【Grant-in-Aid for Scientific Research (S)】

Extended study of the origins of heavy elements via comprehensive mass measurement of short-lived nuclides

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Purpose and Background of the Research

●Outline of the Research

In the solar system, there are 81 stable elements ranging from hydrogen to bismuth, a few radioactive elements such as thorium and uranium, and about 255 nuclides, including their isotopes. Their abundances deviate muti-orders of magnitude, and the fact is not apparent truth. Normal fusion reactions in a star cannot synthesize elements heavier than iron. Neutron absorption and successive beta-decay raise the atomic number of the nucleus one by one. The slow neutron capture process (~1000 years) proceeds along the stable nuclides and is experimentally studied well, while the rapid neutron capture process (~ 1 s) proceeds along nuclides far beyond the known nuclides. The r-process path is determined by the mass of the nuclei in the vicinity of the pathway (more specifically, the neutron separation energies derived from the difference in the mass of nuclei). In particular, the waiting points on the path, which are the origins of abundance peaks at Pt and Te, are at the neutron magic numbers. The most evident indication of their magicity is the shell gap energy (ΔS_{2n}) derived from the second-order difference in masses.

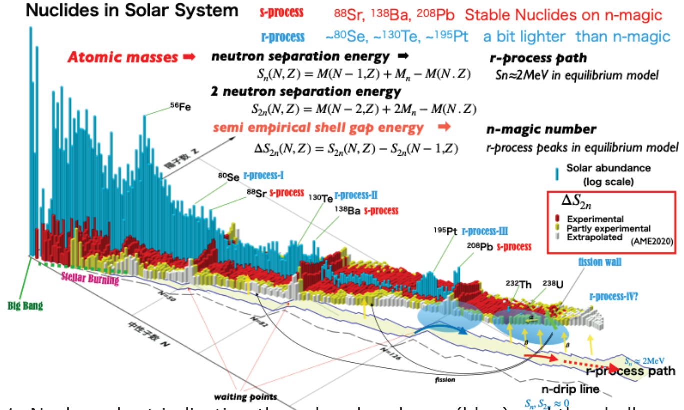

Figure 1. Nuclear chart indicating the solar abundance (blue) and the shell gap energies derived from the masses of atoms.

●Experimental Techniques for Comprehensive mass measurement

Comprehensive mass measurement of more than 1,000 short-lived nuclei involved in the elemental synthesis process is of utmost importance for experimental elucidation. Developing a new instrument based on new technology was necessary. We have developed RF carpet gas cell systems to collect fast radioactive ion beams in ion traps at three short-lived nuclear beam sources, GARIS, BigRIPS-SLOWRI and KEK's KISS at RIBF. The MRTOF (Multiple Reflection Time-of-Flight Mass Spectrograph), which efficiently and precisely measures the mass of short-lived nuclear ions, is now available for comprehensive measurements.

●MRTOF mass spectograph

The MRTOF consists of a pair of electrostatic mirrors. Short-lived nuclear ions collected in an ion trap are injected in a bunch, passed back and forth between the mirrors several hundred times, and then extracted for precise ToF measurement. The mass can be determined by comparing the ToF with that of reference ions. We achieved one million mass resolving power with a flight time of about 10 ms, the best performance in the world, including other mass measurement devices.
This mass spectrograph can perform mass measurements of multiple ions simultaneously, it allows comprehensive mass measurement with high efficiency.

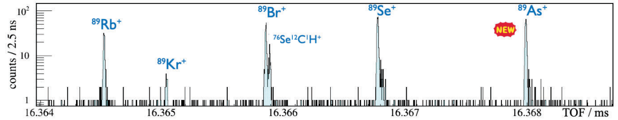

Figure 2. Time-of-Flight spectrum for 89As and isobars measured at BigRIPS-SLOWRI

Expected Research Achievements

●Verification of neutron magic numbers in neutron rich region

We will verify whether the magic numbers of N = 50, 82, and 126 in the more neutron-rich regions, i.e., closer to the r-process pathway. The observed breakdown of the magic numbers and their appearance at different neutron numbers in lighter nuclei provide direct evidence for the origin of the r-process-induced peaks. The Discovery of new quasi-magic numbers will elucidate the origin of the rare-earth element peaks, for example.

●Improving the accuracy of mass formulas

In the platinum and uranium regions, it is still challenging to reach the r-process pathway experimentally. Therefore, measuring the mass of neutron-rich nuclei as far from the stability as possible can significantly improve the accuracy of the mass formula prediction. The accuracy of the network calculation of the r-process will increase dramatically.

●Mass of SHE (nihonium)

The currently discovered superheavy isotopes are on the opposite side of the beta stability line; they are not produced by the r-process. However, the r-process can reach the "island of stability" expected to lie beyond the neutron-rich superheavy isotopes. To confirm this, the presence or absence of quasi-magic numbers in this extremely neutron-rich region is a significant concern. The mass measurement of superheavy elements will lead to the discovery of this phenomenon.
The precise mass measurement of neutron-rich nihonium will verify the atomic numbers of newly discovered elements, Z>114.

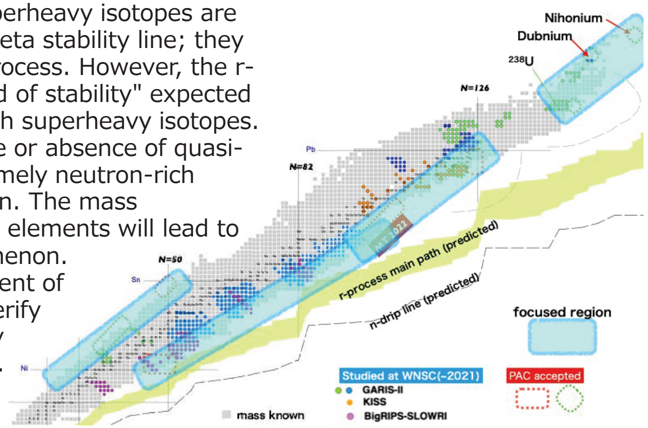

Figure 3. Nuclear chart indicating >400 nuclides we have measured and planned region of nuclides

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