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EXTREMES OF THE NUCLEAR LANDSCAPE: EXPERIMENTAL STUDIES*

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Increasingly more intense beams of radioactive isotopes allow moving into unknown areas of the nuclear chart and exploring the limits in nuclear binding and proton-to-neutron ratio. New aspects of nuclear structure and important results for nuclear astrophysics are obtained. The paper provides some overview of experimental developments, facilities and research results; and is intended to set the stage for the many exciting examples of research presented in these proceedings.

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The strong interaction builds the atomic nucleus, the massive core of all visible matter. The properties of the strong, together with the electroweak force define the boundaries: the limits of nuclear binding and neutron-to-proton ratio; the possible shapes and relevant degrees of freedom; limiting excitation energies and temperature; the extremes of dense nuclear matter in neutron stars and stellar explosions; properties arising from the three-body force and nuclear structures involving strangeness; or quite generally, the boundaries from the underlying theory of the strong interaction, quantum chromo-dynamics (QCD), whose quark and gluon fields shape the nuclear building blocs, *i.e.* the nucleons, the QCD condensates and the nuclear forces. Figure 1 presents a cartoon-like overview of some of these features.

The experimental exploration of the extremes of the nuclear landscape is challenging. But its successes promise basic insights in the existence and the properties of massive, visible matter and in its role in shaping the evolution of stars and of the chemical elements in the Universe.

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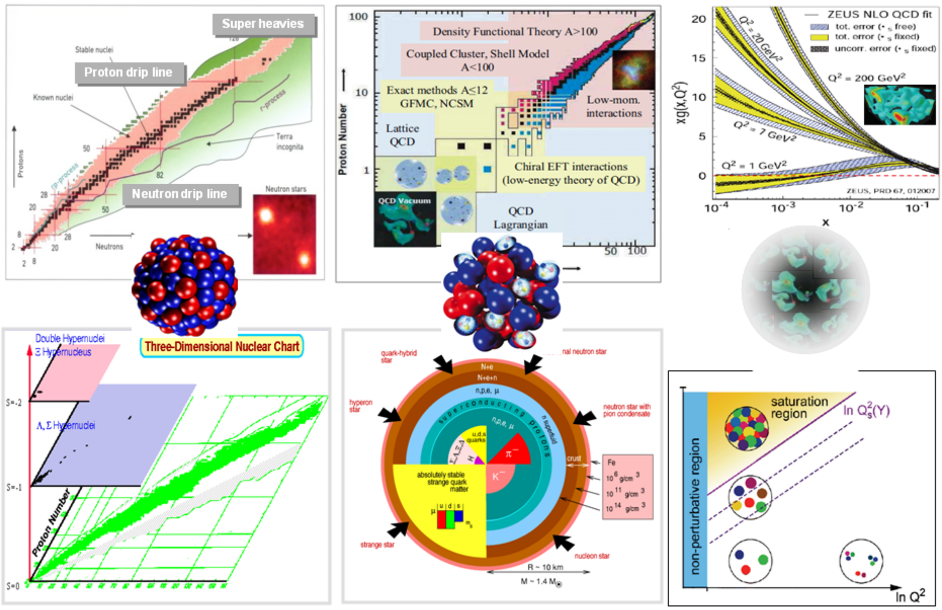

Fig. 1. Extremes of the nuclear landscape: the conventional chart of nuclides illustrating the limits of proton and neutron binding in the nuclear many body system (top left); the chart on a logarithmic scale to emphasize the transition from the sub-nucleonic to the nucleonic regime and their degrees of freedom (top middle); gluon structure functions of the nucleon from ZEUS/DESY (top right), an artist's view of the quark-gluon field in the nucleus and gluon saturation behavior (bottom right); the three dimensional chart of nuclides with strangeness axis (bottom left); dense nuclear matter(s) in a neutron star (bottom middle).

In the context of this conference, the focus is on the nuclear chart, *i.e.* the existence and properties of bound, or quasi-bound nuclei as a function of proton and neutron number. Here an enormous quantitative but, as a result, also a significant qualitative expansion of experimental knowledge is taking place. The technical advances in producing nuclei far from stability at increasing intensities, and in particular in providing them as energetic beams of good quality has opened a new era of experimental exploration. Figure 2 illustrates with some examples the reach for rare isotopes that has been achieved over the nuclear chart, depending on the goals of the respective experimental programs. It is not possible, within the scope of this paper, to do justice to all the substantial advances made and I apologize in advance for their omission. But many more beautiful examples can be found in various other articles of the present proceedings.

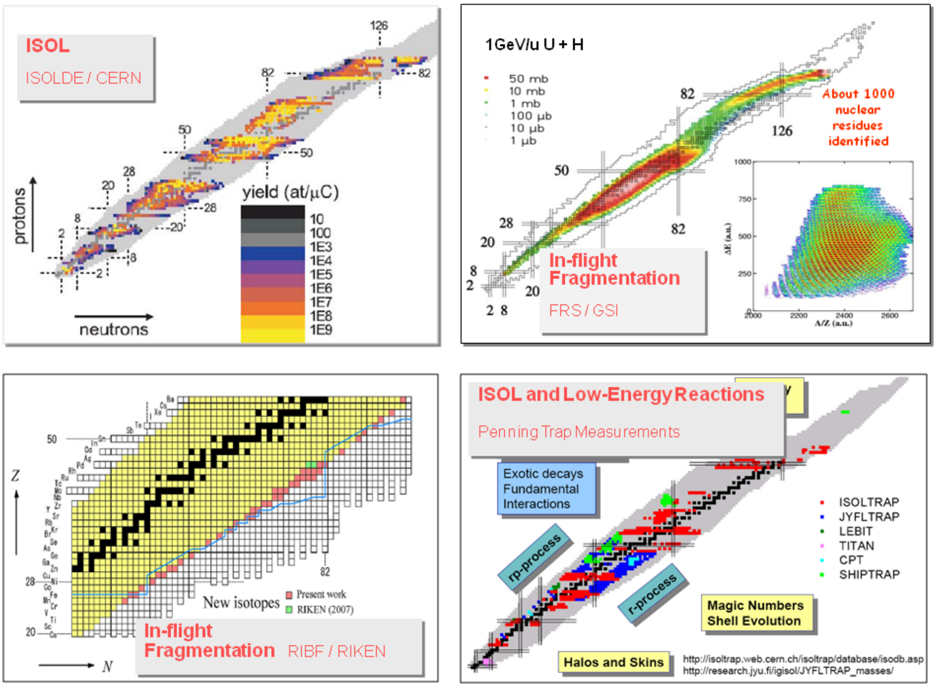

Fig. 2. Examples for the reach of rare isotopes produced by various methods: ISOL at ISOLDE/CERN [1]; in-flight fragmentation at GSI [2] and RIKEN [3]; Penning trap studies at various ISOL and low-energy facilities [4].

