University of Tsukuba | Center for Computational Sciences

Quantum many-body dynamics in nuclear EOS and nucleosynthesis

Information on the nuclear EOS

The equation of state (EOS) of the nuclear matter is a key element to determine the fate of giant stars, supernovae, and properties of neutron stars (Fig. 1). However, there are significant uncertainties at present because of difficulties of numerical calculation and unsettled parts of nuclear (baryonic) interaction. On the other hand, recent experiments in radioactive beam facilities in the world provides new data on elementary modes of excitation in exotic neutron-rich nuclei. We have investigated possibilities to extract the EOS information from current and future experiments. The measurement of electric dipole (*E1*) strengths at low energy can be a candidate for that. In neutron-rich nuclei, the low-energy excited states are strongly populated by the *E1* field. Our large-scale calculation using the time-dependent density functional theory reveals that those *E1* strengths show a strong correlation with the neutron matter EOS, but the quality of the correlation significantly changes from ^{68}Ni to ^{84}Ni. Figure 2 indicates a correlation between the density dependence of the energy of the neutron matter (*L*) and the low-energy *E1* strength in selected nuclei. The future measurement in ^{84}Ni may give a strong constraint on the neutron matter EOS.

Fig. 1: Pulsar (neutron star) in the crab nebula which is the remains of SN1054.

[Courtesy of Hubble Site: Release number: STScI-2002-24]

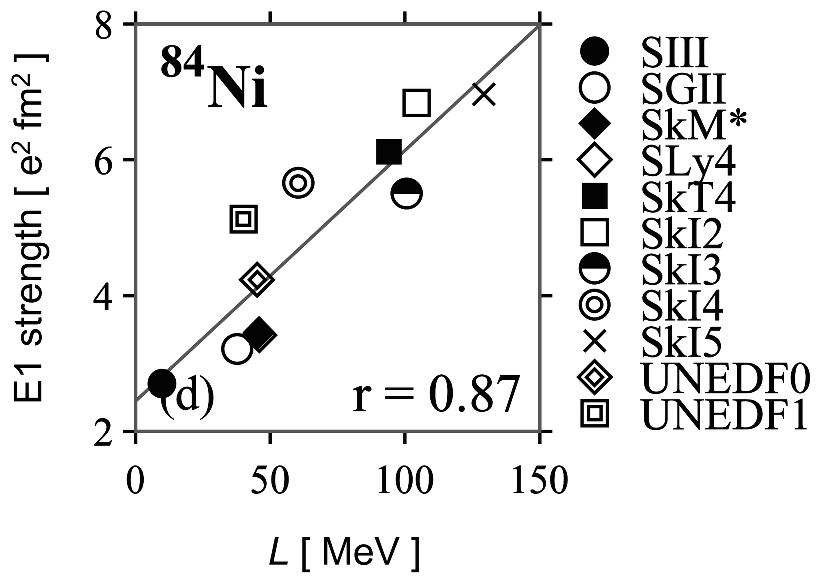

Fig. 2: Correlation plot between low-energy E1 strength in ^{84}Ni and the neutron matter EOS.

Triple alpha reaction for ^{12}C synthesis

In the early stage of the universe after the big, collisions of the protons and the neutrons lead to formation of the deuterons (mass number *A*=2) and helium (*A*=3 and 4). However, this process cannot continue to synthesis of heavier elements, because there are no stable nuclei of *A*=5 and 8. The fusion of two ^{4}He (alpha) particles form ^{8}Be, however, this nucleus exists only for a very short period as a resonance. Thus, it promptly decays back into two alpha particles. The only possible bypass is the triple alpha reaction which creates the ^{12}C nucleus directly from fusion of three alpha particles (Fig. 1). Although it is such an important reaction process, both experimental and theoretical investigations are very difficult, because this is a fully quantum reaction of three charged particles and an extremely rare event.

