ARIEL: TRIUMF'S ADVANCED RARE ISOTOPE LABORATORY*

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TRIUMF, Canada's National Laboratory for particle and nuclear physics, is constructing ARIEL, the Advanced Rare IsotopE Laboratory. The centerpiece of the new laboratory is a 500 kW, 50 MeV electron accelerator to drive production of exotic isotopes by photoreactions. The first phase will produce ^{8}Li for material and subatomic science, followed by neutron-rich fission fragments for nuclear structure approaching the postulated astrophysical r-process. ARIEL will levarage existing infrastructure at TRIUMF, including the existing suite of ISAC experimental equipment and the cyclotron proton beamline for spallation. By 2020 it is envisioned that, with a fully instrumented ARIEL and the existing ISAC complex, it will be routine to perform three simultaneous experiments in nuclear structure, fundamental interactions, and nuclear astrophysics with rare isotope beams from three separate production stations.

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1. About TRIUMF

TRIUMF is Canada's national laboratory for particle and nuclear physics. Originally founded in 1969 in Vancouver by the three major British Columbia research universities, it is owned and operated by a consortium of 18 universities across the country. TRIUMF's research themes are "probing the structure and origin of matter" and "advancing isotopes for science and medicine".

TRIUMF is responsible for operating and maintaining several accelerators at the Vancouver site. The central facility is the 500 MeV, 350 μA H^{-} cyclotron. It has several extraction ports and routinely serves as a driver for simultaneous medical isotope production, meson production, and exotic isotope production. This last function is facilitated by ISAC, the Isotope

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Separator and ACcelerator. Exotic, short-lived isotopes are produced by the ISOL technique. The extraction platform at 60 kV delivers ions (typically singly-charged) through the mass (or more precisely, m/q) separator and optionally to an ECR-type ion source to increase the charge state. From here the beam is delivered to one of three experimental areas. The first, low-energy area delivers beam at the extraction energy to several experimental end stations optimized for mass measurements, lifetime measurements, atomic spectroscopy, and surface science. A room-temperature RFQ and room-temperature DTL accelerate ions up to 1.5 MeV/u primarily for nuclear astrophysics experiments. These two accelerators, the production and separation equipment, and experimental areas, are collectively known as ISAC-I. ISAC-II is the superconducting linear accelerator that provides up to 40 MV of acceleration, and the experimental hall housing gamma- and charged-particle spectroscopy stations and, in the future, a reaction mass analyzer [1, 2].

For over a decade, ISAC has delivered radioactive ion beams and enabled cutting-edge programs in nuclear structure, nuclear astrophysics, fundamental symmetries, and materials science. The next stage of TRIUMF's rare isotope program will be to evolve towards true multi-user RIB capability. This is driven by the high demand for beam. Typically, insight into the structure of exotic nuclei and exotic materials arises from the synthesis of results from several complementary experiments; a complete picture for the ground state of a single nucleus involves measurements of its mass, decay lifetime and modes, and atomic properties. These individual experiments typically run for one week at a time. The ISAC-I accelerated program is largely centred on nuclear astrophysics reactions with low cross sections, with measurements typically running for several weeks. One of the key new initiatives in the ISAC-I low-energy program is a trapping facility enabling comprehensive study of francium nuclei for fundamental symmetry studies. These studies are envisioned to take several months of continuous beam. As it exists now, ISAC is a single-user radioactive beam facility. There is a single ISOL station, so exotic nuclei can only be delivered to one experiment at a time. Any upgrade must be capable of delivering beam to all existing experimental stations to maintain or enhance the existing programs (see figure 1). The solution is a new accelerator and ISOL system to produce RIBs by photofission and photodissociation — the Advanced Rare IsotopE Laboratory (ARIEL) [3].

