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PHONON DYNAMICS IN NEUTRON STAR CRUSTS AND THEIR CONNECTION TO PULSAR GLITCHES

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Abstract. *This paper investigates the role of phonon dynamics in the solid crust of neutron stars and their connection to large-scale structural instabilities. Electron capture reactions in the dense outer layers of compact stars generate excited nuclei, which may transfer their energy to the lattice in the form of phonons. These vibrational modes affect the elastic response of the crust, modifying its stress–strain behavior under extreme astrophysical conditions. Using fundamental parameters such as Young's modulus, density, and sound velocity, we estimate phonon frequencies, wave numbers, and lifetimes across different crustal layers. Numerical analysis indicates that phonon excitations are capable of storing elastic energy and may act as precursors of sudden stress release events. A special focus is given to pulsar glitches, with the Vela pulsar serving as a representative example. The comparison between calculated phonon energies and observed glitch energetics suggests that collective phonon processes could contribute to the mechanism of these abrupt rotational irregularities. By emphasizing the importance of lattice dynamics in neutron star models, this work provides the first quantitative estimates linking microscopic phonon excitations with macroscopic glitch energetics, thus contributing to a deeper understanding of how nuclear-scale transitions manifest as observable astrophysical signals. These findings can contribute to future models of neutron star crust dynamics and related astrophysical observations.*

Keywords: neutron stars, neutron star crust, phonons, electron capture, elastic properties, starquakes, pulsar glitches.

1. Introduction

Neutron stars are among the densest objects in the Universe. Their masses slightly exceed that of the Sun, yet they are compressed into a sphere only 10–15 km in radius [1]. They are the remnants of massive stellar collapses. They exhibit extremely high densities on the order of $\rho \geq 10^{12} - 10^{14}\ g/cm^3$ comparable to that of an atomic nucleus [2]. Their internal structure consists of ultra dense neutron matter, while the outer layers form a solid crystalline crust composed of heavy nuclei embedded in a degenerate electron background. The crust plays a crucial role in the star's dynamical processes, including the mechanisms of starquakes - sudden seismic-like events accompanied by the release of enormous amounts of energy [3].

One of the key processes governing the physical properties of the neutron star crust is electron capture [4], which occurs in its deeper layers. As density increases, electrons acquire sufficiently high energies to be captured by heavy nuclei, thereby transforming them into more neutron-rich isotopes. These reactions produce excited nuclear states that can transfer their energy to the crystal lattice in the form of phonons - quasiparticles responsible for elastic vibrations of the crystalline lattice [2, 5]. Such processes affect the elastic and transport properties of the crust [1, 6, 7].

The phonon dynamics within the neutron star crust determine the transport and dissipation of energy. They may also be associated with the emergence of macroscopic deformations that lead to starquakes. Investigating phonon spectra and their relation to the elastic properties of neutron star matter provides deeper insight into the mechanisms of stress accumulation and energy redistribution in the crust. These processes may play a fundamental role in the interpretation of observable astrophysical phenomena such as gravitational-wave events, sudden changes in pulsar rotation (glitches), and X-ray bursts [3, 8]. Glitches represent one of the few observable manifestations that provide direct information about the internal structure of neutron stars; thus, their study is essential for understanding the physics of dense matter. Pulsar glitches are thought to involve sudden release of crustal stresses [3, 9].

Therefore, the investigation of phonon dynamics induced by electron capture reactions constitutes an important direction in neutron star astrophysics, enabling a link between the microphysics of dense matter and its macroscopic astrophysical manifestations.

2. Methods and numerical experiment

The primary objective of this work is to investigate the phonon dynamics in the neutron star crust induced by electron capture reactions and their connection to the elastic properties of stellar matter. In particular, comparative estimates are provided for the mechanisms of phonon excitation resulting from nuclear transitions, as described in [4], their propagation within the crystalline structure of the crust, and their possible influence on global structural disturbances of the star, including starquakes. The investigation of phonon spectra and their relation to the elastic characteristics of neutron star matter provides valuable insights into the mechanisms of stress accumulation and energy redistribution within the crust.