Figure 3 broadly summarizes the methods used in producing rare isotope beams (RIB). One can group them into two major categories, in-flight production and the ISOL method which involves re-acceleration of stopped radioisotopes. There are a number of smaller variations on the specific techniques; again they can be found in the various contributions to these proceedings. The table inserted in Fig. 3 compares RIBs from in-flight fragmentation and from in-beam low-energy reactions. The reason why the latter are at all competitive comes from the fact that, despite generally much smaller cross-section and thin-target yields, the latter is concentrated in a few channels in contrast to the split of the yield into a considerably larger number of channels in high-energy in-flight fragmentation. In addition, the controlled re-acceleration provides beams of the specific (often low) energies needed for the science under investigation, such as reaction cross-section measurements for astrophysics. Figure 4 shows a world map with operating facilities at the time of the conference. But the world scene of facilities is steadily evolving, with new projects and plans. This is discussed in some more detail further below.

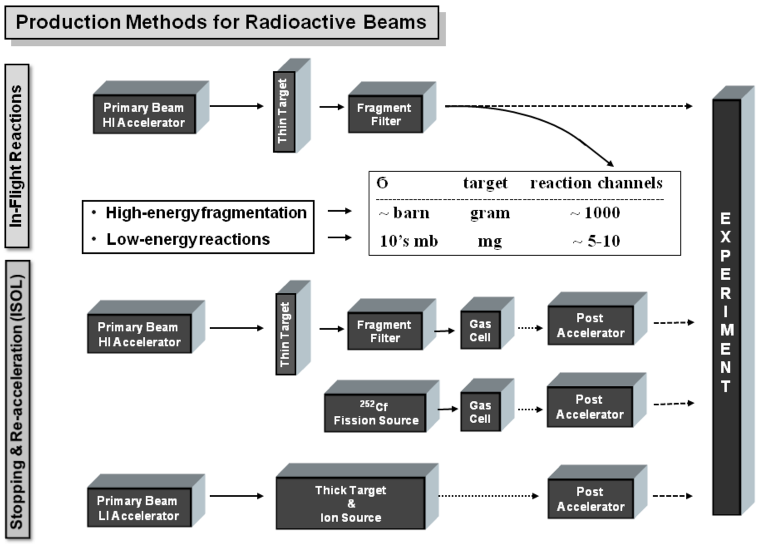

Fig. 3. Schematic of some principal rare isotope beam (RIB) production methods, with in-flight reactions in the upper half of the figure and the ISOL methods, *i.e.* rare isotope production in a target-ion source and/or stopper configuration and subsequent re-acceleration for precision beams at the bottom.

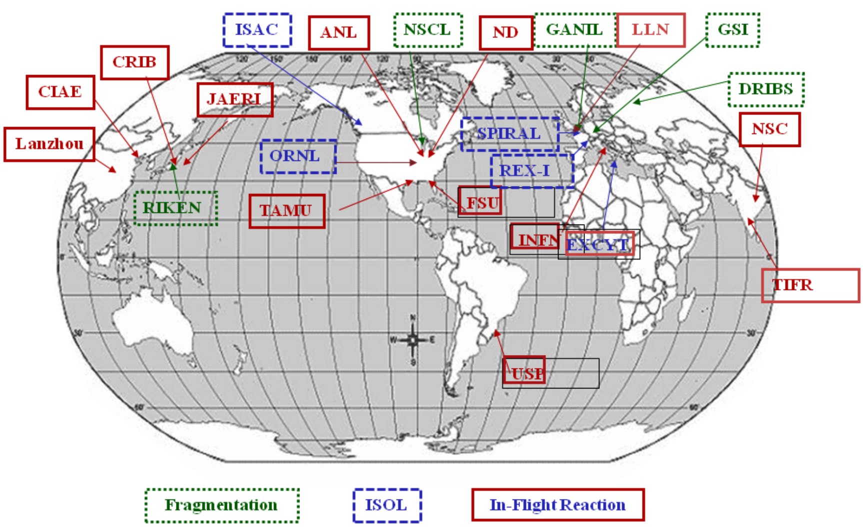

Fig. 4. Worldwide map of operating radioactive beam facilities, sub-divided into facilities based on in-flight fragmentation at high energies, in-flight nuclear reactions at lower energy, and ISOL based facilities.

With the state-of-the-art RIB facilities one can, in principle, move outward from the valley of stability as far as the primary beam intensity allows. This is more difficult for one specific area of the nuclear chart, *i.e.* what might be labeled the *Far North-East*. This is illustrated in Fig. 5: neither fragmentation of uranium nor fusion of lighter targets with neutron-rich beams is likely to reach this area of the nuclear chart.

