CONF-960949--2
ANL/PHY/CP--91824
RECEIVED
JAN 16 1997
OSTI

Physics with energetic radioactive ion beams

Walter F. Henning

Physics Division, Argonne National Laboratory, Argonne, Illinois 60439-4843 USA

Beams of short-lived, unstable nuclei have opened new dimensions in studies of nuclear structure and reactions. Such beams also provide key information on reactions that take place in our sun and other stars. Status and prospects of the physics with energetic radioactive beams are summarized.

I. INTRODUCTION

The study of nuclear structure is extending into new directions with the availability of beams of short-lived nuclei. Much of what we know about the properties of nuclei has been learned from nuclear reactions. With the exception of heavy-ion fusion reactions (and to a certain degree fission), nuclei reached in reactions with stable (target) nuclei are generally confined to regions near the valley of stability. With short-lived nuclei available as energetic beams, reactions in inverse kinematics now allow such studies on nuclei far from stability.

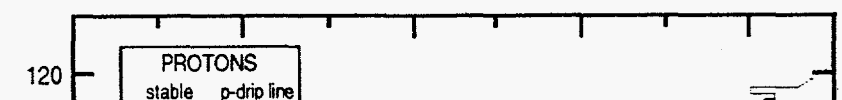

Figure 1. Chart of nuclides outlining the region where nuclei are expected to be particle stable, the region where at least some property of a nucleus has been experimentally established (gray area), and the stable nuclei (black symbols). Also indicated are the paths of explosive nucleo-synthesis (novae and super-novae) , as well as various theoretical pre dictions of the neutron drip line. The inserts illustrate the difference in the location of the Fermi surface (ε_F) between beta-stable nuclei and nuclei near the proton and neutron drip lines.

The interest in such nuclei arises on the one hand from our desire to study nuclei at the extremes, as a critical test of our understanding of the nuclear many-body system, and on the other from the astrophysics interest in reactions involving nuclei far from stability (see Figure 1).

2. NUCLEAR STRUCTURE AND REACTIONS: EXPLORING THE LIMITS

From the nuclear physics point of view, our ability to predict properties of nuclei far from stability with existing models is still very limited. Interesting structure trends and phenomena are predicted, for example, in sophisticated mean-field theories. However, the existence of such behavior remains to be established by experiment. Figure 2 summarizes some predictions for neutron-rich nuclei in the tin region [1].

