Contribution ID: **120** Type: **Oral**

Temperature effects on neutron-capture cross sections and rates through electric dipole transitions in hot nuclei

The Extreme Light Infrastructure for Nuclear Physics (ELI-NP) pillar is located in Romania and is intended to serve the broad international scientific community. Its mission covers scientific research involving two domains: the first is laser-driven experiments related to NP, strong-field quantum electrodynamics, and associated vacuum effects.

The other research domain is based on the establishment of a Compton-backscattering-based, high-brilliance, and intense γ beam with Eγ ⊠ 19.5 MeV, which represents a merger between laser and accelerator technology. This system will allow the investigation of the nuclear structure of selected isotopes and nuclear reactions of relevance, for example, to astrophysics, with increased resolution and accuracy.

Neutron capture processes relevant for astrophysics, like the r-process, take place in stellar environments with high temperature. However, the temperature effects are usually not included in the microscopic calculation of dipole strength functions. Temperature effects are normally included in a phenominological approach, as a parameter in the Lorentzian function for the calculation of neutron-capture rates. In this case, the fine structure changes and/or novel structure induced by temperature effects are missing in the calculation of neutron capture rates, despite its potentially important impact.

Experimentally, the giant dipole resonance (GDR) built on hot nuclei can be measured by fusion-evaporation reactions and inelastic scattering with light ions. However, these studies are limited to stable nuclei, and focus on the GDR energy region, where the evolution of GDR width with temperature is paid special attention.

The self-consistent finite-temperature relativistic random-phase approximation (FTRRPA) model was developed, and it was shown that low-lying dipole strengths are modified by temperature effects, including the concentration of new low-lying dipole strength for ^{60,62}Ni, and the modification of PDR for ^{68}Ni and ^{132}Sn. Later, based on the Woods-Saxon mean field, the thermal continuum QRPA (TCQRPA) model explains the low-energy enhancement of the dipole strength functions with the inclusion of temperature effects. More recently, the self-consistent finite temperature QRPA based on Skyrme density functional was developed, and new low energy dipole excitations were discovered.

With these discoveries, it is interesting to see what are the consequences of the modifications of low-lying dipole strength with the microscopic inclusion of temperature effects on the neutron capture cross sections and rates. Previous sensitivity studies have shown that the neutron-capture rates of Sn isotopes are important for r-process simulation in different astrophysical environments. Therefore, in this work, taking Sn isotopes as an example, we calculate the electric dipole strength at finite temperature using a self-consistent FTRRPA model, and correspondingly investigate the influence on neutron capture cross sections and rates using these dipole strength functions.

The dipole strengths at zero temperature are calculated by a RQRPA model, with the inclusion of pairing correlations. Within the mean field approach, there is a critical temperature above which the pairing correlations vanish, although this sharp phase transition is washed out by including thermal fluctuations beyond mean field. At relatively high temperatures, the pairing correlations are not so important any more, so we use the FTRRPA model for the calculation of dipole strength functions at finite temperature.

The temperature evolution of electric dipole transition strengths of Sn isotopes is studied using self-consistent QRPA and finite-temperature RPA models based on a relativistic density functional. For tin isotopes lighter than ^{132}Sn, temperature only shows its effect at high values of 2 MeV, while for neutron-rich tin isotopes heavier than ^{132}Sn, the low-lying strength distributions get fragmented and spread to the lower-energy region already at temperature of 1 MeV. Using these electric dipole transition strengths as inputs for the TALYS code, the temperature effects on (n, γ) cross sections are studied. For tin isotopes lighter than ^{132}Sn, temperature causes an enhancement of neutron capture cross section at high temperatures of 2 MeV, while for neutron-rich tin isotopes heavier than ^{132}Sn, the cross section is largely enhanced already at temperature $T = 1.0$ MeV, and the bump of cross section caused by the pygmy dipole resonance also becomes broader. The change in neutron-capture rate can be as large as 70\% for ^{136}Sn, considering the temperature effects on electric dipole transition strength in the final compound nucleus with a temperature of 0.86 MeV (corresponding to $T = 10$ GK in the astrophysical environment). The change is around 20\% for tin isotopes lighter than ^{132}Sn and above 40\% for those heavier than ^{132}Sn.

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Session Classification: Poster Session

Track Classification: Poster Presentations