New indirect method to determine proton capture rates in X-ray bursts in the laboratory

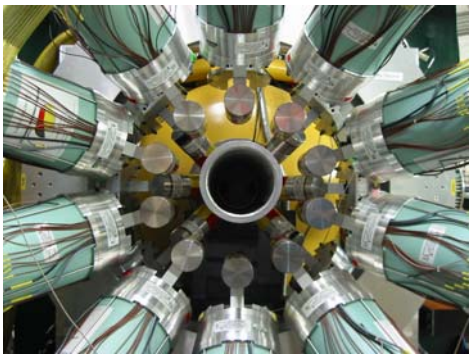

Figure: SeGA detector array at the NSCL.

X-ray bursts are frquently observed bright X-ray flashes powered by thermonuclear explosions of hydrogen and helium on the surface of neutron stars. The hydrogen and helium flows onto the neutron star from a nearby companion star and accumulates for hours to days until it explodes. During such an explosion heavy elements up to Tellurium can be formed by a complex sequence of reactions. In order to compare model predictions with observations, the models need to include accurate reaction rates that need to be determined by laboratory experiments. This is extremly difficult as the reactions involve extremely unstable nuclei that in most cases cannot be produced in quantities sufficient to perform the necessary experiments.

A JINA NSCL collaboration developed a new method that can be used to determine reaction rates for proton capture indirectly. During an X-ray burst, a proton is captured by a nucleus producing a new isotope in an excited state. The energy of the excited states in the final nucleus largely determines the rate of the reaction. The JINA NSCL collaboration demonstrated that the same nucleus in the same excited state can be produced in the laboratory. First a beam of radioactive nuclei with one additional neutron is produced by fragmentation of a beam of stable nuclei accelerated at the NSCL Coupled Cyclotron Facility. The beam of radioactive nuclei then hits a plastic target where in a nuclear reaction occasionally a neutron is removed leaving the final nucleus in the excited state of interest. The excited nucleus deexcites in flight after a very short time, typically femtoseconds, and the emitted gamma radiation is detected in the SeGA detector system. The nucleus then continues to fly through the S800 spectrometer where it is uniquely identified. The recorded gamma-rays in coincidence with the correct nucleus arriving in the spectrometer allow one to determine the energy of the excited state in question with very high precision of a few keV. Combining this information with theoretical shell model predictions for the internal structure of the state improves the uncertainties of calculated reaction rates from factors of 10,000 to just a factor of 2-3.

The first case to demonstrate this technique was the proton capture rate on ^{32}Cl, an unstable nucleus with a half-life of just 298 milliseconds. In this case a radioactive beam of ^{34}Ar was produced to search for states in ^{33}Ar. The JINA NSCL collaboration recently used the information

from this first experiment to present a new reaction rate that can be used for X-ray burst simulations. A surprise was the finding that in this case the reaction rate is actually dominated by capture on the first excited state of the target nucleus, which can be thermally excited at the high temperatures during an X-ray burst. While traditional direct measurements of reaction rates only determine capture rates on nuclei in their ground states (as the temperature in the laboratory is much lower than the 1.5 billion degree of an X-ray burst), our new indirect method does not suffer from this limitation. This, and the fact that most nuclei in the reaction chains of X-ray bursts are accessible at the NSCL make this a powerful new tool to be used in many experiments to come.

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