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PHYSICS MOTIVATION AND CONCEPTS FOR THE ISOSPIN LABORATORY*

J. MICHAEL NITSCHKE

ISL Studies Group, Nuclear Science Division, Lawrence Berkeley Laboratory, University of California Berkeley, California 94720, USA

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A brief synopsis of the emerging science of radioactive nuclear beams is given. Its impact on a wide range of studies in nuclear structure, nuclear reaction dynamics, astrophysics, high-spin physics, nuclei far from stability, material- and surface science, bio-medicine, and atomic- and hyperfine-interaction physics is discussed. It is pointed out that the expected low beam intensities will put stringent requirements on the performance of the accelerators and the experimental detection equipment.

KEY WORDS: Radioactive nuclear beams, on-line isotope separation

1 INTRODUCTION

Nuclear physics and the development of particle accelerators have gone hand-in-hand since the early part of this century. The first nuclear reaction was carried out in 1930 by Cockcroft and Walton using protons accelerated to 300keV in the reaction ^{7}Li(p,2α). Subsequent developments progressed in two directions, heavier masses and higher energies. While heavier projectiles opened new vistas in the synthesis of new elements, the study of high spin phenomena, and the exploration of the nucleon drip lines, to mention only a few, higher energies allowed the study of nuclei at higher temperatures, the equation of state of nuclear matter, and ultimately collective phenomena resulting from the melting of the hadronic phase that may give rise to a plasma consisting of quarks and gluons.

A comparison between the chart of nuclides and nuclear model calculations shows that we know of the existence of only $\sim$1/3 of all bound nuclei. Detailed nuclear structure information is limited to a narrow band of nuclei near the line of β-stability. One of the reasons for this is that, thus far, we have been limited experimentally to projectiles and targets of stable nuclei, due, in the past, to the technical difficulties of producing radioactive nuclear beams (RNB) with intensities sufficient for meaningful experiments.

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Developments in the last two or so decades have changed this situation drastically. For the ISOL (Isotope Separator On-Line) method of producing RNBs high energy proton accelerators are now able to deliver primary beam intensities that are higher than can be handled with existing target technology. Sources with high efficiencies and selectivity for singly and multiply charged ions have been developed, magnetic spectrometers with high resolution and transmission can now be built, and post-accelerators with excellent beam quality, duty factor, and transmission are in routine operation. Conversely, high-energy, high-current-heavy-ion accelerators can provide secondary RNBs with sufficient intensity via projectile fragmentation. In addition, experimental equipment has improved in efficiency, resolution, and acceptable data rates by several orders of magnitude.

In 1989 this author proposed the construction of a dedicated, flexible, radioactive nuclear beams facility that would provide intense beams of nearly all elements for a program of scientific studies in nuclear structure, nuclear reaction dynamics, astrophysics, high-spin physics, nuclei far from stability, material- and surface science, and atomic- and hyperfine-interaction physics. The initial name proposed for the new facility was "IsoSpin Factory" to underscore the key feature of this new physics tool; it was later changed to "IsoSpin Laboratory" (ISL). The ISL is now supported by a broad base of nuclear scientists and has been identified in the 1989 US Long Range Plan on Nuclear Science as one of the new potential construction projects for the second part of this decade. Since 1989 a number of conferences and workshops has been held in which the scientific and technical case for RNB facilities has been made.[1–6] An overview of existing and planned RNB facilities world-wide has been presented in Reference 7. The purpose of this workshop is to focus on the North American plan for the ISL, which was initially summarized in a "White Paper"[8] but has since evolved in its scientific and technical scope.

2 SCIENTIFIC SCOPE

The ISL is based on the coupling of two accelerators: the first to deliver a high current light ion beam to a thick, hot spallation- or fission target and the second to accelerate the emanating radioactive species to energies in the range from a few keV to ~25MeV/u with excellent beam qualities, typical of modern heavy ion accelerators. These beams will facilitate a large panoply of experiments in nuclear- and astrophysics and in the applied sciences.

2.1 *Nuclear Structure*

One of the striking features of radioactive beam science is that the large number of stable and radioactive beam- and target combinations allows the systematic study of nuclear properties over long isotopic- and isotonic chains. It will be possible to create nuclei with exotic matter distributions and follow the evolution of nuclear shapes and nuclear structure from closed shell to closed shell and beyond, as in the case of $^{\sim 100}$Sn to $^{>132}$Sn.

