PROPOSAL FOR A ½ MW ELECTRON LINAC FOR RARE ISOTOPE AND MATERIALS SCIENCE

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Abstract

TRIUMF, in collaboration with university partners, proposes to construct a megawatt-class electron linear accelerator [1] (e-linac) as a driver for U(γ,f) with rates up to 10^{13}–10^{14} fissions/sec, and for ^{9}Be(γ,p)^{8}Li for materials science. The emphasis would be on neutron-rich species. The 50 MeV, 10 mA, c.w. linac is based on super-conducting radiofrequency technology at 1.3 GHz. Though high power/current electron linacs are a mature technology proposed elsewhere for applications ranging from fourth generation light-sources to TeV-scale linear colliders, TRIUMF is in the vanguard for applying this technology to the copious production of isotopes for studies of (i) nuclear structure & astrophysics; and (ii) β-NMR for materials science.

INTRODUCTION

State-of-the-art detector systems at ISAC have been deployed to address critical questions in nuclear physics. TRIUMF facilities and expertise for the development and deployment of rare isotope beams (RIBs) has created an overwhelming international demand for ISAC beam time. *All the ISAC programs critically need more rare-isotope beams*. TRIUMF's 2010–2015 Five-Year Plan outlines a strategy to at least double the RIB program. This goal will be achieved by building an electron linear accelerator (e-linac) photofission driver and a specialized proton beam line, coupled with a target station suitable for handling actinide targets and isotope separation on-line (ISOL). The e-linac will produce RIBs via the photofission of ^{238}U. For the 500 kW beam power envisioned, it is not practical to impinge the electrons directly onto a thick U target. It is preferable to use a converter to produce bremmstrahlung. Fig.1a shows the fission products distribution for 50 MeV, 10 mA e-beam & Hg converter on a 15 g/cm^2 ^{238}U target.

Complementarity of e & p for Neutron-rich RIBs

Nature has an excellent way of producing neutron-rich radioactive isotopes: fission of the U nucleus using either a high-energy proton or an electron beam. The latter produces a limited range of isotopes, albeit in large quantities. The limited range about the fission-mass peaks implies the beams are cleaner, i.e. fewer isobaric contaminants. By contrast, the proton beam produces a broader range of isotopes, see Fig.1b; this leads to RIBs with significantly more isobaric contaminants. Thus, the strengths and weaknesses of the two drivers (e & p) are coupled. Proton-induced fission is clearly unbeatable for certain regions. While γ-induced fission production may decline more rapidly far from stability on the neutron-rich side, it does posses the strong vantage of comparative cleanliness. This will prove decisive in forays towards the neutron drip line: most experiments that seek to go far from stability are limited, not by the low production of the most exotic nuclides, but rather by large isobaric contamination.

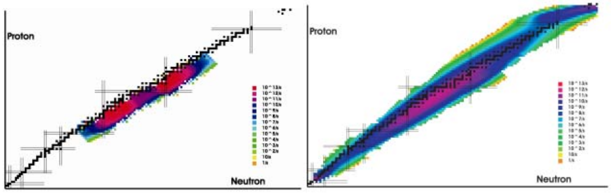

Figure1: In-target production assuming 4.6×10^{13} photo-fission, Fig. 1a (left); and 10 µA, 500 MeV proton beam on to a 25 g/cm^2 UC$_x$ target, Fig. 1b (right).

NUCLEAR STRUCTURE

A critical question in nuclear physics concerns the limits of existence: at what point do nuclei become unbound? This question is of importance to our understanding of the nature of the nucleonic system and of the astrophysical nucleosynthesis of heavy nuclei. The position of the proton drip line has been delineated for many elements because this region is accessible by stable-beam experiments. The location of the neutron drip line is largely unknown except for the lightest elements, up to oxygen.

All nuclear models use detailed properties of known nuclei to determine the proper form of the effective nuclear interactions. However, it is mostly at (or near) stability where these have been determined. The exact location of closed proton and neutron shells, strongly influence nuclear binding energies. *Accurate and precise* mass measurements on nuclei farther from stability are needed to fix model interactions and parameters.

Properties as a Function of N/Z Asymmetry?

The advent of RIBs makes it possible to explore how the properties of nuclei evolve along a chain of isotopes from neutron-deficient to neutron-rich nuclei. This capability has led to the discovery of new and unexpected phenomena close to the edge of stability. Photofission produced RIBs will shed light on what happens to the magic proton and neutron numbers. Several theoretical calculations predict that the familiar shell gaps that give rise to those *magic* numbers, or major shell closures, may change drastically in neutron-rich nuclei across the whole nuclear chart. This is in stark contrast to magic numbers in atomic physics, where their constancy gives rise to the *periodic* table. Striking observations are the appearance of new magic numbers and disappearance of others resulting in rotational-like behaviour in nuclei previously predicted to have closed shells. Shell locations also have a profound

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impact on nucleosynthesis models, specifically the *r*-process path, and also on the nature and density of the excited levels through which reactions, like (n,γ) and (p,γ), proceed.