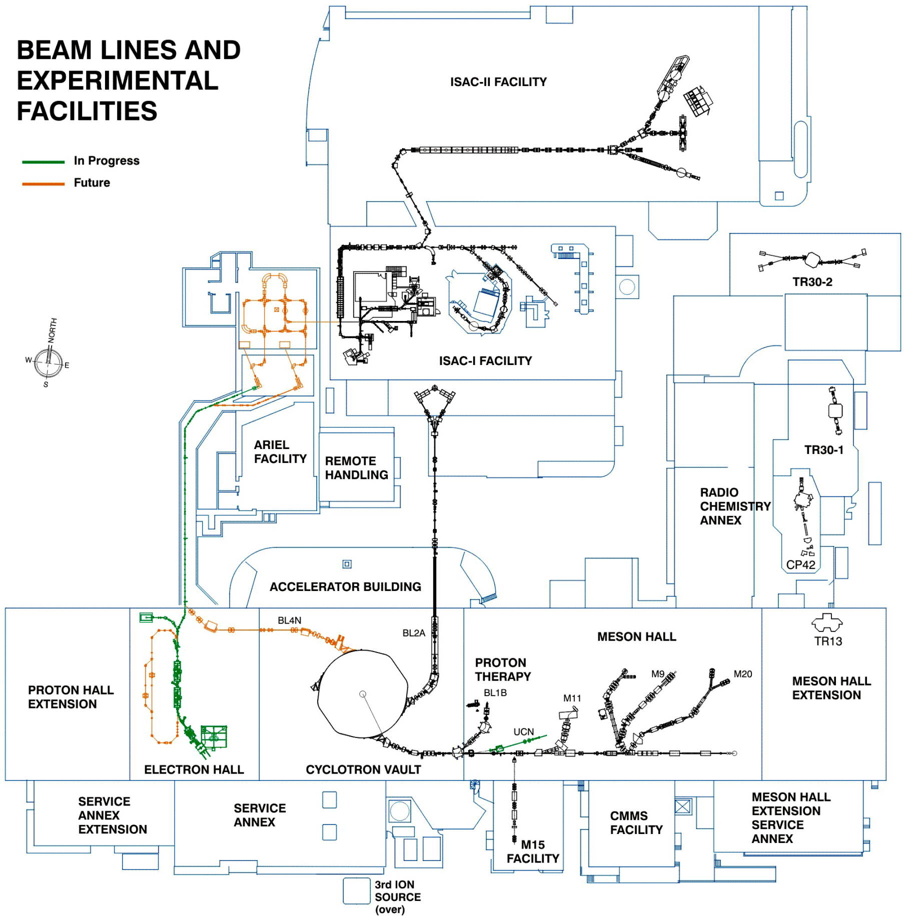

Fig. 1. TRIUMF site layout showing ARIEL.

2. The ARIEL plan

The fission of transactinide nuclei, be it spontaneous, hadron induced, or electromagnetically induced, has long been a tool for producing neutron rich nuclei. High-energy protons also induce spallation reactions on, for example, uranium ISOL targets. While may of these spallation products, such as francium and radium, be frequently of intrinsic physics interest themselves, they also present the greatest radiological hazzards, namely volatile alpha emitters such as the radon and polonium isotopes. Fission products span a broad range of medium-mass (A = 80 to 160), neutron-rich nuclei and cover a large fraction of the postulated astrophysical r-process. As such, photofission and ISOL extraction promises to provide beams with superior isobaric purity and with a lower radioactive waste burden than spallation.

Photofission in ARIEL will be driven by a superconducting electron linear accelerator (e-linac) operating at up to 50 MeV and a power up to 500 kW. For a fixed power of beam on target, the induced fission rate drops precipitously with decreasing energy [4, 5]. Above 25 MeV, the photofission production rate for fixed power continues to increase, but slowly, and the dependence is not as strong as below 25 MeV (see figure 2). This has driven the initial and final operating configurations for the e-linac.

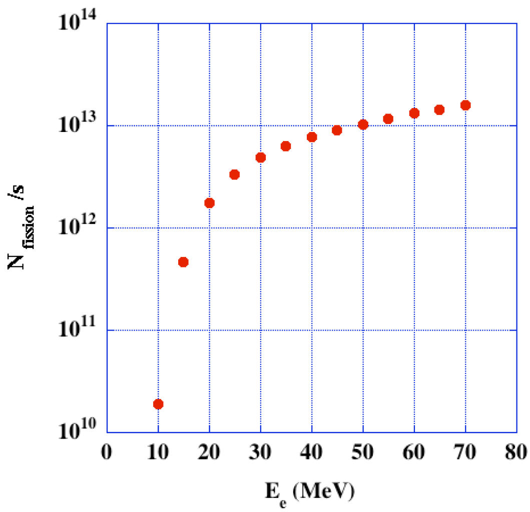

Fig. 2. Number of photofissions per second for 100 kW electron beam on a $2X_0$ tantalum converter 150 mm in front of a 15 mm diameter stack of 25 g/cm^2 ^{238}U [8].