The topics in nuclear structure are too numerous to discuss here in detail; a partial list includes:

study of shell model states near singly and doubly magic nuclei through single particle transfer reactions;

nuclear structure near N=Z, including neutron-proton pairing correlations, nuclear shapes, Coulomb energy effects, mirror nuclei, superallowed β-decay, and tests of shell-model predictions near ^{100}Sn and other closed-shell nuclei;

Coulomb excitation of unstable nuclei, giant resonances;

new collective modes, octupole-, oblate-, and triaxial deformations; synthesis of new neutron-rich nuclei in the trans-uranium region, and new attempts at the synthesis of super-heavy elements;

nuclear structure near the drip lines;

high-spin physics, new regions of extreme nuclear deformation and configurations;

ground-state properties of exotic nuclei: masses, spins, moments, radii, skins and halos; and

charged-particle- and cluster radioactivity, including β-delayed radioactivities.

An overview of nuclear physics with radioactive beams is given by Warner in Reference 4.

2.2 *Nuclear Reactions*

Radioactive projectiles remove the restraint to the natural N/Z ratios of stable beams in nuclear reactions. The extended wave functions of loosely bound nuclei near the drip lines (skins and halos) may result in entirely new reaction processes such as the free flow of neutrons in sub-barrier fusion reactions ("neck formation") or "molecular bonding" mediated by the valence neutrons. Conversely, the same processes will yield information about nuclear wave functions, and the diffuseness and thickness of the outer nuclear optical potential. By combining exotic projectiles and/or targets, large reaction Q-values can be achieved that may lead to enhanced cross sections and the possibility of multiple (sequential) neutron transfers. Similarly, large probabilities for pair transfer will allow the study of collective effects resulting from the nuclear pairing field. One could, perhaps, hope to find a nuclear analogue to the Josephson effect.

Mapping of the fission-energy-vs.-deformation surface could be attempted by studying the fusion ("inverse fission") of two nuclei with special nuclear structure, i.e., near the doubly magic ^{132}Sn, leading to isotopes of Fm. Elucidating this process could point to reactions conducive to the formation of super-heavy elements. Other experiments directed towards an understanding of the fission process in heavy nuclei would involve the formation of currently not reachable nuclei with heavy RNBs on light stable targets in inverse kinematics, i.e., d(^{209}Th,p). The experiments require only modest beam intensities since the fission exit channels have high cross sections and are easily detectable with high efficiency. A unique feature of the ISL will be the production of *isomeric* beams and targets allowing reaction studies based on high spin states such as in $^{178}Hf^{16+}$.

Classical elastic scattering experiments are ideally suited for low beam intensities. When carried out with a series of RNB isotopes they would reveal the spin- and isospin dependent nature of the nuclear potential. Large impact parameter scattering between mirror nuclei could be used to search for the pion content of nuclei without interferences due to non-zero Q-values in ordinary nuclei.[11] An example of a possible reaction is ^{18}Ne + ^{18}O.

It is obvious that, because of the low beam intensities, many nuclear reaction studies with RNBs will be carried out in inverse kinematics, which will ensure high detection efficiencies. However, sufficient energy is needed to study highly asymmetric systems like d(^{132}Sn,p)^{133}Sn.

2.3 *Astrophysics*

The importance of RNBs for astrophysics stems mainly from the fact that in hot stellar environments many of the interacting nuclei are radioactive and that reactions with radioactive beams and targets could previously be studied in the laboratory only with difficulty. Such studies are, however, essential for the understanding of several stellar phenomena such as the hot CNO cycle, the rp-, s-, r-, and p-processes, and primordial nucleosynthesis, the big bang, as well as the energy balances of stars. Required are measurements of cross sections, reaction rates, masses, half-lives, β-strength functions, and decay properties. For the r-process the crucial experiments involve nuclei near the n-drip line, for the rp-process near the p-drip line, and for the s-process near β-stability. Spectroscopic measurements are also needed to interpret data from γ-ray observational astronomy.

Astrophysical RNB experiments face special challenges. Measurements of nuclear reaction rates far below the Coulomb barrier can have cross sections in the nanobarn or picobarn range, the width of important resonances may be very small ($\sim$meV or less), the n-drip line can only be reached for the lighter nuclei, and for many neutron-rich nuclei even basic ground-state properties like masses and half-lives are not known. For these and other reasons astrophysical experiments may pose the highest demands on the performance of the ISL, for example, maximum beam energies of 15–25MeV/u for inverse kinematics, small energy spread, beam purities $\leqq 10^{-5}$, and absolute energy calibrations to a few keV/u.