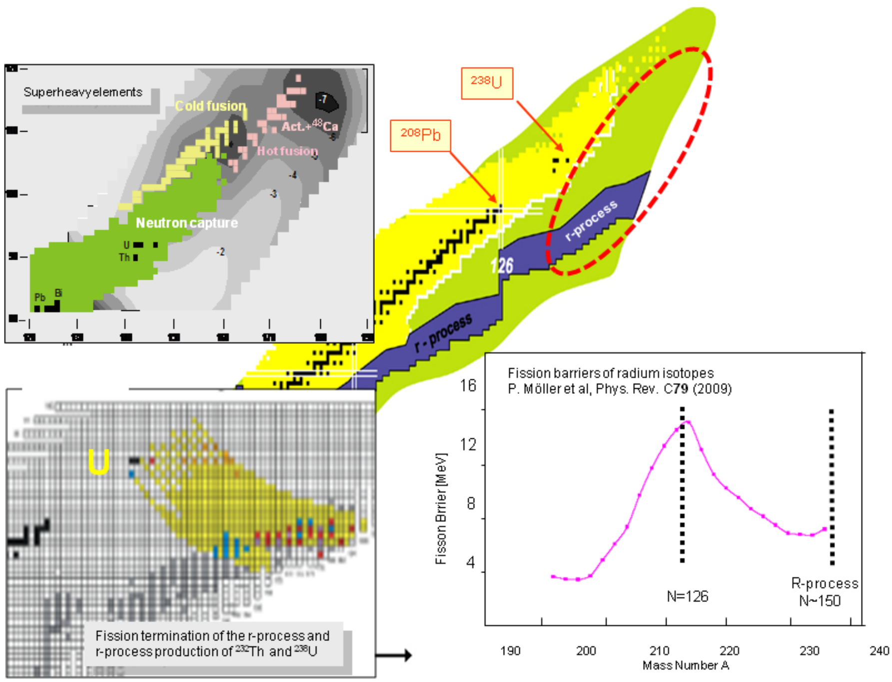

Fig. 5. The *Far North-East*, as marked on the nuclear chart, is difficult to reach with the current methods of RIB production. This is the region where the r-process will likely end and undergo fission recycling; basically no experimental information on fission barriers is available for neutron-rich heavy nuclei. Predictions [5] for radium isotopes are shown in the insert on the right. The behavior of the fission barriers might provide unique information on the symmetry energy. In addition, this region borders on the missing bridge between the superheavy island found in 'hot' fusion reactions and the mainland of the nuclear chart.

On the other hand, this region poses some as yet unexplored basic questions and perhaps new phenomena. These include the prediction that due to the symmetry energy the fission barriers will decrease again on the neutron rich side, contrary to the classical liquid drop fissility Z^2/A. Related to this is the question whether and where fission recycling sets in for the r-process path and how to understand r-process production of ^{232}Th and ^{238}U.

The *Far North-East* of the nuclear chart is further of interest with regard to the study of the bridge between the super-heavy island and the regular mainland in the nuclear chart. A potential solution to reaching at least some of these nuclei may be the use of deep-inelastic reactions. In some earlier work it was found in collisions of uranium beams with medium mass target nuclei [6] that the deep-inelastic process leads into the neutron-rich region for the uranium-like fragments. Figure 6 shows some of the results obtained for the reactions $^{238}U + ^{110}Pd$ and $^{238}U + ^{124}Sn$ near the Coulomb barrier. The trend seems reasonably consistent with driving-potential predictions indicated by the dash-dotted curves in Fig. 6. Calculations with a transport code at higher energies predict the behavior shown in Fig. 7 [7]. One notes that, at energies well above the barrier, the trajectories for the uranium-like fragments are strongly forward peaked; first, of course, due

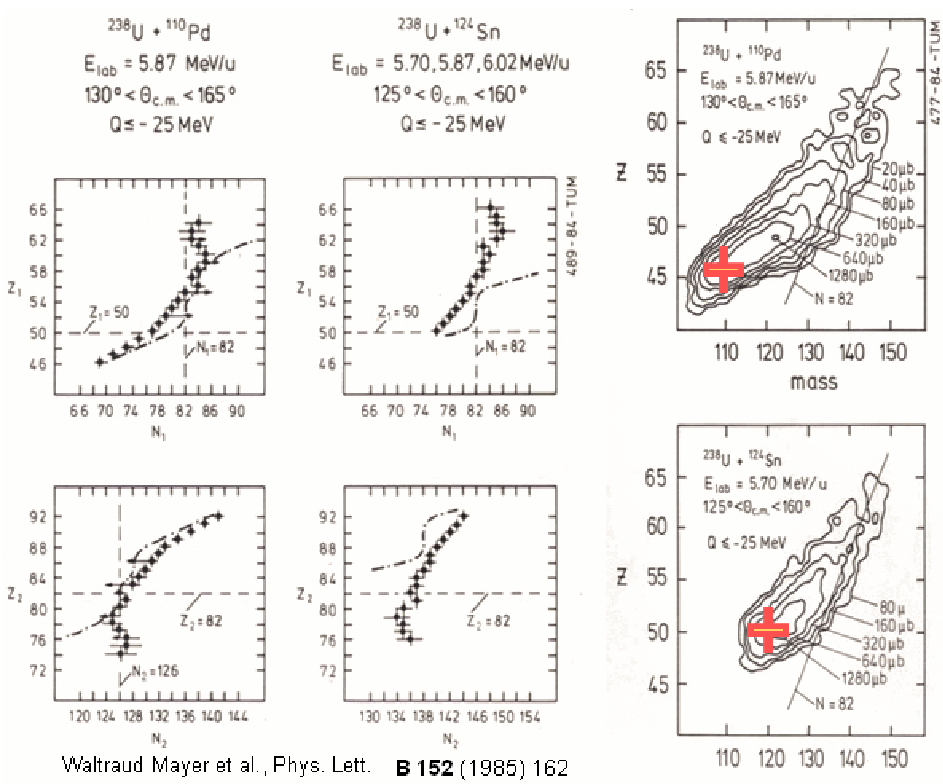

Fig. 6. Results of deep inelastic scattering near the Coulomb barrier for beams of uranium incident on medium-mass target nuclei. Plotted are cross-section contours for the light reaction products (right) and average masses and charges (left); the dash-dotted curves represent driving-potential predictions.

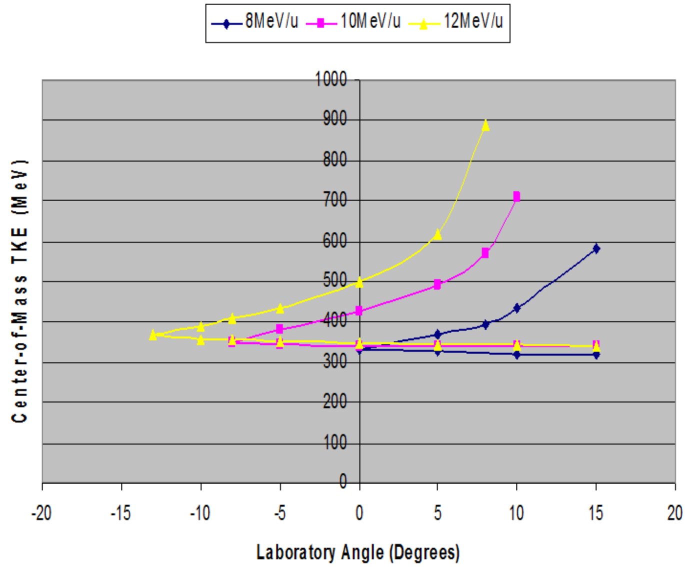

Fig. 7. Transport model calculations for deep inelastic reactions of 8, 10, and 12 MeV$/u$ uranium beams on ^{110}Pd [7]. The Wilczynski plots reveal strong forward focusing of the strongly damped reaction products at these energies well above the barrier.

