuclei at electron capture reactions give daughter nuclei in excited states. Excited nuclei due to nonlinear interactions lead to a high-order harmonic generation. High energy gammas interact with charged particles, give a neutrino radiation and also knock out nucleons from neighbour nuclei.

It is also shown that interactions of neutrons with two and more nuclei in an overdence lattice give a large number of new resonance states. These resonances result in a formation of specific local oscillations in the corresponding layers of the lattice. The periodic enhancement of these processes in the dependence on the elemental composition of the primary neutron star matter is considered.

1. Introduction

We consider processes, reactions and few-body effects that occur in the crystalline structures of neutron star crusts in the region of density $10^6 g/cm^3$ - $10^{13} g/cm^3$. In this area the substance is the overdense crystalline lattice formed with bare nuclei placed in the degenerate electron Fermi liquid. It is the unique environment for the development of interrelated reactions, nonlinear phenomena and new resonance states.

The main sources of information about the neutron stars are the characteristics of radiation from the surface and the near surroundings; the thin atmosphere and land surface, strong magnetic field, accreting outside material from the nebula or the nearest star, and so on.

It is noticeable, that describing the processes in the neutron star crusts one can use the quantum theory for the quasiparticles supplemented with methods provided by physics of nonlinear phenomena, and the quantum theory of few-body systems, taking into account resonance states. In this short paper, we explain two our recent studies.

2. Processes and reactions in the overdense structures of neutron star envelopes

Considering a high density region in the envelopes of neutron stars, one should pay attention to the fact that the electrons displaced off the atomic orbitals form the degenerate electron Fermi liquid. In such a place, instead of undergoing the β-decay, absorption of electrons by nuclei with the emission of neutrinos will take place [1]. In this area, the atomic nuclei still retain their individual properties, as the distance between them are much greater than the size of the nuclei themselves.

Based on the different variants of the primary chemical composition of neutron stars, we investigate the chains of electron capture reactions and the dependence on the depth in the envelopes. The reactions have different characteristics for even-even, even-odd, odd-even and odd-odd initial nuclei. For example, the reactions starting from the $^{56}_{26}Fe^{(0+)}$ nuclei are expressed as the following chain:

$$^{56}_{26}Fe + e^- \rightarrow ^{56}_{25} Mn^{(3+)} + \nu \ (Q = 3.7MeV) \ ; \ \ ^{56}_{25}Mn + e^- \rightarrow ^{56}_{24} Cr^{(0+)} + \nu \ (Q = 1.63MeV)$$
$$^{56}_{24}Cr + e^- \rightarrow ^{56}_{23} V^{(1+)} + \nu \ (Q = 9.2MeV) \ ; \ \ ^{56}_{23}V + e^- \rightarrow ^{56}_{22} Ti^{(0+)} + \nu \ (Q = 7.14MeV)....$$

In this chain of reactions, the threshold energy Q for each of the odd proton number of the parent nuclei is less than the threshold energy of the previous reaction. It means that the second reaction for $^{56}_{25}Mn^{(3+)}$ is open and could be realized immediately after the first, because the electron energy $E > Q$.

However, taking into account the quantum numbers of the parent and daughter nuclei in the second reaction, i.e. for $^{56}_{25}Mn^{(3+)}$ and $^{56}_{24}Cr^{(0+)}$, one can see that direct transitions between the nuclei in ground states would be difficult (the second order forbidden). But the transition in the excited state is open: $^{56}_{25}Mn^{(3+)} + e^- \rightarrow ^{56}_{24} Cr^{*(2+)} + \nu \ (Q = 1.01MeV)$. The formation of an excited state of $^{56}_{24}Cr^{*(2+)}$ becomes therefore the most probable. This excited state is long-lived, since excited energy is less than the Fermi-electron energy. Moreover, the wavelength of the gamma is much greater than the distance between the nuclei. Therefore, the emission of the gamma by the excited nucleus is improbable.

In this case the transfer of energies to the environment represents a very complex process, which involves other factors such as the existence of neighboring excited nuclei, tunneling effects and emergence of quasi-particles, as well as the generation of Fermi electrons.

Excited nuclei in a high number density will contribute to the high-order harmonic generation of gamma rays. In turn, the high-energy gammas could cause reactions with the ejection of neutrons from neighboring nuclei and produce neutrino-antineutrino pairs [2].