During electron capture, excited nuclear states transfer energy to the lattice as phonons. In the crystalline crust of a neutron star, we consider longitudinal (acoustic) phonons whose dispersion in the long-wavelength limit is linear. In the present work we focus on longitudinal acoustic phonons as a first-order approximation, since they are directly associated with density perturbations in the crystalline lattice. The dispersion relation and the sound velocity are given by

$$V_s = \sqrt{\frac{E}{\rho}}, \omega_k = V_s k \tag{1}$$

where $E$is the Young's modulus of the crust, ρ is the mass density, V_s is the sound velocity, ω_k is the phonon frequency, and k is the wave number. Typical values used in our estimates are E = 10^{30}–10^{31} dyn/cm² for the Young's modulus and ρ ∼ 10^{11}–10^{14} g/cm³ for the density, ranging from the outer to the inner crust [2, 10, 11]. These parameters determine the sound velocity and, in turn, the characteristic phonon frequencies. Detailed discussions of dense matter equations of state can be found in [2, 11]. For characteristic wave numbers $k \sim 10^8 - 10^{10} cm^{-1}$, the phonon frequencies lie in the range $\omega_k \sim 10^{20} - 10^{22} s^{-1}$ (see Table 1), consistent with possible interactions with excited nuclei [2, 6]. The characteristic wave number can be estimated as $k \approx \pi/L$, where L represents the typical spatial scale of stress redistribution in the neutron-star crust. Table 1 shows that phonon frequencies increase with density, reflecting the stiffer lattice in the inner crust. This analysis demonstrates how energy transfer from nuclear excitations is mediated by phonons in both outer and inner crust layers.

Table 1. Physical parameters of neutron star crust layers.

Region of crust	Density ρ (g/cm³)	Young's modulus E (dyn/cm²)	Sound velocity V_s (cm/s)	Wave vector k (cm^{-1})	Phonon frequency ω (Hz)
Outer crust	10^9-10^{11}	10^{30}-10^{31}	~10^8	10^{10}	~10^{18}-10^{19}
Inner crust	10^{12}-10^{14}	10^{31}-10^{32}	~10^9	10^{11}-10^{12}	~10^{20}-10^{22}

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Phonons may decay due to scattering in interactions with neutrons as well as through other processes. For an order-of-magnitude estimate of the phonon lifetime τ, we write:

$$\tau \sim \frac{1}{\Gamma} \tag{2}$$

where Γ is the phonon damping width. For order-of-magnitude estimates we assume $\Gamma \sim 10^{8} - 10^{10}\text{s}^{-1}$. Substituting these values gives phonon lifetimes in the range $\tau \sim 10^{-8} - 10^{-6}\text{s}$ [1, 6].

This indicates that the excited phonons may exist long enough to participate in starquakes. Similar estimates of phonon damping in the neutron star crust are discussed by Chamel [1], where the dispersion and damping of collective excitations, including phonons, are studied. It is shown that, due to the strong mixing of drifting and elastic modes, both the phonon density of states and their propagation length are significantly modified. The aforementioned studies provide a detailed treatment of the methods for calculating phonon dispersions in the crystalline crust, taking into account the Young's modulus, matter density, and nuclear structure parameters in agreement with recent estimates of crustal elasticity [1, 6]. It is demonstrated that the range of permissible wave numbers is determined both by the intrinsic properties of the crust - such as lattice rigidity and density - and by external conditions, including temperature, magnetic field strength, and defect distribution. These effects have also been addressed in recent theoretical models. In particular, Baiko [12] points out that 10^{12} cm^{-1}, nonlinear effects in the dispersion relation begin to manifest, which may lead to local variations in propagation velocities and enhanced scattering. These results are of considerable importance for modeling the elastic properties of the crust and for predicting oscillation spectra under astrophysical perturbations.