to the inverse kinematics of the uranium beam incident on medium-mass nuclei, but even more so because of the dynamics of the dissipative reaction process. The yields for reactions with large negative Q-values (thus for multi-nucleon transfer channels) are essentially forward focused within a ± 5 degree angular acceptance. This could be of great advantage from an experimental point of view in that it might allow an efficient collection of the reaction products which otherwise are widely spread over angle and energy. Perhaps a gas-filled, clam shell-type magnetic focusing device might be a good solution.

Rare isotope beams play a major role in nuclear astrophysics since much of the element production, in particular explosive nucleosynthesis, occurs along paths away from stability. This is indicated in Fig. 8. To obtain experimental information, *i.e.* reaction rates and nuclear properties in the laboratory, RIBs are crucial. There has been considerable progress recently in experimental information, in particular in the region of the rp-process were, *e.g.*, a series of proton capture reactions have been measured on nuclei from ^{17}F [8] to ^{31}S [9] as illustrated in Fig. 9.

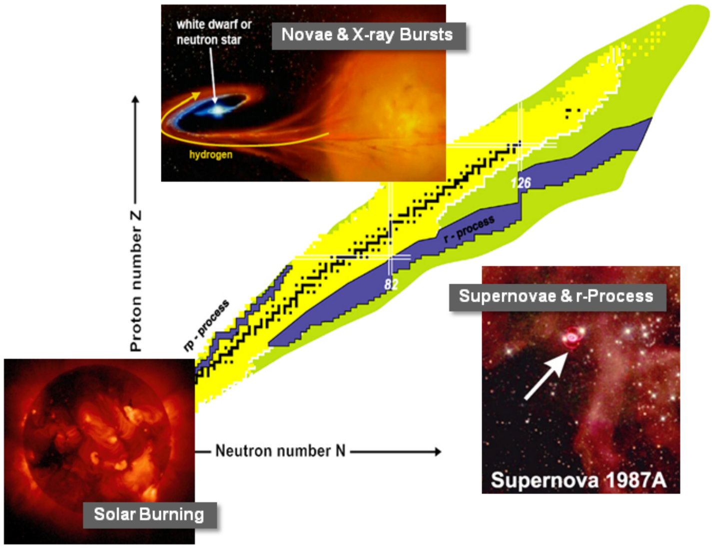

Fig. 8. Key processes in nuclear astrophysics where radioactive beams provide important input via reaction rate measurements and nuclear structure studies.

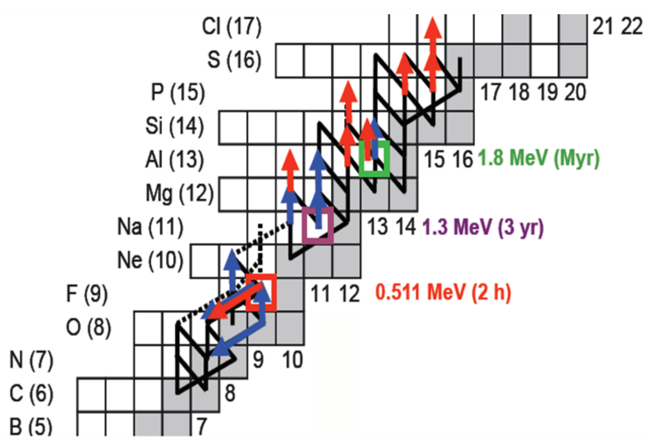

Fig. 9. Schematic overview of recent proton capture measurements in the rp-process region of the nuclear chart [10].

Similarly, a wide range of mass measurements with ion traps have provided important information on Q-values for the calculation of statistical reaction rates that in turn influence the X-ray light curve for X-ray bursts. Many facilities pursue these studies as illustrated in Fig. 10. Also included in Fig. 10 are predictions for a new reaction sequence starting in the iron

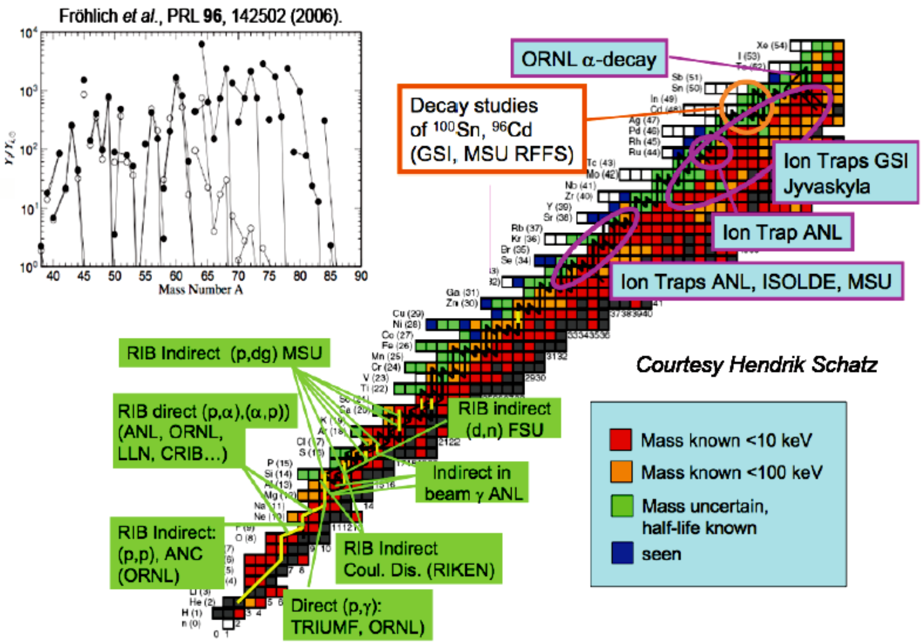

Fig. 10. Ion trap measurements of masses in the rp-process region which provide Q-values needed for the calculation of statistical reaction rates which in turn impact X-ray light curves from bursters. The inset on the upper left shows predictions for elemental abundances relative to solar for the new νp process predicted by Fröhlich *et al.* [11].

group that is similar to the rp-process but originates from the intense neutrino/antineutrino flux in a supernova: Antineutrinos react with protons to produce neutrons whose capture bypasses the decay of long-lived nuclei and significantly influences the elemental abundances relative to solar in the mass 70 to mass 90 region [11].

