

Dynamics of nuclear reactions in the outer crust of transiently accreting neutron stars

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Some neutron stars are located in low-mass X-ray binaries (LMXBs), i.e. have low-mass companions. In these systems, matter from the companion is transferred via Roche-lobe overflow and accretes onto the neutron star. The accretion process can be either transient or persistent. During accretion, the previously accreted material is compressed under the weight of newly accreted matter. In the outer crust, the pressure is primarily determined by degenerate electrons; consequently, this compression leads to an increase in the electron chemical potential. Such an increase can drive electron capture reactions out of equilibrium. Previous studies investigating the nuclear evolution of accreted matter in the neutron star crust can be divided into two groups: (1) those that consider variable accretion rates but assume electron capture reactions occur instantaneously; and (2) those that account for finite reaction rates but assume a steady (stationary) accretion rate.

A recent study [1] examined non-stationary accretion while accounting for finite electron capture rates. However, the capture rate was computed using the zero-temperature approximation. Under this approximation, the reaction rate is exactly zero below the threshold density and increases sharply above it. Using this approach, the authors of [1] demonstrated that the crust structure is non-stationary. During an accretion episode, the composition of the outer crust evolves away from beta equilibrium due to the accumulation of nuclei above the threshold. During a quiescent state, these accumulated nuclei are burnt out, which results in a nearly beta-equilibrium composition restored before the next accretion episode begins. This leads to a cyclical pattern in the crust's composition.

In this work, we investigate the dynamics of nuclear reactions under conditions of non-stationary accretion, incorporating finite-temperature reaction rates. We show that this approach substantially alters the physical picture. Due to thermal excitations, electron capture reactions become effective even below the nominal threshold density. At the same time, the reverse reaction is suppressed: it is inhibited by a subsequent electron capture on the daughter nuclei. This second capture is superthreshold because of nuclear pairing effects – the daughter nucleus is odd-odd, so the threshold density is low. Furthermore, the dependence of the reaction rates on density becomes less pronounced. Consequently, the composition of the outer crust evolves more slowly compared to the model presented in [1]. As a result, the composition at the onset of an accretion episode depends on the long-term accretion history of the system. In particular, this effect can lead to a substantial release of energy during a strong accretion episode as a result of burning of nuclei that accumulated in the crust during earlier accretion.

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[1] Suleiman, L., Zdunik, J. L., & Haensel, P. (2024). Layers of electron captures in the crust of accreting neutron stars. *A&A*, 690, A301.

Primary author(s) : ZEMLYAKOV, Nikita (Ioffe Institute); CHUGUNOV, Andrey (Ioffe Institute)

Presenter(s) : ZEMLYAKOV, Nikita (Ioffe Institute)

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