The evaluation of phonon energy yields the following picture. We employ the expression

$$E = \hbar \cdot \omega_k. \tag{3}$$

Substituting $\hbar \approx 6{,}582 \times 10^{-22}\ \text{MeV} \cdot \text{s}$ and $\omega_k \approx 10^{19}\ \text{s}^{-1}$, we obtain:

$$E \approx (6{,}582 \times 10^{-22}) \times (10^{19})\ \text{MeV} \approx 6{,}58 \times 10^{-3}\ \text{MeV} \approx 6{,}6 \times 10^{-3}\ \text{MeV} \approx 6.6\ \text{keV}. \tag{4}$$

This corresponds to approximately 6.6 keV. Energies of this order may interact with low-energy nuclear or lattice excitations in the neutron-star crust. Even when considering an ensemble of $N \approx 10^{30}$ such phonons, the total energy amounts to $E \approx 10^{26}\ \text{eV} \approx 1{,}6 \times 10^{7}$ erg.

These estimates can be employed to discuss the potential role of phonons in starquakes, where they may excite elastic waves in the crust and contribute to the redistribution of the stored energy.

Consider the Vela pulsar (PSR J0835–4510), a relatively young object with a rotation period $P \approx 89\ \text{ms}$ and a distance of ~ 800 light years. It is known to exhibit sudden spin-up events (glitches) with a typical relative magnitude $\frac{\Delta\nu}{\nu} \approx 10^{-6}$ [3]. If a glitch is attributed to the sudden release of elastic energy stored in the crust, the corresponding change in the star's rotational energy can be estimated as

$$E \approx \frac{1}{2} I \cdot (\Delta\Omega)^2, \tag{5}$$

where $I \approx 10^{45}\ \text{g} \cdot \text{cm}^2$ — is the neutron-star moment of inertia, and $\Delta\Omega/\Omega \approx 10^{-6}$

$$E \approx 0{,}5 \times 10^{45} \times (10^{-6} \times \Omega)^2,$$

$$\Omega \approx 2\pi/P \approx 70{,}6\ \text{rad/s} \rightarrow \Delta\Omega \approx 7{,}06 \times 10^{-5}\ \text{rad/s},$$

$$E \approx 0{,}5 \times 10^{45} \times (4{,}98 \times 10^{-9}) \approx 2{,}49 \times 10^{36}\ \text{erg}.$$

The comparison demonstrates that the energy of a typical glitch ($\sim 10^{36}$ erg) exceeds the energy stored in an ensemble of 10^{30} phonons ($\sim 10^{7}$ erg) by roughly 29 orders of magnitude. This indicates that, for phonons to contribute meaningfully to the glitch energy budget, either an enormously larger number of excitations must be involved or mechanisms of collective phonon interactions need to be invoked.

Our calculations, summarized in Table 1, indicate that phonon oscillations may span the frequency range $10^{19} - 10^{22}$ Hz. The energy of a single phonon is estimated as $E_{phonon} = 6$ keV, while the total energy associated with phonon processes can be evaluated in terms of the accumulated stresses within the crust. The connection between the calculated phonon oscillations and pulsar observations lies in the possibility that stresses may accumulate in the crust due to phonon excitations [8].

In this case, the energy released during structural oscillations should be comparable to the elastic energy stored in the crust [5]. A rough estimate of the accumulated elastic energy in the crust can be made as follows:

$$E_{elast.} \approx \frac{1}{2} E \varepsilon^2 V \tag{6}$$

where E is the Young's modulus, ε is the characteristic strain, and V is the volume of the crust.

Using the values of the Young's modulus from Table 1 and adopting typical parameters $\varepsilon \approx 10^{-4}$, $V \approx 10^{18} cm^3$ we obtain $E_{elast.} \approx 10^{41} erg = E_{glitch}$ - which is of the same order as the energy released during a glitch. This indicates that the elastic stresses accumulated in the crust can, in principle, account for the observed energetics of pulsar glitches. The accumulation of elastic stresses occurs over long-time scales (months to years), whereas phonon perturbations propagate on much shorter time scales determined by the sound velocity. Figure 1 shows the time evolution of the total elastic energy stored in the crust under constant stress. The linear increase suggests that stress accumulation may contribute to starquakes associated with pulsar glitches.