On the neutron-rich side, the recent production of new nuclei is approaching the predicted r-process path (Fig. 3); mass and lifetime measurements are beginning to provide first data for this mass region. New data are expected from a radioactive source (^{252}Cf fission) driven RIB facility, CARIBU at Argonne National Laboratory utilizing the ATLAS superconducting heavy-ion accelerator. Also, direct reaction data have been recently measured at ORNL for medium mass nuclei around ^{132}Sn [12] providing spectroscopic factors. These are of significant nuclear physics interest *per se* because of the closed shell nature of ^{132}Sn, but also indirectly for the r-process by providing neutron capture rates to discrete states that are important near magic shells.

Finally, a relevant development for nuclear astrophysics is perhaps the very interesting far sub-barrier fusion hindrance recently discovered in several systems [13]. If this is a general feature of heavy-ion fusion reactions then it will be of particular significance for the extreme low-energy Gamow peak region in reactions of astrophysical importance. Figure 11 shows an example of a fusion reaction study at low energies. If indeed, as sometimes speculated, this reflects the repulsive nature of the inner part of the scattering potential a specially designed scattering experiment might help reveal

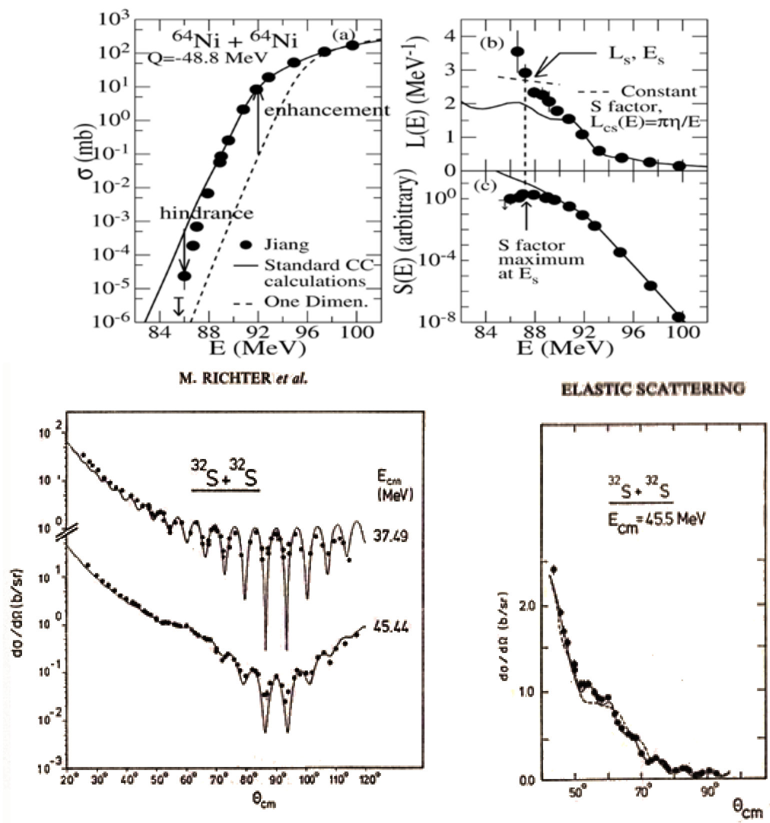

Fig. 11. On top the recently discovered far sub-barrier fusion hindrance is shown for $^{64}Ni + ^{64}Ni$ together with the corresponding S factor as a function of collision energy [13]. The lower panel shows elastic Mott scattering for the identical ion system $^{32}S + ^{32}S$. The optical model fits reveal particular sensitivity to the interference pattern as emphasized in the linear plot on the right. The results show an unambiguous preference for a shallow real potential with a small yet significant contribution to the scattering amplitude from very small impact parameters and deep penetration [14].

some of the underlying physics: It was observed a long time ago in symmetric scattering systems that the quantum mechanical Mott oscillations, which arise because the beam- and target-like nuclei are indistinguishable in the exit channel, are sensitive to the small scattering amplitudes from the interior [14]. This is illustrated in Fig. 11. Whether this can be detected far below the barrier for systems relevant for astrophysics, such as $^{16}O + {}^{16}O$ or $^{12}C + {}^{12}C$ is difficult to say, but perhaps worth investigating.

The availability of radioactive beams away from stability has triggered a range of reactions in inverse kinematics for nuclear spectroscopy. They include simple transmission experiments at high energy that allow one to extract the interaction cross-section and thus some measure of the size of the nucleus; single- and multi-nucleon knock-out reactions and momentum distribution measurements to determine bound and unbound shell model configurations in light nuclei; inelastic and Coulomb excitations over a large mass and energy range to study collectivity in a nucleus; and direct nucleon transfer reactions at low energies that provide spectroscopic factors and strength distributions. An example of the latter for medium heavy nuclei is the ^{132}Sn neutron transfer reaction measurement mentioned above [12]. The inverse kinematics with RIBs poses serious challenges for high-resolution experiments when compared to the classical studies on heavy nuclei with light ion beams in normal kinematics. The results are shown in Fig. 12. The energy resolution is about 300 keV compared to the 10 keV that can usually be obtained with light-ion beams.