To map shell structure, extensive systematic studies of nuclear properties must be performed, starting with nuclei near the stability line, and progressing outwards. The following key experiments must be undertaken:

1) Mass measurements - evidence for major shell closures are found in deviations of the masses from smooth trends;
2) β-decay - yields crucial information on the energies, angular momenta, and parities of excited states & isomers;
3) Coulomb excitation, measuring key matrix elements that depend on the nuclear wave functions;
4) Single-nucleon transfer reactions that probe the microscopic, single-particle nature of nuclear wave functions; &
5) Measure charge radii via precision laser spectroscopy.

Studies Shell Structure Evolution at ISAC

A major impediment to studying very neutron-rich nuclei is the problem that for isotopes far from stability, yields go down and isobaric contamination goes up. In many cases, this problem proves to be the limiting factor for the ISOL approach to studying neutron-rich nuclei produced by fission and spallation of actinide targets with high-energy protons. The proposal to build a photofission driver offers the advantage of a significant reduction (and even in many cases elimination) of short-lived neutron-deficient isobars, see Fig.1. Note, high-current proton beams on an actinide target do provide intense beams of neutron-rich isotopes in mass regions that are not in the "regular" fission fragment islands (see Fig.2); and thus complement the photofission-driver capability.

The physics program proposed [3] focuses on nuclei in the neutron-rich region around ^{132}Sn where the e-linac will have peak yields. A similar program reaching beyond ^{78}Ni can be envisioned with a combination of the e-linac and proton beam line with a ^{238}U target.

NUCLEAR ASTROPHYSICS

The field of nuclear astrophysics aims to understand the origins of the chemical elements in the universe and what powers stellar explosions such as novae and x-ray bursts.

How & Where are the Heavy Elements Produced?

While the origin of the light elements is well established, the environment where the heaviest elements were created remains uncertain. The slow (*s*) and rapid (*r*) neutron capture processes are thought to be responsible for the production of nearly all the heavy elements (A > 70). Many nuclei in the valley of β stability are produced by the *s-process*, a series of slow neutron captures. The most neutron-rich and the heaviest nuclei are produced by the *r-process*, a series of rapid neutron captures, interspersed with photodisintegrations and β decays, in a very hot environment with a huge number of free neutrons. Abundance differences between light and heavy r-process nuclei, derived from astronomical observations, support the hypothesis of two *r*-process sites: for nuclei with $A > 130$ (the main *r*-process), and for $A \leq 130$. Two possible astrophysical *r*-process sites, neutron star mergers and core-collapse supernovae, have been modeled extensively. The former is inconsistent with the necessary timescale; and wide parameter ranges of the latter are consistent with the observed elemental abundances. With the precise conditions uncertain, the *astrophysical-site-independent waiting point approximation* is adopted: temperature and neutron density are so high that neutron captures proceed rapidly until reaching an isotope for which (n,γ) and (γ,n) reactions are in equilibrium [2]. Once the free neutrons are exhausted, or photodisintegrations freeze out, the vast majority of isotopes are waiting point nuclei; they are *r*-process progenitors which β-decay back toward stability.

Mass Measurements

The identities of the waiting point nuclei depend on mass differences between adjacent isotopes. Mass trends near the closed neutron shells, have a profound influence on the final abundances. Nuclei with closed neutron shells (*e.g.* N = 50, 82, and 126) are particularly tightly bound, are strongly represented among the waiting point nuclei, and contribute substantially to abundances peaks *e.g. A* ~80, 130, and 195. To date, the masses of only ten *r*-process progenitors have been measured. Neutron-rich U(γ,f)-produced beams will allow TRIUMF to make important contributions to *r*-process knowledge through mass measurements. We shall reach the *r*-process path in a number of places, but substantial coverage near N = 82 represents the most exciting opportunity. The best option will be direct mass measurements using TITAN[1]. Other options will be pursued at EMMA[2] and TIGRESS[3]. E-linac yield calculations indicate that we shall reach some of the most important waiting point nuclei whose masses have not yet been measured or confirmed, *e.g.* ^{131,132}Cd, $^{131-133}$In, ^{134,136}Sn, ^{137,139}Sb, & ^{138,140,142}Te.

Beta-decay and Neutron Emission

In addition to strongly influencing the progenitor abundances, β–decay lifetimes determine the timescale of the *r*-process, particularly at and near the closed neutron shells. Beta-delayed neutron emission probabilities, P_n, affect *r*-process final abundances by shifting a decaying nucleus by one mass unit and liberating neutrons at late times far from thermal equilibrium. Experimental data on the β–decay lifetimes & P_n values of *r*-process progenitors and daughters have been obtained for about 50 nuclei from ^{68}Fe to ^{140}Te. An example of the type of precise study enabled by the powerful combination of EMMA, DESCANT[4] and TIGRESS with the pure, neutron-rich beams that will be available from photofission is the study of β-decay lifetimes and neutron emission probabilities of ground states and isomers in *r*-progenitors around N = 82.