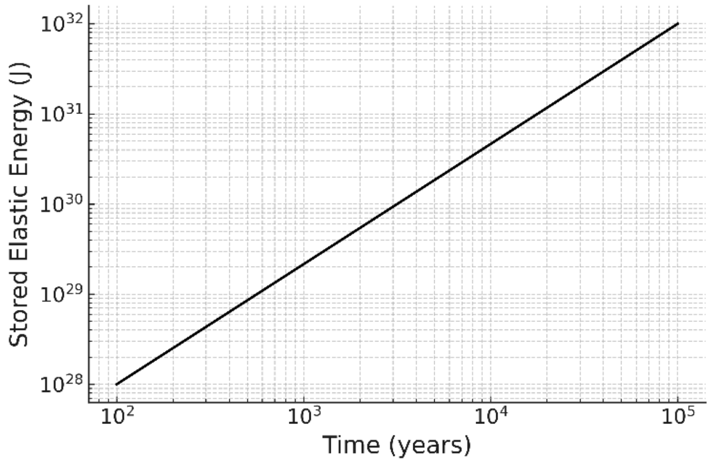

Fig.1. Energy accumulation in the crust of a neutron star.

Accumulation of elastic energy in the neutron-star crust over time under constant average stress, showing potential for triggering starquakes (glitches). This model is based on the expression for the elastic strain energy density. The accumulated energy over $10^4 - 10^6$ years can reach values of $10^{39} - 10^{41}$ erg – which is comparable to the energy released during glitches. This provides quantitative evidence that stress accumulation processes in the neutron star crust may serve as a source of starquakes (glitches), provided that a sudden release of energy occurs. The plot demonstrates the growth of accumulated elastic energy in the crystalline crust of a neutron star as a function of time, under the assumption of constant average stress. The model is derived from the relation for elastic energy density.

$$u = \frac{1}{2} \sigma \varepsilon \tag{7}$$

where σ is the mechanical stress and ε is the elastic strain.

By integrating this quantity over the crust volume, one obtains a linear dependence of the total accumulated energy on time under the assumption of a constant strain rate. Moreover, the modeling results are consistent with estimates derived from observational data on frequency glitches in pulsars such as PSR J0835–4510 (Vela), reinforcing the hypothesis that elastic processes in the crust play a key role in the glitch mechanism. Fig. 2 shows phonon frequency spectrum in the neutron-star crust, showing a peak at $\sim 10^{19}$ Hz corresponding to lattice oscillations in ultra-dense matter. Although these frequencies are much higher than

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typical macroscopic observables such as pulsar glitches, the cumulative effect of phonon processes may contribute to energy transport and stress redistribution within the crust.

Figure 3 shows the modeled phonon density of states compared with astrophysical scales. The comparison demonstrates that phonon frequencies in the crust span a wide range ($10^{19} - 10^{22}$ Hz) and may contribute to the accumulation of elastic energy.

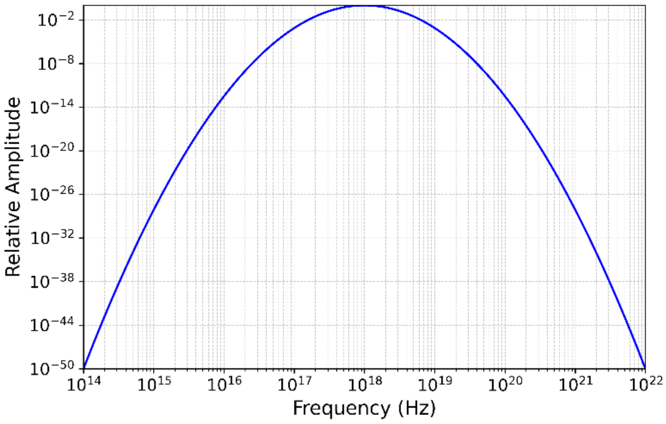

Fig. 2. Phonon frequency spectrum in the neutron star crust.