We have succeeded to calculate the formation probability of ^{12}C in stars at finite temperature. The essential idea is the use of the imaginary-time propagation for the radiative capture reaction of three alpha particles. It turns out that, to achieve the convergence, we need to explicitly treat very large distance between two alpha particles. The imaginary-time evolution also reveals what kind of reaction process is important at a given temperature (Fig. 2): At relatively high temperature ($T > 0.074$ GK), a resonance state in ^{12}C plays a dominant role. At low temperature ($T < 0.028$ GK), the non-resonant capture process is dominant, and in between ($0.028 < T < 0.074$ GK), the reaction through the resonance state of ^{8}Be mostly contributes to the formation of ^{12}C.

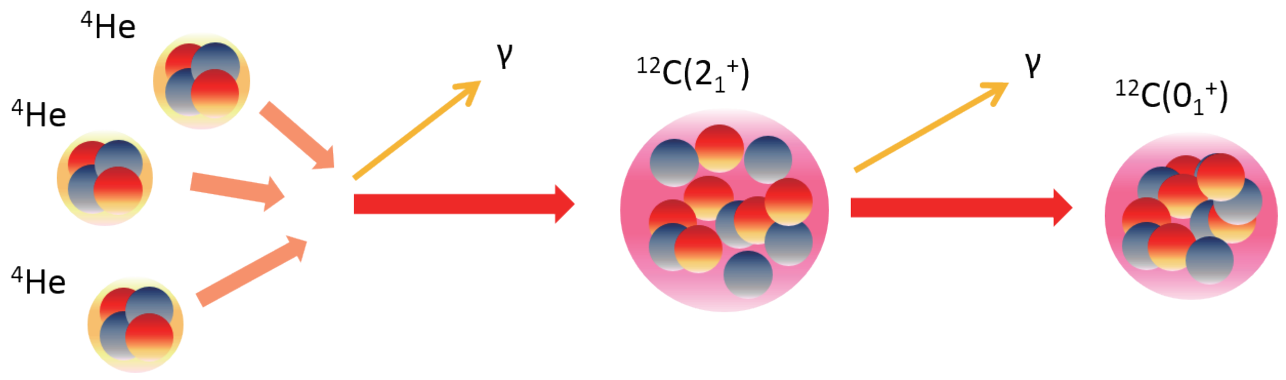

Fig. 1: Radiative capture process of the formation of ^{12}C.

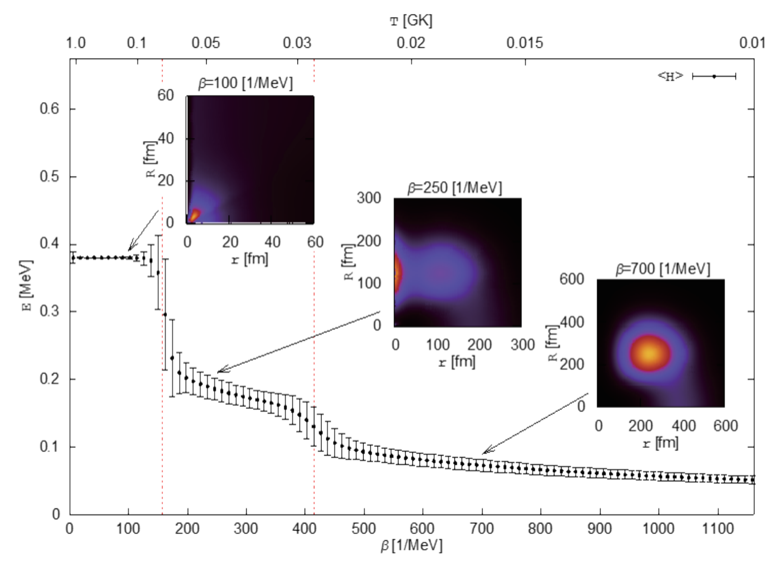

Fig. 2: Energy expectation value and variance as a function of temperature for ^{12}C. Calculated density distribution at three different temperatures are also shown.