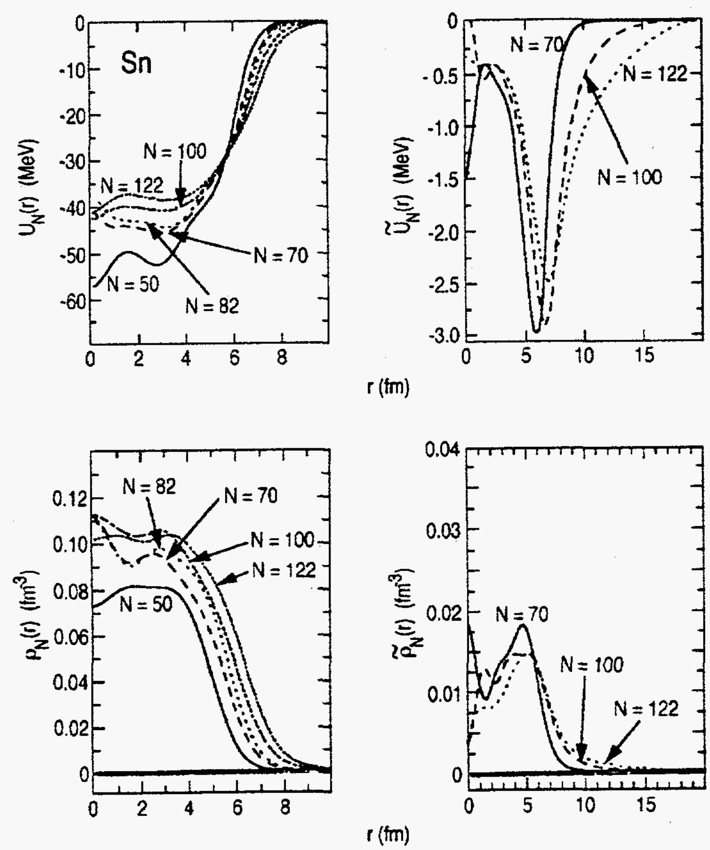

Figure 2. Prediction of mean field model calculations [1] for the neutron single-particle (U(r)) and pairing ($\tilde{U}$(r)) potentials and the neutron (ρ_N) and neutron pairing ($\tilde{\rho}$N) densities for neutron-rich Sn nuclei.

In such nuclei the last neutrons occupy states very close to the Fermi surface (and are also not confined by a Coulomb barrier as proton-rich nuclei; see insert in Figure 1). Consequently substantial neutron tails, possibly neutron skins are predicted to develop with essentially pure neutron matter on the outskirts of these nuclei. Much of the initial work with light radioactive beams including the pioneering experiments at the Bevelac, addressed the study of neutron 'halos', in particular of ^{11}Li [2,3]. Figure 3 schematically illustrates what has been learned by now about the lightest unstable nuclei from radioactive beam work.

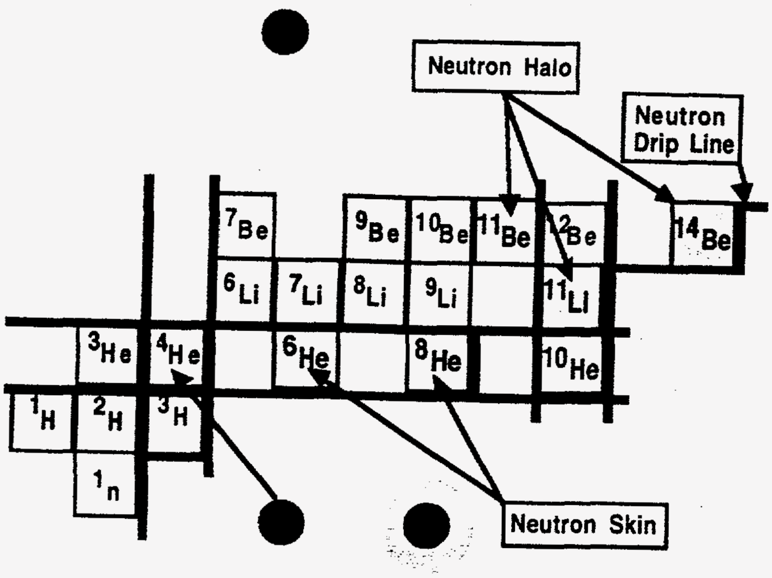

Figure 3. Section of the chart of nuclides in the region of the lightest nuclei, illustrating the location of nuclei with neutron halos and neutron skins as observed in reactions with radioactive beams.

For the heavier nuclei, as shown in the theoretical work of reference 1, the effects of such matter distributions on the mean potentials and, in turn, for example, on the spin-orbit splitting may be significant (single particle sequences predicted for different potential types [1] are illustrated in Figure 4). Such closeness to the Fermi surface also has significant impact on particle correlations such as pairing. According to the calculations of reference 1, significant pairing fields build up well outside the nuclear matter half-density radius (see Figure 2).