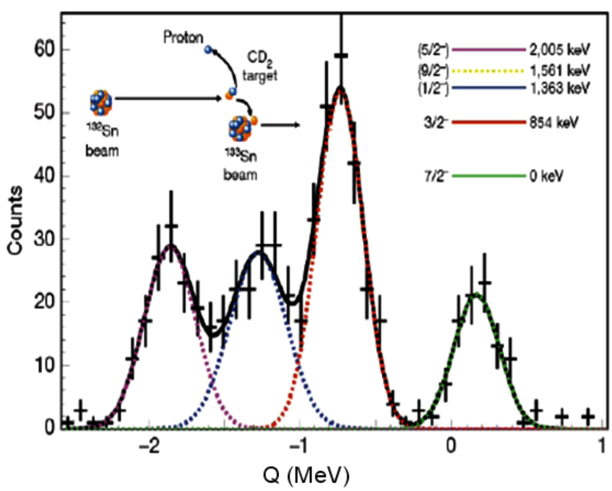

Fig. 12. Q-value spectra measured for the neutron transfer reaction $d(^{132}\mathrm{Sn},^{133}\mathrm{Sn})p$ to single-particle states in ^{133}Sn. Within errors the results of a DWBA analysis yield spectroscopic factors near unity for the four states indicated [12].

In addition to reaction spectroscopy, ground state and decay properties have been measured for a range of nuclei far from stability. This is schematically illustrated in Fig. 13 with programs to measure masses with Penning traps (see also Fig. 10) or storage rings; and with some selected examples of, *e.g.*, a half-life study in a storage ring, and hyperfine studies via collinear laser spectroscopy; laser driven atom trap measurements of isotope shifts and charge radii of neutron-rich isotopes have also been performed in recent years.

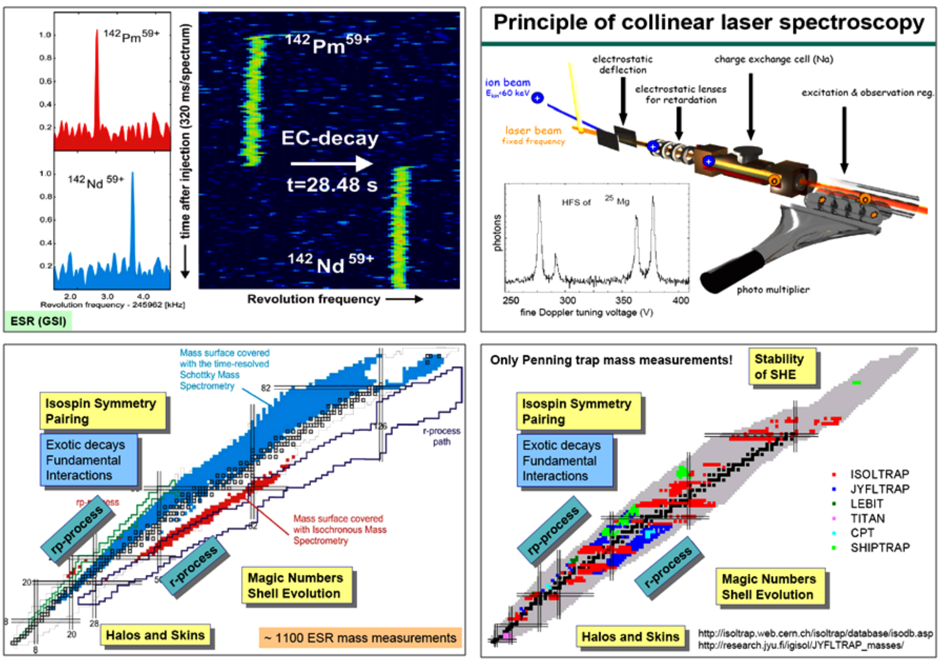

Fig. 13. Examples for measurements of ground state properties in nuclei far from stability: Mass measurements with Penning traps (bottom right) and the GSI/ESR heavy-ion storage ring (bottom left), a half-live measurement of electron capture decay in the ESR (top left), and hyperfine structure studies with collinear laser spectroscopy (top right).

It is the comprehensive nature of the results from all of these experiments, from reaction spectroscopy to decay studies and to the measurement of ground-state properties, that allow us to explore the characteristic properties of these unknown regions, to establish new shells and sub-shell closures as well as new regions of collectivity, and in some respects perhaps to reveal sensitivities to the underlying effective forces and mean field parameters of the nuclear many-body system that may be hidden in the more tightly bound, isospin symmetric systems in the valley of stability. A nice example that illustrates perhaps such an emerging broader picture and information on the underlying forces and many-body aspects are the nuclear structure studies along the $N = 40$ neutron shell (Fig. 14) presented at the recent INPC2010 conference [15]. Data now exist from the proton-rich (^{80}Zr) to the very neutron-rich nuclei (^{64}Cr). In addition, the $N \sim 40$ nuclei straddle the region between the filled f–p neutron shell and the open $g_{9/2}$ neutron shell. It has been argued that the mean field for very neutron-rich nuclei leads to very diffuse surface density. This in turn leads to reduced spin-orbit forces and strong coupling to the continuum [16] and high sensitivity to the spin-isospin part of the nucleon–nucleon interaction, in particular the monopole parts of the tensor force [17] (and also the three-nucleon force). In the specific situation for the $N \sim 40$ region one expects, when going from ^{68}Ni to ^{60}Ca, *i.e.* when removing protons from the $f_{7/2}$ shell, the monopole pairing interaction to weaken. As a consequence, for the attractive $\pi f_{7/2}$–$\nu f_{5/2}$ interaction this is moving the $\nu f_{5/2}$ state up in energy and, because of the weakening of the $\pi f_{7/2}$–$\nu g_{9/2}$ repulsive interaction, bringing down the $g_{9/2}$ neutron state. The intruder state characteristics of the $g_{9/2}$ state allows it to occupy levels already in nuclei with fewer than 40 neutrons, leading to enhanced collectivity, deformations and rotational excitations.

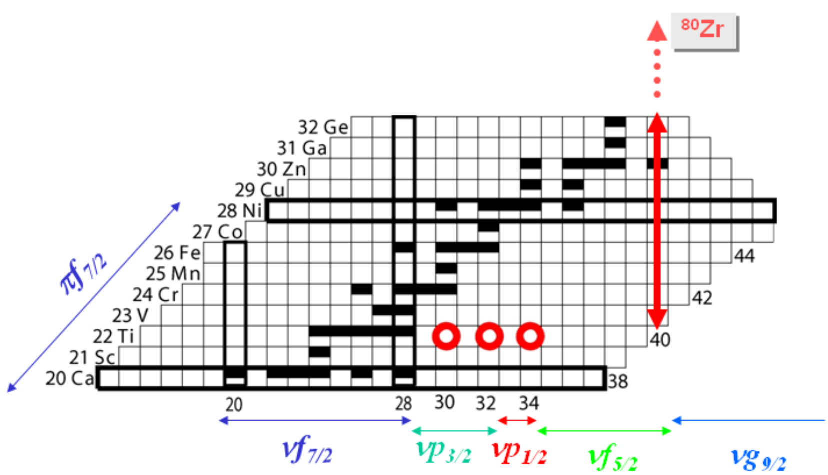

Fig. 14. Nuclear structure near the $N = 40$ neutron shell closure. Extensive theoretical studies together with a broad experimental program utilizing RIBs around the world have provided a wealth of information that begins to paint a comprehensive picture of the effective forces and degrees of freedom governing this part of the chart of nuclides [15].