The Nuclear Physics of Neutron Stars

Neutron stars are one possible end state of massive stars. Recent calculations explore nuclear processes that take place in the crusts of neutron stars accreting material and undergoing x-ray bursts. As the ashes of a burst sink into the crust, electron captures drive the nuclei to a very large *N/Z*. Once they reach the neutron drip line, they emit neutrons before undergoing further electron captures as the pressure and density increase. Finally, pycnonuclear fusion occurs. The captures and fusion reactions heat the crust, affecting predictions of astronomical observables such as recurrence time of superbursts and x-ray transients in variably accreting neutron stars. Only by improving knowledge of neutron-rich nuclei will we be able to interpret reliably these observations. A large fraction of the ashes are predicted to be ^{104}Cd. So targeted studies of the electron capture products of *rp*-process ash nuclei such as ^{104}Y and ^{104}Sr using TITAN will be very germane.

Conclusion

To construct realistic models of r-process nucleosynthesis and stellar explosions requires knowledge of many nuclear properties; their measurement constitutes the major justification for the proposal to develop neutron-rich nuclear beams at TRIUMF. The ISAC facility at TRIUMF is the ideal location to study neutron-rich heavy nuclei and their reactions because of its combination of beams of short-lived nuclei, variable-energy accelerators, and suite of world-class experimental facilities. The proposed e-linac photofission driver will significantly increase this experimental capability.

BETA-NMR FOR MATERIALS SCIENCE

The possibility of using novel materials in radically new technologies, such as quantum computers and magnetic spintronics, has provided significant motivation to study materials that currently seem exotic, but may turn out to be tomorrow's *silicon*. Using similar types of probes, muon spin rotation (μSR) and beta-detected NMR (β-NMR) employ implanted spin-polarized particles that sense their magnetic environment and report this information through their spin-dependent anisotropic beta decay, thus acting as ultra-sensitive magnetic probes for fundamental studies of matter at the atomic scale.

The low energy ion beams for β-NMR, typically ^{8}Li^{+}, are near-surface probes, and their implantation depth can be varied. In contrast, high energy muons always go far into the bulk; and depth control is not practical at TRIUMF. The information available in β-NMR (as in μSR) is greater than from traditional chemical radiotracers because the decay registers not only the probe's presence but also, through parity violation, provides the spin state of the probe particle at the time of decay, yielding information similar to nuclear magnetic resonance (NMR). In contrast to NMR, the beta-decay detection scheme enables measurements using far fewer probe spins and yields extreme sensitivity. While still in its infancy, the β-NMR technique at TRIUMF is now shown to be an effective, depth-resolved, sensitive, local probe of metamaterials and near-surfaces. Other β-NMR facilities exist, but none combine in-flight laser polarization of the radioisotope, low beam energies (typically 30 keV at ISAC), and variable implantation depth; nor do they have the high beam intensities of ISAC and CMMS[5] spectrometer capabilities.

The Science of Metamaterials with β-NMR

When materials are combined to form a layered heterostructure (metamaterial), the resulting properties may differ substantially from those of bulk materials, *e.g.* the crystal structure of atoms at the surface can differ from that of a simple truncation of the bulk. In fact, all structural, magnetic, and electronic properties of metamaterials and crystals near a free surface are depth-dependent. Little is known of such phenomena, because there are so few depth-resolved techniques. TRIUMF has demonstrated β-NMR as a powerful probe of metamaterials on length scales from 200 down to 2 nm.

Single-molecule Magnets

The use of nanoscale magnets for information storage or quantum computing requires monodisperse magnets that can be addressed individually. A major step towards this goal came recently with the discovery of molecules that function as identical magnets, and the ability to deposit a monolayer of them on a suitable substrate. These single-molecule magnets (SMMs) exhibit fascinating quantum mechanical behaviour that dramatically affects macroscopic magnetization. But the small amount of material present in a monolayer makes it impossible to determine magnetic properties with conventional techniques. Researchers at TRIUMF used β-NMR to investigate the magnetic properties of SMMs in a two-dimensional lattice, measuring temperature dependence of the magnet moments, of Mn_{12} or Fe_{4} SMMs [4] grafted to a silicon substrate. Intriguingly, properties of SMMs in this low dimensional configuration differ largely from the bulk.

Importance of e-linac

Over the period 1999–2006, TRIUMF β-NMR has receiv-ed about 4 weeks of beam per year. With such limited time, there is no chance for β-NMR to grow into a broad-based research tool like μSR. To make the leap to user facility, it is essential to implement a parallel source of RIBs such as the proposed photofission source. As β-NMR uses exclusively light isotopes, like ^{8}Li, species may be produced directly by photodisintegration, *e.g.* the ^{9}Be(γ, *p*)^{8}Li reaction, which is estimated to yield at least as much ^{8}Li as the conventional ISAC target. With the proposed new e-linac source, we anticipate that the beam time available for β-NMR will quadruple.

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1: TRIUMF Ion Trap for Atomic and Nuclear science. 2: Electro-Magnetic Mass Analyser. 3: TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer. 4: Deuterated Scintillator Array for Neutron Tagging. 5: Centre for Molecular and Materials Science.