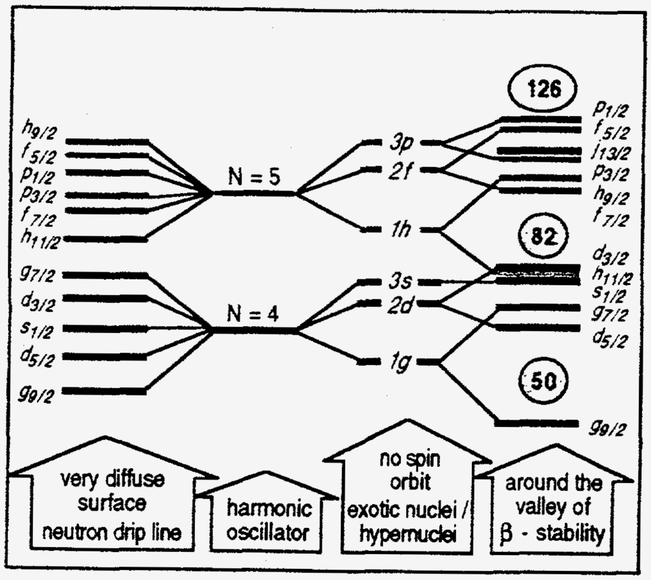

Figure 4. Sequences of single-particle shell-model states as calculated for various potential shapes and strengths of spin-orbit splitting [1].

Direct reactions provide information on energies and form factors of single particle states, on effective nucleon-nucleon interactions from the particle(hole)-particle(hole) multiplett splittings, on collective properties and on the shapes of nuclei. Radioactive beams allow us to study such reactions effectively in inverse kinematics. Figure 5 illustrates schematically the principal experimental approach to such measurements and, as an example, the kinematics and expected laboratory angular distribution for a direct neutron transfer reaction on doubly-magic, unstable ^{132}Sn. First measurements of direct reactions with radioactive beams can be found, for example, in the proceedings of the recent RNB-3 and RNB-4 conferences [3]. A good example are recent Coulomb excitation measurements at high energy performed at MSU [4]. Using a clever arrangement of position-sensitive sodium iodide detectors for Doppler shift correction, Glasmacher et al. were able to measure transition probabilities to the first excited 2^+ states in a number of unstable neutron-rich sd-shell nuclei. The results are shown in Figure 6. Clearly direct reactions in inverse kinematics will allow to considerably expand our knowledge of nuclear structure far from stability.

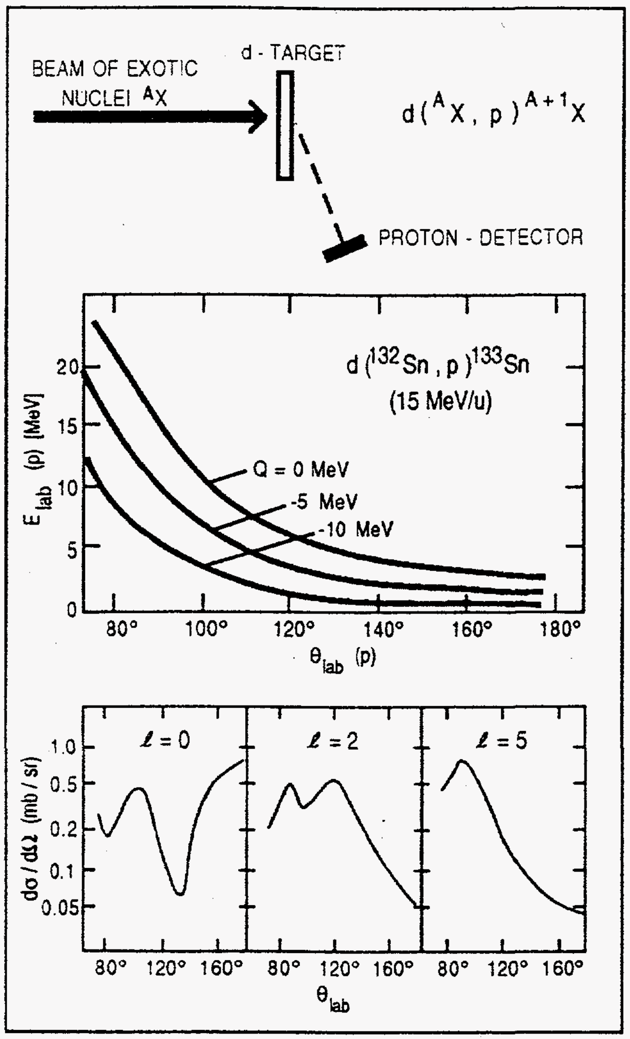

Figure 5. Schematics of an inverse reaction setup with a radioactive beam on a light nucleus (proton or deuteron) target. Also shown is an example of the kinematics and laboratory angular distribution of the reaction products.