2.4 *Atomic Physics and Material Science*

Intense, pure beams of radioactive ions of many elements, with variable energies and of isotopes with different half-lives can become of great importance in materials research. This is based on the observation that a radioactive nucleus implanted in a host material will sense its electromagnetic environment via the hyperfine interaction and may reveal the characteristics of this environment in its decay features. Precise three-dimensional localization of implanted ions in a large variety of matrixes — including insulators — can be obtained. Concentrations can be varied over many orders of magnitude and solubility limits can be exceeded. The usual alloying rules and limitations, in general, do not apply to implantation processes and metastable systems and exotic alloys may be formed. Radiation damage may change the properties of the target in ways that can not be achieved by other means, creating new phases and materials. These processes can be studied through a number of research techniques:

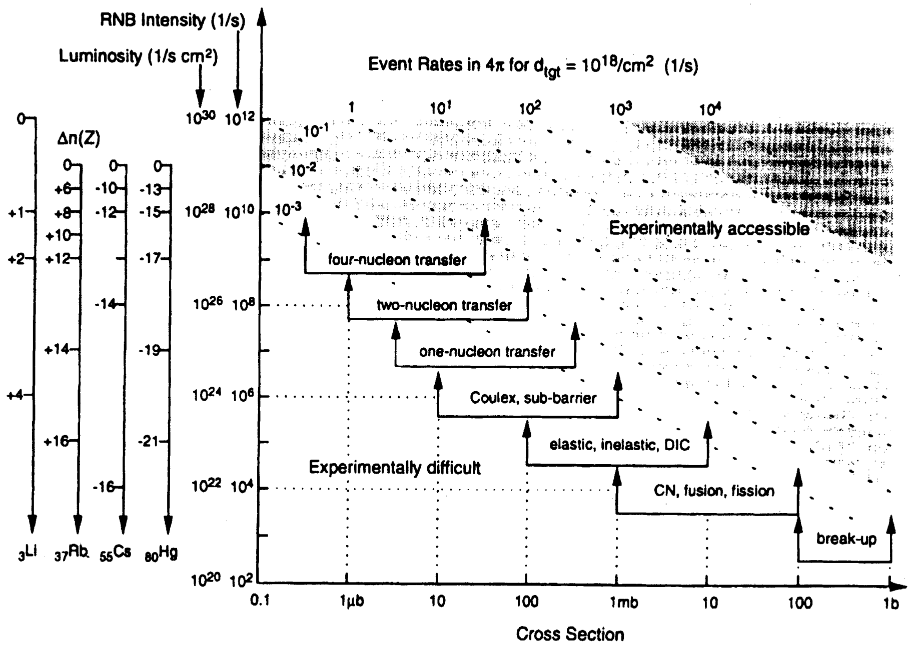

FIGURE 1: Correlations between RNB intensities, experimental cross sections, and event rates in a typical RNB experiment. On the left are shown the number of neutrons counted, from stability for four representative elements.

on-line nuclear orientation
NMR spectroscopy
Mössbauer spectroscopy
perturbed angular correlations
channeling of charged particles
high-resolution conversion electron spectroscopy
positron analysis
nuclear reaction analysis
use of radio tracers.

For some of these techniques polarized RNBs are desirable. An overview of the potential of radioactive ion beams in material science is given by Sawicki in Reference 2.

3 EXPERIMENTS

Compared to conventional stable-heavy-ion accelerators the beam intensities at the ISL will be several orders of magnitude lower for beams that are far from β-stability. This has to be taken into account in the planning and execution of experiments. It will require close interaction between the accelerator operation and the experimenter to decide on the best trade-off between "exoticness" and intensity. Certain elements will be easier to produce as RNBs than others. During the start-up phase of the ISL, for example, alkalis, noble gases, and halogens will be easier to obtain with good intensities than refractory elements like Os, W, Hf, etc. Taking this into account in the choice of the beam/target combination can make a difference of many orders of magnitude in the event rate of an experiment.

Figure 1 shows an attempt at a rough correlation between several types of nuclear physics experiments — shown over a range of cross sections — and the RNB intensities needed for a given detector sensitivity, assuming a typical target thickness for heavy ion experiments of 10^{18} cm^{-2}. For example, if the detector is sensitive to a few counts per hour, brake-up reactions could be carried out with beams as low as $10^3 s^{-1}$, while rare multi-nucleon transfer reactions may require intensities of $10^9 s^{-1}$ or more. It is in the nature of the nuclear phenomena involved that, in general, the most interesting beams — the ones that are furthest from stability — have the lowest intensities. This is illustrated on the right side of Figure 1, which shows the correlation between the distance from stability [expressed in positive or negative neutron numbers, Δn(Z)] and the expected beam intensities at the ISL (uncorrected for radioactive decays in the target and ion source). Because of the strong decline of the intensity with neutron number it is advisable that the ISL be designed for the highest RNB currents that are technologically feasible.

