RARE ISOTOPE BEAMS
IN ASTROPHYSICS

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Unstable isotopes govern the late evolution of stars and their explosive phenomena, such as novae, supernovae, x-ray bursters and neutron star mergers. Most of them are still out of reach of terrestrial experiments. Upcoming facilities will allow scientists to produce/observe them and shed light on fundamental questions about our universe.

Rare isotopes and their astrophysical origin

Only a small fraction of the existing nuclei is stable, about 250 in total. All the elements have isotopes that are unstable and disintegrate, or decay, by emitting radiation. Some nuclei have no stable isotopes and eventually decay to other elements. Unstable nuclei are numbered several thousands, and most of them have not been observed yet. Especially rare isotopes – unstable nuclei with extreme neutron-to-proton ratios - are still uncharted. Where do they come from? Once the Big Bang was ruled out as a major nucleosynthesis site, efforts focused on nucleosynthesis in stars (Hoyle 1946). Follow-up studies outlined the key role played by stars as nuclear crucibles where most of the cosmic elements have been (and are being) forged, but observational evidence of their contribution to the galactic abundances was yet missing. The detection of technetium in the spectra of some giant stars (Merrill 1952) provided smoking-gun confirmation to this hypothesis. Technetium is, in fact, the lightest species with no stable isotopes. Since its longest-lived isotope has a rather short half-life, $T_{1/2}(^{98}\mathrm{Tc}) \sim 4.2$ Myr, compared with the age of the universe, its detection proved that nucleosynthesis is an ongoing process. Further evidence in this regard has been provided by the detection of other radioactive nuclei, such as ^{26}Al or ^{44}Ti.

Since then, many unstable isotopes have been identified as major players in a suite of astrophysical scenarios. Classical novae, for instance, are powered by the decay of the short-lived, β^+-unstable nuclei ^{13}N, ^{14,15}O,

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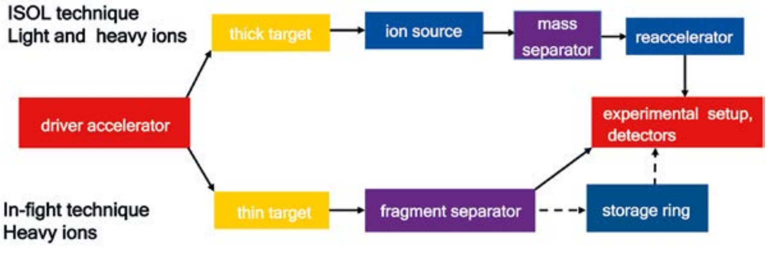
▲**FIG 1:** Left: Tarantula Nebula in the Large Magellanic Cloud. Supernova 1987A is clearly visible as the very bright star in the middle right. Image taken with the ESO Schmidt Telescope. Right: Tattered remains of a supernova explosion known as Cassiopeia A (Cas A), the youngest known remnant from a supernova explosion in the Milky Way. Image taken with the NASA/ESA Hubble Space Telescope

and ^{17}F, that must be carried away by convection to the outer, cooler envelope layers to escape destruction by proton-capture reactions. Synthesis of ^{22}Na in novae has been predicted to be potentially observed through the 1275 keV gamma-ray line. In a somehow related scenario, type I X-ray bursts, the main nuclear path is delineated by the proton-drip line and by the presence of certain waiting-point nuclei, such as ^{22}Mg, ^{26}Si, ^{30}S, and ^{34}Ar. Light curves from type Ia supernovae are in turn powered by the decay chain $^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$. The first unambiguous detection of the early 158 keV and 812 keV ^{56}Ni γ-ray lines and late 847 keV and 1238 keV ^{56}Co lines has been reported for SN 2014J, the closest type Ia supernova detected since the advent of γ-ray astronomy. The distribution of ^{26}Al in our Galaxy and its correlation with ^{60}Fe has provided valuable inputs to link their origin to massive progenitors (most likely, core-collapse supernovae), helping in turn to better constrain models of these explosions.