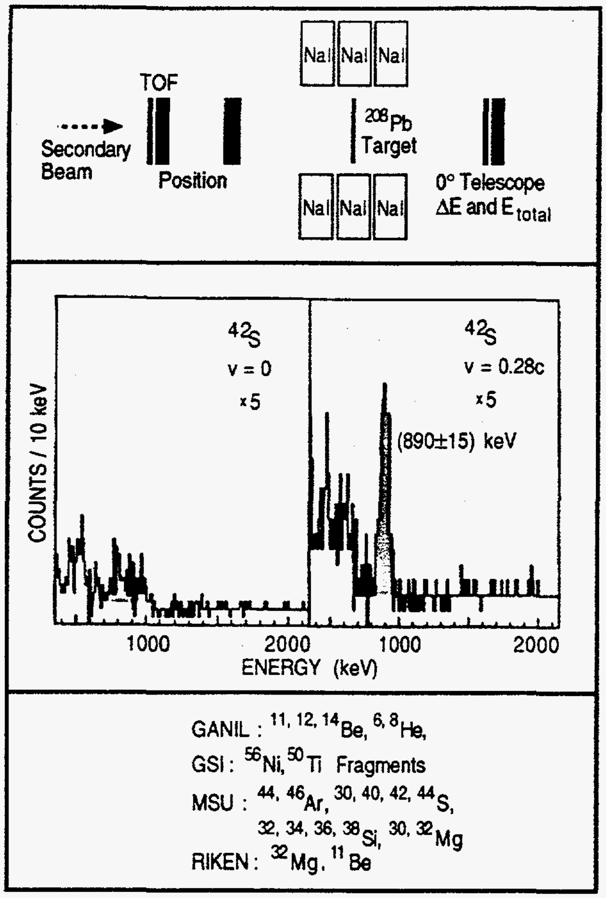

Figure 6. Results of a Coulomb excitation experiment at MSU using beams of short-lived neutron-rich sd-shell nuclei and a Pb target. A positron-sensitive array of NaI detectors allowed excellent Doppler shift correction (middle spectra).

3. NUCLEAR ASTROPHYSICS WITH BEAMS OF SHORT-LIVED NUCLEI

Radioactive beams provide the tools to study reactions between nuclei as they occur in nucleosynthesis. The goal of nuclear astrophysics is to understand how the chemical elements that make up our world are formed in the cosmos. The pioneering work won Nobel prizes for Hans Bethe and William Fowler, who began to unravel the complex cycles and chains of nuclear reactions that they believed would explain how nuclei are created and destroyed in the hot cauldrons of the Big Bang and inside stars. Today's most advanced observatories such as the Hubble Space Telescope are providing new evidence on this evolution by mapping out the elemental abundances in almost primordial gas clouds and the very earliest stars. It is the role of nuclear physics to establish the microscopic underpinnings of these and other observations.

Much of the nuclear synthesis occurs under explosive conditions like those found in novae, supernovae, and shortly after the Big Bang itself. Many of the important reaction chains proceed along paths which involve nuclides far from the valley of stability. Ever since the earliest theoretical models of nucleosynthesis, it has been a challenge to the experimentalists to find ways of investigating these processes in the laboratory. This challenge is now being addressed with radioactive beams with energies equal or exceeding those found in stars.

First experiments in nuclear astrophysics have used beams generated through several quite different technical approaches. For example, the low-energy tandem Van de Graaff at Notre Dame University was used to generate, in flight, ^{8}Li (lifetime of 0.8 sec) which was used to study crucial Big Bang reactions [5]. At intermediate mass and energies, detection and identification of proton-rich nuclei at GANIL and MSU has provided important information on the path of the rapid proton capture (rp) process [6,7]. By simply establishing the existence or non-existence of particle stability for specific isotopes near the proton drip line in the mass A=60-70 region crucial information on the time scales involved in the explosive rp process have been established (Figure 7). At the other end of the energy scale, uranium beams of several tens of GeV at the GSI Laboratory in Darmstadt, Germany, were fragmented in a reaction target [8]. From the forward focused beams of fission products more than a hundred new neutron-rich isotopes were identified for the first time in a region which is near the astrophysical rapid neutron-capture process (r-process). The r-process is responsible for making most of the heavy elements (heavier than iron) and is important during the few seconds of a supernova explosions. These exotic nuclei were observed for the first time; their lifetimes and other properties that are required for modeling the r-process remain to be measured.

