Strong neutrino cooling by cycles of electron capture and β- decay in neutron star crusts

The temperature in the crust of an accreting neutron star, which comprises its outermost kilometre, is set by heating from nuclear reactions at large densities, neutrino cooling and heat transport from the interior. The heated crust has been thought to affect observable phenomena at shallower depths, such as thermonuclear bursts in the accreted envelope. Here we report that cycles of electron capture and its inverse, β- decay, involving neutron-rich nuclei at a typical depth of about 150 metres, cool the outer neutron star crust by emitting neutrinos while also thermally decoupling the surface layers from the deeper crust. This `Urca' mechanism has been studied in the context of white dwarfs and type Ia supernovae, but hitherto was not considered in neutron stars, because previous models computed the crust reactions using a zero-temperature approximation and assumed that only a single nuclear species was present at any given depth.

The thermal decoupling means that X-ray bursts and other surface phenomena are largely independent of the strength of deep crustal heating. The unexpectedly short recurrence times, of the order of years, observed for very energetic thermonuclear superbursts are therefore not an indicator of a hot crust, but may point instead to an unknown local heating mechanism near the neutron star surface.

The discovery of a new neutrino cooling process in neutron star crusts provides new motivation to understand the detailed composition of X-ray burst ashes, as only burst ashes with specific mass numbers will lead to cooling when incorporated into the crust. It will also be important to understand the underlying nuclear physics that determines the degree of heating and cooling in a specific mass chain. Nuclear masses and the strength of ground state to ground state beta decay transitions in very neutron rich nuclei need to be known to determine the size of the effect. While some of these exotic nuclei can be studied at current accelerator facilities such as NSCL, many others need to wait for new facilities such as FRIB.

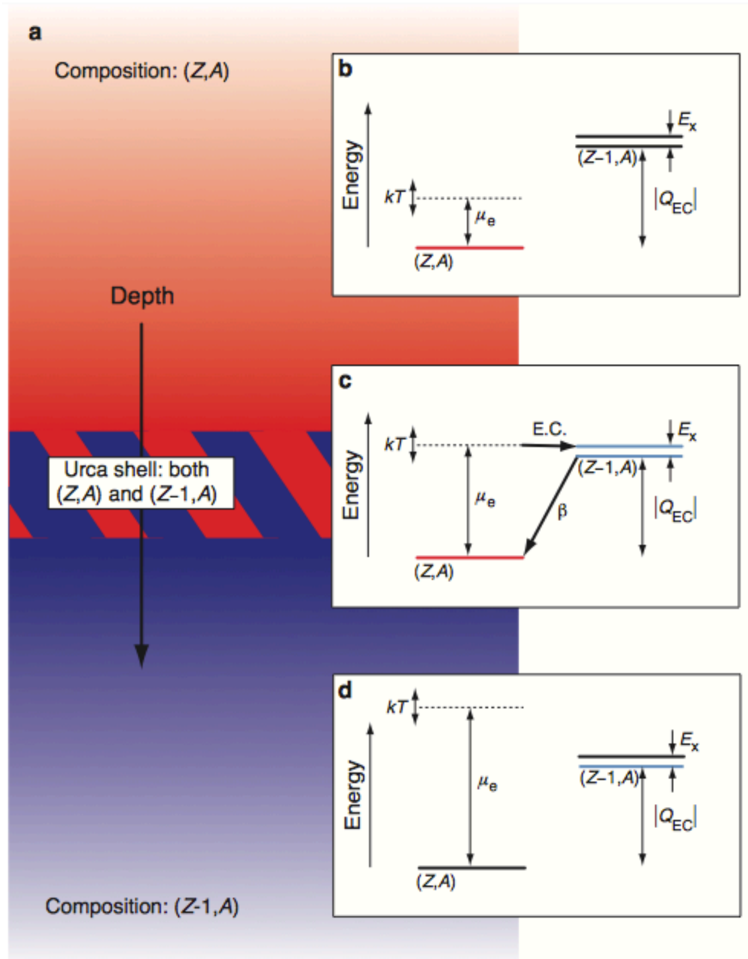

Illustration of compositional layers in the neutron star crust; b–d, energy level diagrams. In the Urca shell between the regions with composition (Z,A) and (Z-1,A) $\mu_e \approx |Q_{EC}|$. As a result, both electron capture and β− decay are possible, and rapid cycling between the nuclei (Z, A) and (Z − 1, A) leads to a strong neutrino emissivity.

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