Synthesis of rare nuclei beyond $A \approx 60$ takes place mostly entirely by exposing lighter seed nuclei to a source of neutrons. Such a mechanism provides a natural explanation for the fact that the solar system abundance curve peaks near the mass numbers $A \approx 84$, 138 and 208, corresponding to the neutron magic numbers of $N = 50$, 82, and 126, respectively. The neutron capture may be either slow (s-process) or rapid (r-process), mostly depending on the flux of neutrons. In particular, the r-process, whose production site is yet to be self-consistently identified (core-collapse supernovae and/or neutron star mergers?), is activated under a so large neutron exposure that the decay constant of an unstable nucleus (such as ^{130}Cd, ^{131,133}In or ^{160}Gd) created after neutron capture is small compared to the decay constant of the competing (n,γ) reaction ($\lambda_\beta << \lambda_{n\gamma}$). In this case, the nucleosynthesis path runs close to the neutron dripline.



▼**FIG 2:** Simplified scheme of production of radioactive nuclear beams with ISOL technique and in-flight separation.

Facilities and techniques

Dedicated facilities have been built to produce and accelerate radioactive nuclides to study their nuclear properties and interactions. Two methods are mostly used to carry out such studies: the isotopic separation online (ISOL) and the in-flight separation (Gelletly 2000, Blumenfeld 2013).

In the ISOL technique, the radioactive nuclei are created from the interaction of a stable (or neutron) beam hitting a thick target. A medley of nuclides is generated inside the target and the species of interest is separated from the others after being extracted, for instance by diffusion, and injected into an ion source. Then, it is reaccelerated onto a secondary target to induce, for instance, the nuclear reactions of astrophysical importance.

The main advantage of ISOL facilities is the availability of high-quality beams, in terms of intensity and focusing, the latter being comparable with those of stable-ion beams. However, the range of available isotopes is rather limited since some of them have too short lifetimes for enough nuclei to survive the delay times of the ISOL method (from ~10 milliseconds for ion guides and gas catchers or high-temperature target assemblies to hours or more, *e.g.*, in the case of batch-mode production).

ISOL facilities include the pioneering laboratories at Louvain-la-Neuve (Belgium) and ISOLDE (CERN, Switzerland), second-generation facilities such as SPIRAL2 (GANIL, France) and FRIB (NSCL, USA), and forthcoming ones such as SPES (LNL, Italy).

The in-flight separation technique opens to the investigation of radioactive ions with lifetimes of microseconds. High-energy beams (hundreds of MeV) of heavy nuclei are driven onto thin targets to induce fragmentations. The kinematic conditions lead to fast forward-focused cocktail beams; fragment separators are placed downstream to single out the radioactive beam of interest that is focused onto a secondary target to carry out nuclear reactions. However, beam quality in terms of energy spread and angular focusing is usually worse than in the case of ISOL beams, and beam energy fine tuning is more complicated to achieve. An additional advantage of in-flight production is the possibility to inject freshly produced radioactive ions into a storage ring, as planned at GSI, Germany, where CRYRING will make it possible to recycle and slow the ions down to about 100 keV/u, opening interesting opportunities for nuclear astrophysics.

In-flight facilities worldwide include FRIB (NSCL, USA), LISE (GANIL, France), RIBF (RIKEN, Japan), with several smaller scale facilities like TwinSol at the Notre Dame University (USA) or SOLEROO at the Australian National University.

As foreseen by the FRIB long-range plan, soon about 80% of the isotopes predicted to exist for elements up to uranium and beyond will be produced and investigated.