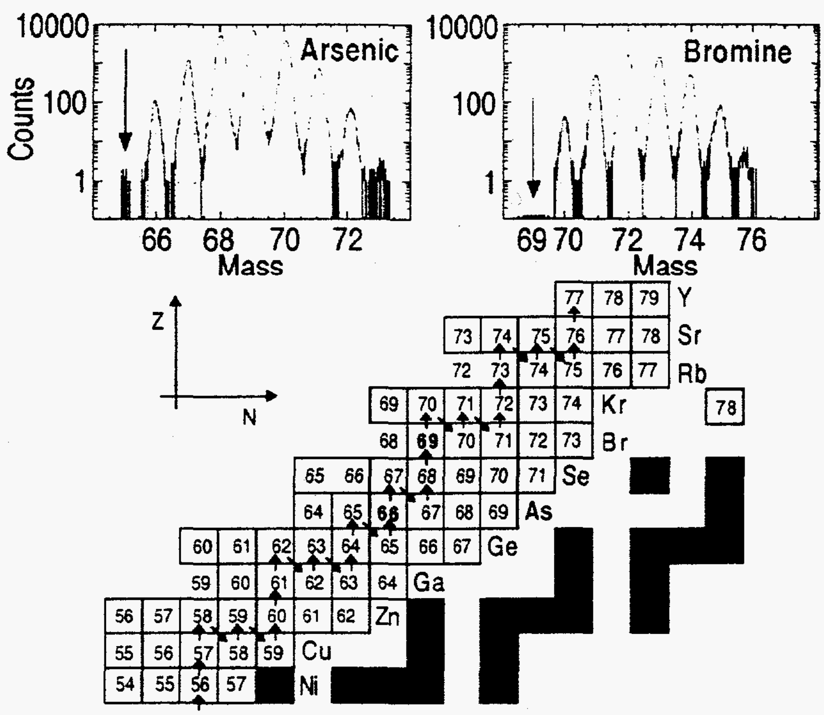

Figure 7. Results for fragmentation yields observed in flight following the frag mentation of a beam of stable krypton nuclei. In the region of the short-lived nuclei near the proton drip line the particle stability and existence or non-existence of a specific nucleus provides important information on the path and time scales involved in the astrophysical rp process.

Beams of short-lived ^{13}N (lifetime 10 min), ^{18}F (lifetime 110 min) and ^{19}Ne (lifetime 17 sec) have been generated by first producing these nuclei with a primary production accelerator and then introducing them into the ion source for acceleration in a second accelerator [9-12]. This two-accelerator concept is complementary to the in-flight production of radioactive ion beams mentioned before. It has the advantage that the secondary beam is produced with the quality and precise energy necessary to measure the specific cross sections of astrophysical interest, which often depends sensitively on energy because of resonances or thresholds. In this way, important reactions have recently been studied with beams of ^{18}F and ^{19}Ne. Reactions on these nuclei provide the opportunity for a breakout from the CNO cycle in hot stars, and are the assumed gateways leading to the generation of elements heavier than oxygen via the rapid proton capture (rp) process.