It is clearly impossible to discuss even a representative sample of all the experiments that will be carried out at the ISL. A more manageable approach is to look at some of the instrumentation that may be necessary or desirable to deal with the idiosyncrasies of RNB experiments.

As a general requirement, detector systems, spectrometers, and beam lines have to be protected from deposits of long-lived beams or beams with long-lived daughters. Typical collimator/target arrangements will have to be modified. A collimator or target holder that intercepts, for example, only 10^4 ions/s (= 10^{-3}% of a typical radioactive beam of 10^9 ions/s) of a short-lived β^+-emitter will radiate, after a few half-lives, 2×10^4 511keV-photons/s into 4π. If the detection system is sensitive to this radiation the singles rates may become too high and/or useless data may be collected. In this connection, the micro structure of the RNB becomes important not only for time-of-flight measurements but also for background reduction. One of the requirements for protecting experimental equipment from the primary RNB is excellent beam quality from the post-accelerator, including the absence of halos.

Several specific instruments for the ISL are under discussion.[5] The cost of initial instrumentation will be a significant fraction of the total cost of the facility.

Highly desirable is a 4π array for γ rays and charged particles, equipped with Si-microstrip detectors and, perhaps, a time projection chamber. This could be combined with a "neutron-wall."

Another important instrument is an E$\times$B separator for fusion reactions, with large acceptance ($\sim$20msr), higher order corrections, and ray-tracing capability. One can also imagine experiments where the 4π array, the neutron wall, and the spectrometer are combined.

For reactions carried out in inverse kinematics a high resolution ($R \sim 10^4$) magnetic spectrograph with large solid angle ($\sim$20msr) is needed. It should have large momentum acceptance ($\Delta p/p \approx 10\%$) and ray tracing capability.

To achieve large solid angles (500msr – 4π) for the collection of reaction products coaxial devices, like superconducting solenoids, are useful. They are very effective in separating the beam from weak reaction channels, their resolution, however, is poor.

Penning and Paul traps have become powerful devices for measuring nuclear and atomic properties even of single ions.[12] Conversely, large volume traps may in the future be able to store large numbers of ions, which would have many uses at RNB facilities (Moore in Reference 5).

Ultimately it may be desirable to couple the ISL with a storage ring. This requires an effective bunching mechanism for injection to conserve the average RNB intensity. The ring could be used for internal target experiments to increase the luminosity over single pass experiments and to cool the circulating radioactive ions, as well as to accelerate them to higher energies. Electron cooling would improve beam quality by several orders of magnitude and would allow collinear experiments to study interactions between radio-active-, laser-, and electron beams. A storage ring would add considerably to the cost of the facility and may be considered a future option.

Astrophysicists need to measure (n,γ) cross sections for many neutron-rich isotopes. At the ISL several of these isotopes would be collected on-line as radioactive targets [probably on a moving tape collector to avoid build-up of long-lived daughter products, using the BRAMA concept (c.f. separate contribution to this workshop)] and irradiated by a small neutron generator that could generate a "stellar" neutron spectrum (kT $\approx$25keV) from the reaction ^{7}Li(p,n)^{7}Be. At a proton energy of 1912keV and a proton current of 150 μA a kinematically collimated beam of 10^9n/s can be obtained.

It is anticipated that at the low-energy front end of the ISL (E_{RNB} $\leqq$100keV) much of the type of instrumentation that is presently installed or being developed at ISOLDE/CERN will be used.

4 CONCLUSION

The advent of RNBs in this decade may rival in importance the development of heavy ion beams in the 1960s. The possibility of vastly expanding the exploration of the isospin degree of freedom will create exciting new vistas for nuclear- and astrophysics. The ISL will allow the investigation of new features in nuclear reactions, give access to special nuclear regions and states, create nuclei with new modes of excitations and deformations, explore exotic matter distributions at extreme N/Z ratios, and create new nuclei at the limits of stability of nuclear matter. In astrophysics it will be possible to simulate in the laboratory conditions under which stellar processes like supernovae, nucleosynthesis, and different burning scenarios proceed. RNBs may even help to shed light on the early history of the universe. For material science the flexible nature of RNBs is attractive because it is possible to choose freely for a given element the half-life, nuclear decay properties, spatial distributions, and densities.

However, as in many scientific endeavors, the most exciting discoveries will be those that cannot be foreseen.

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