As discussed in [15], these predictions go hand in hand with an extensive experimental effort. Studies with focus on this mass region of the nuclear chart have been performed at facilities around the world and have already provided a substantial amount of data. Among them: beta decays to ^{64,66}Fe at CERN/ISOLDE; beta decay to $^{60-63}$Cr at GANIL; rotational bands built on the $9/2^+$ isomer in ^{55,57}Cr and a low-lying $9/2^+$ isomer in ^{59}Cr at ANL; large deformation of ^{62}Cr at RIKEN; excited states populated in inelastic scattering in ^{60,62,64}Cr and ^{62,64,66}Fe at MSU; studies at several facilities of the structure of iron up to ^{68}Fe and of manganese up to ^{63}Mn; the pygmy resonance in ^{68}Ni at GSI. For a more detailed discussion and appropriate references see the nice summary of these studies in [15].

The example of the $N \sim 40$ mass region was given to illustrate the broad and exciting program that is evolving with RIBs worldwide. Similar attempts aim at other mass regions, such as the often discussed "island of inversion" of neutron rich nuclei near the lower neutron shells ($N \sim 20$); the neutron drip line that has been reached for the lightest nuclei; emerging attempts around the doubly-magic ^{100}Sn and ^{132}Sn isotopes; $N = Z$ nuclei and the proton drip line; and, of course, the studies driven by the astrophysical paths of element production discussed above. It is not surprising that the ever increasing demand for intense beams of rare isotopes, reaching further out and into the regions of unknown nuclei, leads to a continuous effort on the facility side to upgrade, improve and expand, and to develop and construct new, more powerful next-generation systems. In this sense I want to conclude this discussion with an overview of the currently operating facilities (Fig. 15), the next-generation facilities approved, funded and/or under construction (Fig. 16), and the perhaps far-future generation of novel facilities presently under discussion (Fig. 17).

For the latter (EURISOL, KoRIA, RIBF Upgrade, and CARIF) novel multi-step schemes are being investigated where intense sources of rare isotopes based on a light-ion beam driven high-intensity ISOL system are generated (step 1) and then used to inject and accelerate in a second machine to high energies for in-flight fragmentation (step 2). The expectation is that this will allow reaching nuclei even further away from stability.

The basic question for these schemes is whether the efficiencies achievable for the extraction and re-acceleration of the ISOL yields (in particular for those with short lifetimes where extraction delays can be detrimental) can provide, in the end, a higher secondary RIB fragment yield than a heavy-ion beam of smaller intensity which undergoes, in flight, two sequential fragmentation processes in a thick target (or two sequential targets) with no time delay and loss.

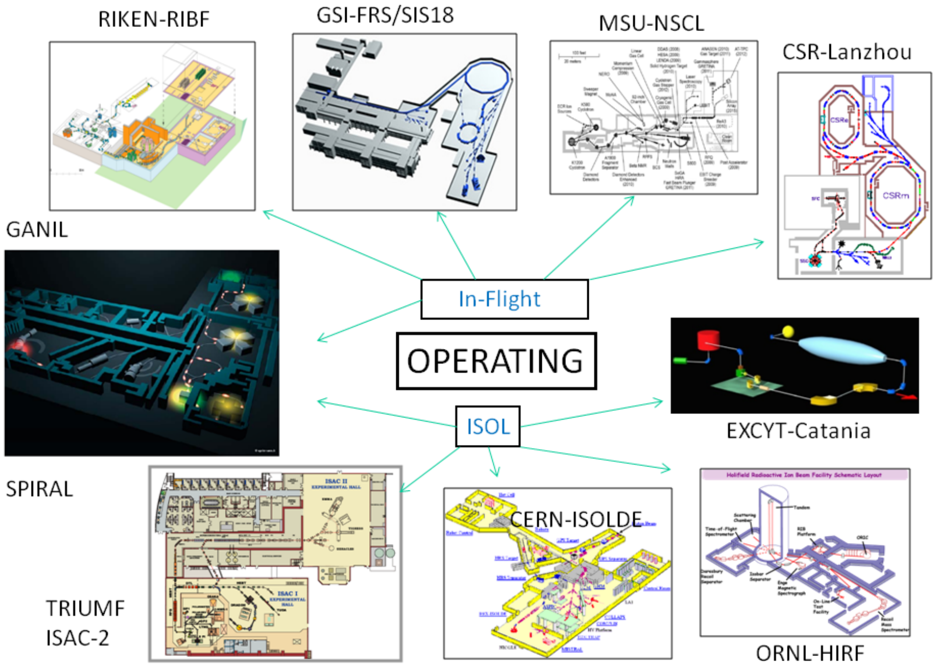

Fig. 15. Major RIB facilities currently in operation. This does not account for the many smaller experimental facilities at accelerators whose primary purpose are stable-isotope beams but often have quite effective RIB programs utilizing in-beam reactions or beams from radioactive materials in ion sources.

There is no question that the ISOL production yields for RIBs, with MW primary light ion beams (protons, deuterons *etc.*) incident on thick (heavy-nucleus) targets can be several orders of magnitude higher than the yield from fragmentation of a MW high-energy heavy-ion beam. This is particular the case for an ISOL target of uranium with large fission yields, including those from secondary neutrons, and substantial neutron multiplication. The fragment yield from a MW heavy-ion beam can at most be a fraction of the heavy-ion beam intensity, which altogether means perhaps three orders of magnitude larger ISOL production yield. However, as already indicated the same order of magnitude may apply to the reduction factor in ISOL beam intensity after extraction and re-acceleration. Clearly more R&D is needed to provide unambiguous quantitative answers to these questions.