At Louvain-la-Neuve where much of the two-accelerator technique was pioneered, the $^{18}F(p,\alpha)$ reaction was recently measured [9] and an upper limit determined for the breakout reaction ^{19}Ne (p,γ) using two cyclotrons [10]. At Argonne National Laboratory the (p,α) and (p,γ) reactions were studied with ^{18}F beams generated from an ion-source sample produced by a medical cyclotron (^{18}F is frequently used for positron topography in medicine) and accelerated with the ATLAS superconducting ion linac [11,12]. Figure 8 illustrates schematically the path of the rp-process in the nuclear chart, details of the reaction network in the region near the CNO cycle with possible "break-out" pathways to heavier elements, and an example for a measured reaction cross section taken from the work at Argonne.

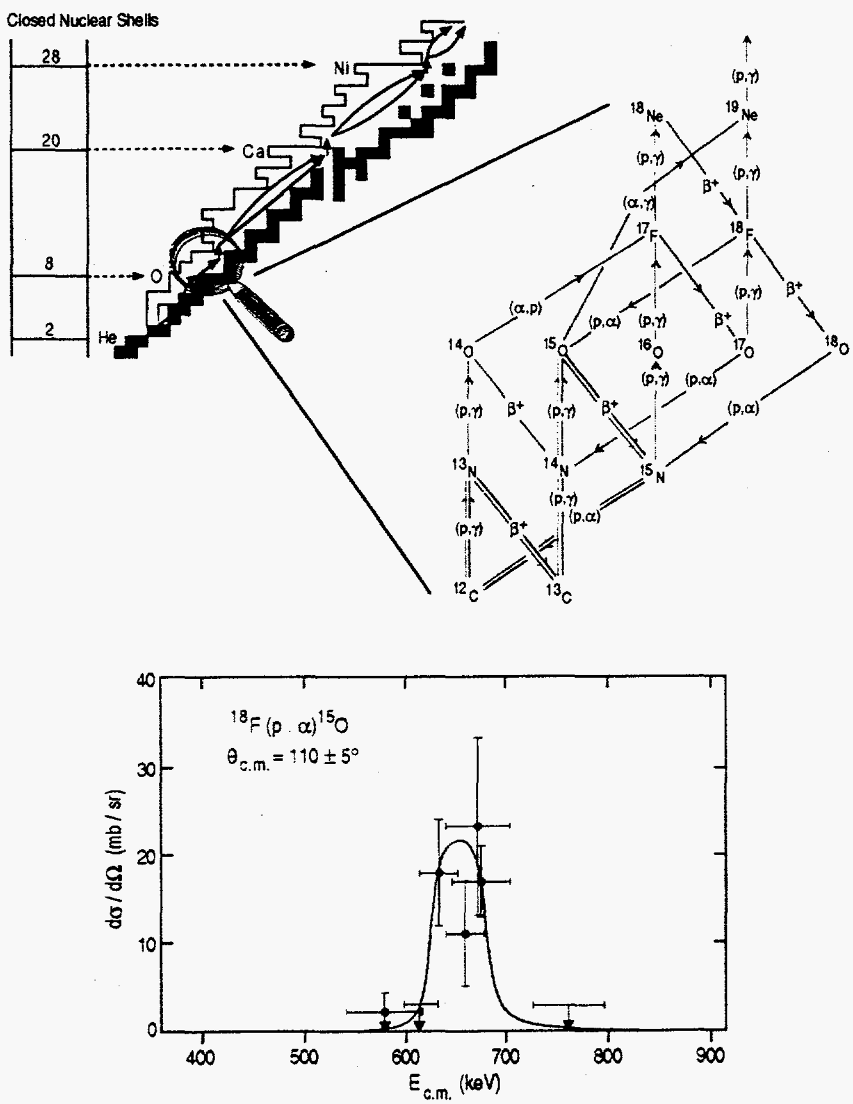

Figure 8. The top of the figure schematically illustrates the path of the rapid proton capture (rp) process in the chart of nuclides (with closed proton shells indicated), and a magnified view of the detailed reaction network near the region of the CNO cycle. The bottom of the figure shows the experimental reaction cross section for a previously unknown resonance which dominates the reaction rate for the $^{18}F(p,a)$ process at temperatures present in nova explosions [11].