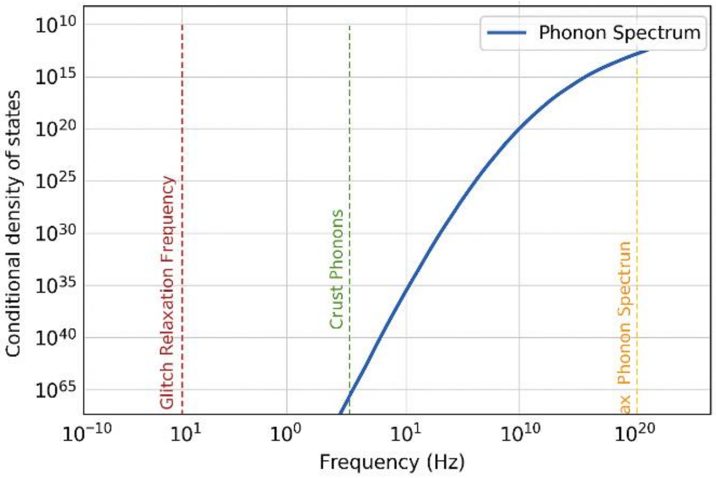

Fig. 3. Model phonon density of states compared with astrophysical scales.

The presented illustrations are based on the theory of elasticity, phonon dispersion, and available astrophysical observations, and are constructed using physically motivated scaling relations applicable to dense matter in the crust of neutron stars. While the adopted models are necessarily simplified, they reproduce the principal dependencies between density, elastic properties, and vibrational modes. Therefore, the obtained results should be regarded primarily as order-of-magnitude estimates rather than precise quantitative predictions.

3. Results and discussion

Our estimates for phonon energies and lifetimes are consistent with recent microphysical studies of lattice excitations in neutron star crusts [1, 2, 6]. Using typical lattice parameters, the energy of a single phonon in the inner crust is on the order of 10^{-4} $-$MeV, while lifetimes can reach 10^{-8}–10^{-6}s [1, 6]. These results confirm that phonons can strongly interact with both nuclear clusters and superfluid components, leading to complex dispersion relations and damping mechanisms.

Compared to previous studies, our work extends the analysis by evaluating the potential energetic contribution of collective phonon excitations to pulsar glitches. Although a single phonon carries negligible energy relative to a typical glitch ($\sim 10^{36}$ erg), the cumulative effect of coherent phonon modes over the entire crust volume ($V{\sim}10^{18}cm^3$) can contribute up to 10^{41}erg, comparable to observed glitch energetics [3, 5].

This suggests that microscopic lattice dynamics may act as a trigger for macroscopic structural failures, bridging nuclear microphysics and observable pulsar phenomena [9, 13, 14].

Our findings align with [5], who highlighted the role of superfluid elasticity in storing and releasing energy, and with [4], who modeled electron capture reactions as sources of phonon excitations. These results are also consistent with studies of shear properties and seismic activity in neutron star crusts [15].

Moreover, comparison with observational glitch statistics [3, 8] indicates that phonon-mediated stress accumulation may partially account for the frequency and magnitude of glitch events.

The limitations of our model include a simplified treatment of lattice parameters, neglect of magnetic field effects, lattice defects, and coupling with superfluid components. Future work should incorporate these factors and examine whether collective phonon processes can reliably provide the energy required for glitch events, potentially through numerical simulations and more detailed microscopic modeling.

4. Conclusion

In this study, we investigated the phonon dynamics in the crust of neutron stars and their possible contribution to structural instabilities induced by electron-capture reactions. Our results demonstrate that nuclei in excited states can induce collective phonon oscillations, with their frequencies corresponding to nuclear-scale transitions. The calculated lifetimes suggest that phonons can persist long enough to participate in stress accumulation processes.

Although the energy of a single phonon is extremely small compared with the energy released during observed glitches, their collective action and the associated accumulation of elastic stresses in the crust may contribute significantly to the total energy budget. This result highlights the importance of including lattice dynamics in neutron star models and suggests that microscopic nuclear processes may leave observable imprints on macroscopic astrophysical phenomena such as starquakes, glitches, and possibly gravitational-wave or X-ray bursts.

Future investigations should incorporate the effects of magnetic fields, superfluid coupling, and realistic crust-failure scenarios. This will help to determine whether phonon processes can indeed connect microscopic excitations with macroscopic astrophysical signals.

Conflict of interest statement

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

CRediT author statement

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