In conclusion, the increasingly more powerful RIB facilities are providing beam intensities that allow pushing the extremes of the nuclear landscape further and further. This poses new challenges for the experimental systems. Many innovative approaches have been developed and successfully applied.

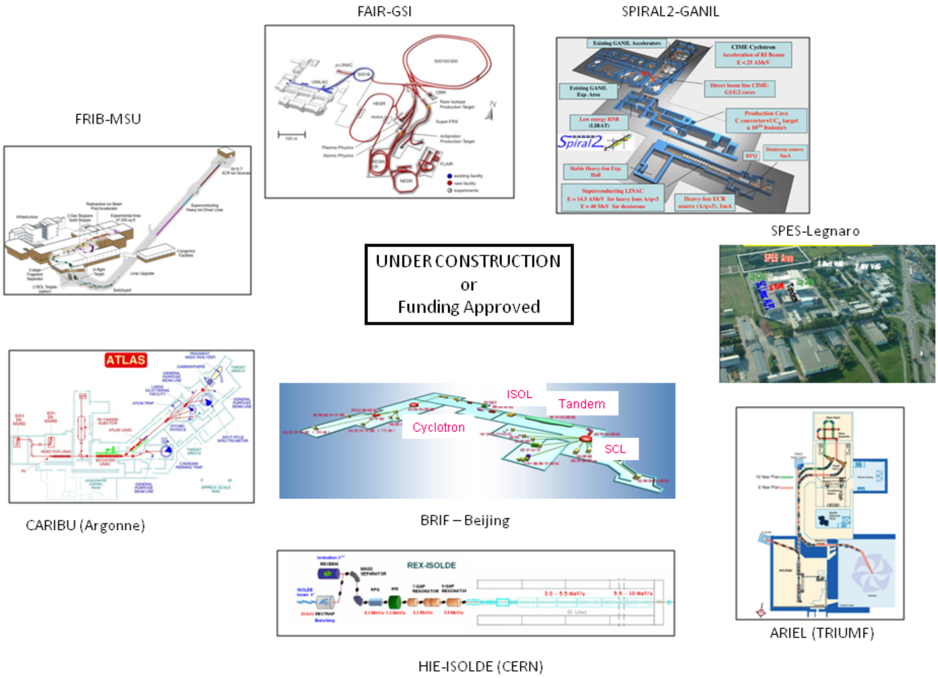

Fig. 16. Approved future RIB facilities nearing completion and/or under commissioning; or under construction; or in the R&D and design phase.

For most of these there was not enough room in the context of the present paper to mention all of them and/or to discuss the details. Various other contributions to the present proceedings will contain much of this additional information.

A lot of new and exciting information is being gained about nuclei that challenge our understanding of the nuclear many-body system, of the characteristics of the effective forces, and of the interrelationship between the relevant degrees of freedom. In addition, these studies are providing key information for nuclear astrophysics. They also may lead to applications that could not be discussed in the context of the present paper. Clearly the scientific future of the field is very promising. The new facilities around the world will provide the basis for a continued and expanded exploration of the unknown territories of the nuclear landscape, moving closer towards its extremes.

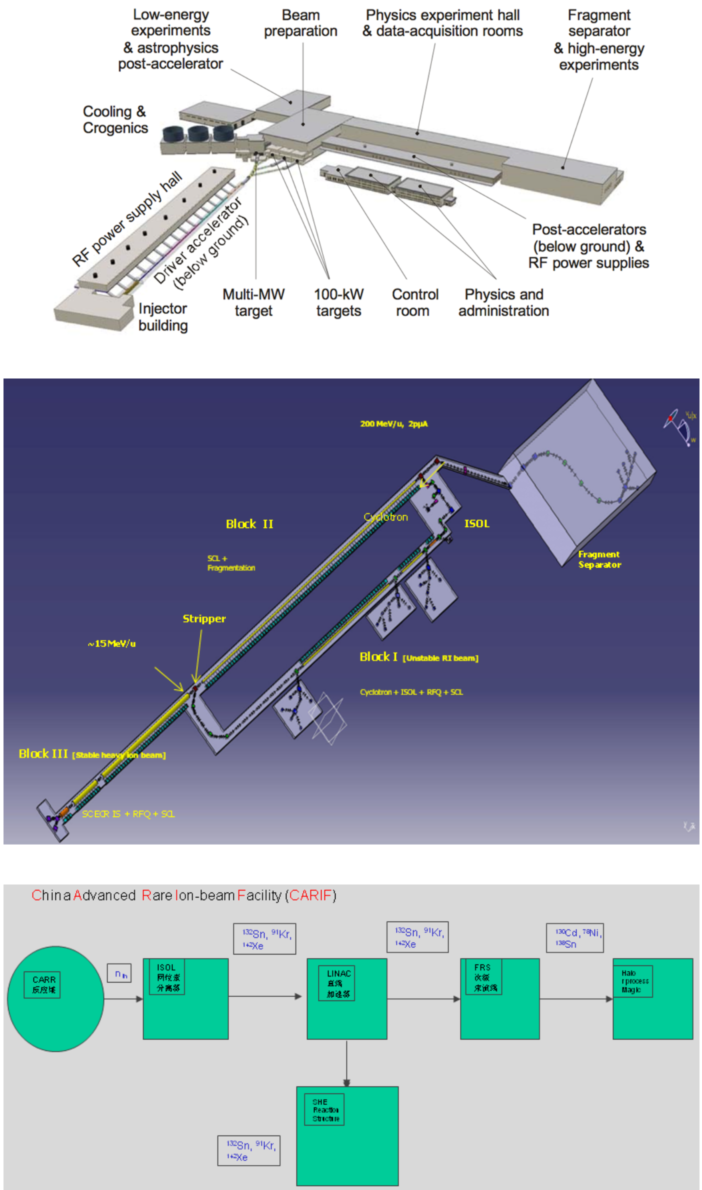

Fig. 17. Conceptual future RIB facilities based on the concept of 2-step production of very neutron-rich rare isotopes, *i.e.* accelerator (or reactor neutron) based ISOL production of radioisotopes and re-acceleration to high energies for in-flight fragmentation: EURISOL (top); KoRIA (middle); CARIF (bottom).

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