4. CONCLUSION AND OUTLOOK

The potential of using radioactive beams for studying, in the laboratory, key reactions of importance for nucleosynthesis, as well as novel aspects of nuclear structure in itself, has triggered interest world wide in the upgrade and construction of accelerators to generate the high-quality beams of short-lived nuclei required. Such projects exist now or are underway in the US, Canada, Japan and several countries in Europe (see Figure 9).

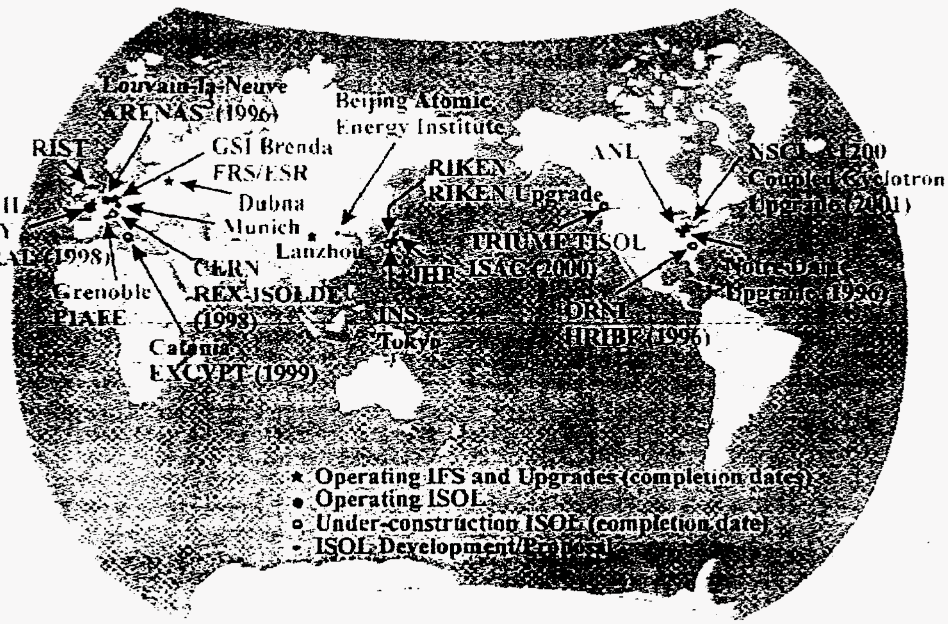

Figure 9. World map with locations of existing radioactive beam facilities and those under construction or in the planning.

This work is supported by the US Department of Energy, Nuclear Physics Division, under contract W-31109-ENG-38.

REFERENCES

1. J. Dobaczewski *et al.*, Phys. Rev. C 53 (1996) 2809.
2. T. Kobayashi *et al.*, Phys. Rev. Lett. 60 (1988) 2599.
3. Proceedings of the Third International Conference on Radioactive Nucleon Beams, Editions Frontieres, Gif-sur-Yvette (France), 1993; Proceedings of the fourth International Conference on Radioactive Nucleon Beams, Omiya (Japan) 1996.
4. T. Glasmacher *et al.*, to be published in Phys. Rev. Lett.
5. X. Gu *et al.*, Phys. Letters B 343 (1995) 31; and references therein.
6. J. A. Winger *et al.*, Phys. Lett. B299 (1993) 24.
7. B. Blank *et al.*, Phys. Rev. Lett. 74 (1995) 4611.
8. M. Bernas *et al.*, Phys. Lett. B 331 (1994) 19.
9. R. Coszach *et al.*, Phys. Lett. B 353 (1995) 184.
10. R. D. Page *et al.*, Phys. Rev. Lett. 73 (1994) 3066.
11. K. E. Rehm *et al.*, Phys. Rev. C 52 (1995) R460; Phys. Rev. C 53 (1996) 1950.
12. K. E. Rehm *et al.*, submitted for publication.
13. T. Motobayashi *et al.*, Phys. Rev. Lett. 73 (1994) 2680; T. Motobayashi *et al.*, Phys. Lett. B, in press; see also J. v. Schwarzenberg et al., Phys. Rev. C 53 (1996) 2598.