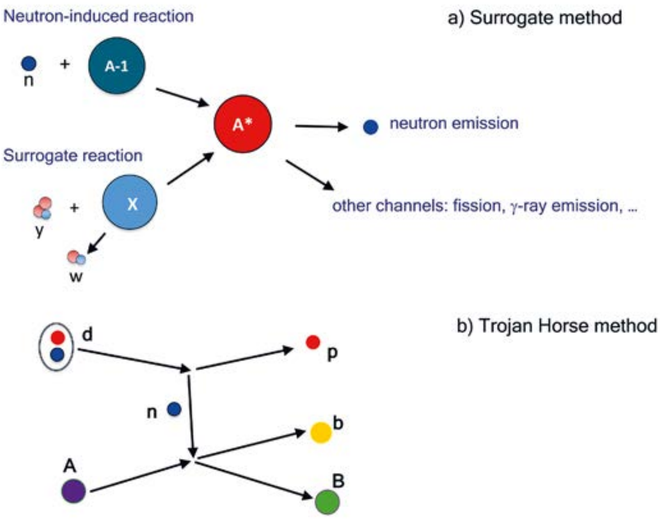
Nuclear inputs and methods

Impressive progress has been achieved to perform laboratory measurements with rare isotopes, despite intrinsic difficulties, such as extremely small cross sections, low beam intensities or the absence of appropriate radioactive targets. Charged-particle reactions on short-lived nuclei are usually measured in inverse kinematics using hydrogen and helium targets, with recoil separators to detect and identify the recoiling products and to reject the beam. The pioneering measurement with a rare-isotope beam was $^{13}N(p,\gamma)^{14}O$ using a ^{13}N beam (3×10^8 particles/s) produced at Louvain-la-Neuve. A successful experimental method to study the properties of resonances is the resonant elastic and inelastic scattering, which has provided an extensive amount of data on unbound states in proton-rich nuclear systems relevant to reaction rates in explosive burning scenarios. With rare isotope beams, a thick-target is often used, where the beam is stopped and β-γ spectroscopy is performed to study electromagnetic decay of isomeric and excited nuclear states, and to measure gamma rays following beta-decay of excited states into the daughter nuclei. The stopped beam spectroscopy may also offer information on exotic decay modes such as β-delayed proton(s) or neutron(s) emission in the nuclei toward the drip lines. Nuclear mass measurements are also needed in the modelling of various nucleosynthesis processes, in particular r-process pathways, with typical masses larger than $50\ \mathrm{GeV}/c^2$. Two distinct classes of techniques exist: determination of Q-value through reactions or decay; direct mass measurement through mass spectrometry, time-of-flight, cyclic/frequency measurements.

To access the reaction rates, indirect techniques are also employed and in some cases are the only viable alternative. One such technique is the surrogate method (Escher *et al.* 2007), mainly used for neutron capture reactions: a surrogate $X(y,w)A^*$ reaction is used to populate the same A^* compound nucleus of the (n,γ) reaction and then the desired decay channel is measured. The method relies on the assumption that the decay of the compound nucleus is independent of the entrance channel. Another indirect approach, the Trojan Horse method (Tumino 2021), exploits a quasi-free $A(d,bB)p$ transfer reaction to determine the cross section of the $A(n,b)B$ reaction at astrophysical energies: deuterons are used as virtual n-targets, with the remaining proton acting as a spectator in the A+n interaction.

Conclusions

Nuclear reactions involving rare isotopes determine the signatures of elemental and isotopic abundances found in the spectra of any astrophysical object. This is a major reason why the rare isotope science is the trending topic of nuclear research worldwide. Rare isotope beams in nuclear astrophysics represent the beginning of a new era of exploration and discovery that will challenge experimentalists and theorists alike. ■



▲ FIG 3: a) The surrogate-reaction method in a schematic representation. The surrogate reaction is here a transfer reaction $X(y,w)A^*$. b) The Trojan Horse method for neutron induced reactions represented with its characteristic pole diagram. The upper vertex shows the deuteron break-up, while the lower vertex the $A(n,b)B$ neutron induced process.

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