The e-linac will consist of a 300 keV thermal electron gun, an injector cryomodule with a nine-cell elliptical superconducting niobium accelerating structure, and two accelerator cryomodules with two accelerating structures each. The vault in which it will be installed is a repurposed experimental hall next to the main cyclotron. A transfer line tunnel has been built to accommodate both the electron beam and a second proton beam driver. The e-linac will operate at 100 kW and 25 MeV in 2014, and later on will be upgraded to 500 kW and 50 MeV.

Two new target stations will be built for ARIEL. Initially, one target station will be used with up to 100 kW electron beam, while the second is used for photoconverter development. The latter is needed for 500 kW operation. As with ISAC, each the RIB production target stations will employ a relatively low resolution, $\Delta M/M = 500$ preseparator magnet. The first production target will be BeO, the ^{9}Be($e\gamma$,p)^{8}Li reaction in support of the TRIUMF surface science program. For an optimized, solid metal photon converter with 25 MeV, 100 kW electron beam, the in-target production rate is predicted to be approximately 10^9 ^{8}Li/s [6]. For this program, a low-resolution preseparator alone will be adequate.

The next stage of science will be enabled by a high-resolution mass spectrometer and electron-beam ion source (EBIS). The design goal of the mass separator is $\Delta M/M = 20,000$. The EBIS will be used as a charge breeder, increasing charge q so that the A/q of RIB ions matches the acceptance of the existing ISAC-I accelerator infrastructure. These devices will be coupled into the ISAC-I beamlines before ARIEL targets are comissioned, and so will augment the existing programs in areas requiring $A > 30$ beams and isobar separation.

In the final target configuration, one target will consist of a liquid lead photon converter with 500 kW, 50 MeV incident electrons, driving a helium-cooled arrangement of uranium carbide target cylinders. Absolute yield to experiment will, of course, depend on release, ionization, extraction, and transport efficiencies; expected in-target production rates are given in Table I. The second target will be driven by protons from a new beamline off the main cycltron. A beamline switchyard will allow the beams produced in these stations to be delivered to the high-resolution mass separator or, in less demanding applications, a medium-resolution mass separator, and then on to the existing ISAC accelerators and experimental stations.

TABLE I

FLUKA simulation of in-target production, with 500 kW and 10 mA electron beam on a molten Pb converter, followed by a helium-cooled, seven-cylinder UC_x target. Geometry details may be found in [9].

Isotope	In-target production [/s]
^{72}Ni	2.0×10^8
^{78}Zn	3.4×10^9
^{91}Kr	2.3×10^{11}
^{94}Kr	1.3×10^{11}
^{97}Rb	1.1×10^{11}
^{132}Sn	2.5×10^{10}
^{134}Sn	2.4×10^9
^{142}Xe	5.2×10^{10}
^{144}Xe	7.9×10^9
^{144}Cs	6.0×10^{10}
^{146}Cs	9.2×10^8

3. Current status

The full civil infrastructure for two ARIEL targets — refurbished vault, transfer tunnel, and target building — has been completed. The 300 kV electron gun is installed. Three strings of accelerating cavities have been fabricated by a local company. The e-linac is on track for the first beam in February 2014. The high resolution mass separator and EBIS charge breeder are funded and being designed. Details of the implementation timelines for ARIEL may be found in the TRIUMF 2015–2020 Five Year Plan [7].

The e-linac and target developments are part of a joint venture between TRIUMF and the Variable Energy Cyclotron Centre (VECC), Kolkata, India. Capital investment in ARIEL comes from the Canadian Foundation for Innovation and its provincial partners, British Columbia Knowledge Development Foundation, Manitoba Research and Innovation Fund, and Nova Scotia Research and Innovation Trust. TRIUMF receives federal funding via a contribution agreement through the National Research Council of Canada. The author thanks Nikita Bernier, Pierre Bricault, Reiner Krücken, Marco Marchetto, Lia Merminga, and Mina Nozar for assistance in preparing this manuscript.

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