The avalanche process - induced discharge of coherent radiation or excess of excitation of nuclei followed by the release of the mass of free neutrons occurs until reaching the critical density values of the excited nuclei. One can expect that some of these powerful emissions can cause "glitches" in the emission of pulsars.

For odd isobars, the situation is simpler: each subsequent reaction has an energy threshold above the energy threshold of the previous reaction, so the new nuclei remain in the ground state in the chain of electron capture reactions.

3. Neutron resonances in overdense lattice

It is known that a neutron-nucleus scattering at low energies has the resonance behavior and a number of resonances increases rapidly in keV-energy region [3]. Breit-Wigner's two-body resonances described by $t(E) = -(2\pi\rho)^{-1}\Gamma_2/(E - E_{R,2} + i\Gamma_2/2)$, 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 resonance, respectively. Here the index 2 denotes two-body values and we take $\hbar = 1$.

Free neutrons collide with nuclei fixed at nodes of the lattice, and as a result a neutron resonates with nuclei and makes a re-scattering few-body resonance state. For example, we discuss a simple case of isolated neutron resonances and the subsystem of two heavy nuclei. The new resonance states could be described as [4]

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

where 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.

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It is very important that the characteristics of the three-body resonances depend not only on the resonance energy and width of the neutron-nucleus two-body subsystem but also on the distance between two heavy nuclei.

Then, one can introduce the effective interaction between two nuclei in the form $\xi_n \cdot V^{ef}$, where ξ_n is a number density of free neutrons in the local layer of the crystalline structure. Following the well-known Hellmann-Feynman relationship $dE_n^{ef}/d\xi_n =< \chi_n|V^{ef}|\chi_n > / < \chi_n|\chi_n >$, where the wave function of the neutron χ_n can be taken such as a particle in a potential well, we can write the expression of the effective energy as $E_n^{ef} \approx \xi_n < \chi_n|V^{ef}|\chi_n > / < \chi_n|\chi_n >$ 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 balance of forces in the corresponding layers of the overdense crystal, and causes local oscillations in these layers.

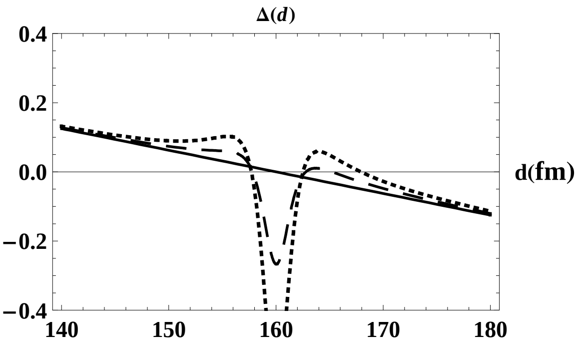

Figure 1. The sum of pressures in relative terms: $\Delta = (P_G + P_C + P_{res}^{ef})/P_C$. The balance of gravitational, Coulomb and Neutron resonance forces gives $\Delta(d_0) = 0$. The solid line corresponds the neutron density $\xi_n = 0$, i.e. $P_{res}^{ef} = 0$, the dashed line - $\xi_n = 6 \cdot 10^{-5} fm^{-3}$ and the dotted line - $\xi_n = 1.44 \cdot 10^{-4} fm^{-3}$

Pressure can be determined from the general expression [1]: $P = n^2 \partial(E_{tot}/n)/\partial n$, where n^{-1} is the volume per one baryon, E_{tot} is the total energy density of the respective forces. 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 [5].

Figure 1 shows the deviation of the equilibrium values of d_0 in the absence and the presence cases of neutron resonances in the local layers of the overdense crystal. The resulting local oscillations allow us to predict that the radiation accompanying the few-body neutron resonances will have an oscillatory behavior. This may explain the micro-pulse emission of the periodic pulses observed in some pulsars (for example, PSR 1133+16) [6, 7, 8].

Conclusion

We here presented the two interesting phenomena which are expected to occur in neutron star envelopes. When we take into account the nonlinear and few-body interactions, they give various phenomena furthermore. It concerns the neutrino flow pulsations, star-quakes and so on.

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