Dear Jean-Michel,

Please find attached a Letter of Intent for the TRIUMF Subatomic Physics Experimental Evaluation Committee. If you have any questions regarding these plans, please do not hesitate to contact me.

Yours sincerely,

Alexander Murphy
Letter of Intent to the TRIUMF Subatomic Physics Experimental Evaluation Committee.

Study of reactions important to synthesis of $^{44}$Ti in Core Collapse Supernovae

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Introduction.
Core collapse supernovae are some of the most intriguing and scrutinised phenomena in the Universe. In trying to understand them, one of the most powerful diagnostic tools at our disposal is evidence of $^{44}$Ti production. Unlike any other observable, it combines the specificity of isotopic (not elemental) abundance, can be observed promptly and directly, and can be associated with specific aspects of the core collapse mechanism. The quantitative interpretation of such observations, such as those currently being sought with the INTEGRAL satellite, or derived from examination of isotopic anomalies in meteorites, urgently requires several key nuclear reaction rates to be measured, and it is my intent to conduct a programme of research at TRIUMF to acquire the requisite data.

The key development that will allow this new research to be conducted is the provision of post-accelerated beams of $^{44}$Ti and $^{45}$V. With appropriate beam development of the TRILIS laser ion source, and making use of the charge state booster, these could soon be available from ISAC for delivery to the TUDA and DRAGON facilities (Jens Lassen, private communication). It is in recognition of the likely beam development time, and to aid any such efforts, that I submit this Letter of Intent. Full proposals to the TRIUMF EEC for each of the experiments suggested will follow. It should be noted that a research grant has been presented to the EPSRC (UK funding agency) to provide a postdoctoral researcher specifically to support this experimental programme.

Details of Proposed Research.
Stars more massive than about 8 times that of our Sun evolve over a period of $\sim 10^6$ years into what is frequently described as an onion-skin-like structure. An outer layer of hydrogen surrounds shells of hydrogen burning into helium, helium burning to carbon, carbon to neon and oxygen and inner shells of magnesium and silicon, and a central core of iron and nickel. These fusion burning processes provide heat to support the great weight of the star, but with the binding energy per nucleon maximising, heavier elements cannot be synthesised. Consequently, when the final fuel has been exhausted, the core, a roughly 3000 km diameter sphere of iron, collapses to about 100 km in a few milliseconds. At this point the core’s density is raised to several times that of nuclear matter, and the temperature to several billion Kelvin. A shock wave, energised predominantly by neutrino emission, is sent out through the overlying layers. Matter in these layers is heated, undergoes nucleosynthesis, and is be expelled.

The ensuing explosion is formidably complex, hampering the development of a predictive theory of the explosion. However, certain observables may be linked to particular aspects of the supernova phenomenon, breaking the overall problem into more manageable parts. The isotope $^{44}$Ti is one such observable, since it is produced in the region just above the collapsing core. Depending on the location of the ‘mass-cut’, that is the boundary between which material is successfully expelled and that which falls back onto proto-neutron star, the amount of $^{44}$Ti observed will vary. If this is determined, and compared to a reasonably accurate prediction of the total amount that was synthesised, the location of the mass cut can be determined, and this compared to hydrodynamics simulation. Few other observables have such
a clear impact upon our understanding of the underlying mechanisms at work within the core collapse supernova environment.

$^{44}$Ti has been shown to have a beta-decay half-life of 60 years (see NPA 686 (2001) 591 and references therein), transforming to $^{44}$Sc and then to $^{40}$Ca. In this process it emits a gamma-ray with an energy of 1.157 MeV. Any direct observation of a source of such radiation, such as was achieved by CGRO when observing the Cassiopeia-A supernova remnant (A&A 284 (1994) L1), thus indicates the presence of processes capable of synthesising $^{44}$Ti. It is believed that the only mechanism able to produce sufficient quantities of this isotope is that of the $\alpha$-rich freeze out (ApJS 26 (1973) 231, ApJ 460 (1996) 408), which occurs in the shock-heated silicon shell just above the collapsed core of a supernova. Various authors have simulated this as pure $^{28}$Si with an initial temperature of $5 \times 10^9$ K and a density of $10^7$ g/cm$^3$. As the material expands, one finds the shockwave dissociates the silicon into protons, neutrons and alpha particles, which then reassemble under conditions approximating nuclear statistical equilibrium. As the expansion proceeds, the temperature drops, equilibrium is broken, and new isotopic abundance patterns emerge.

Work by The et al. (ApJ 504 (1998) 500) explored large scale network calculations of this environment, including systematic variation of the nuclear reaction rates involved in determining the abundance of $^{44}$Ti. The reactions whose uncertainties were of most significance were $^{40}$Ca($\alpha,\gamma$)$^{44}$Ti, $^{44}$Ti($\alpha,p$)$^{47}$V, and $^{45}$V($p,\gamma$)$^{46}$Cr, together with the triple alpha process. Furthermore, the quantity of $^{44}$Ti synthesised was found to be largely insensitive to variations in other reaction rates. Consequently, a limited programme of experiments aimed at determination of just these reaction rates can constrain the nuclear uncertainties in a process that, in reality, involves many hundreds of other reactions. The $^{40}$Ca($\alpha,\gamma$)$^{44}$Ti reaction is the subject of an already accepted proposal, and thus the reactions I wish to address here are $^{44}$Ti($\alpha,p$)$^{47}$V, and $^{45}$V($p,\gamma$)$^{46}$Cr.

The $^{44}$Ti($\alpha,p$)$^{47}$V reaction will be examined using the TUDA facility. Although the reaction proceeds through resonances in the well studied $^{47}$V nucleus, there exists insufficient level information at energies relevant to astrophysics. A direct measurement has previously been conducted (PRL 84 (2000) 1651) but did not explore the astrophysically interesting energy regime. A beam of $^{44}$Ti ions will be made incident upon a helium gas target (currently being developed) and protons will be detected in CD- or LEDA-type segmented silicon detector arrays.

The $^{45}$V($p,\gamma$)$^{46}$Cr reaction rate is almost completely unknown since it has never been directly measured and virtually nothing is known about the levels that might make resonant contributions. The measurements of Garrett et al. (PRL 87 (2001) 132502, and private communication) have only identified higher spin states that will not be involved. Moreover, the work of Horoi and Murphy (PRC 66 (2002) 015801) derived rates by considering the available isobaric analogue information and shell model estimates, concluding that isolated resonances could result in significant deviation from the rate estimated by Hauser Feshbach statistical models.

A resonant elastic scattering measurement will be proposed, aiming to identify the locations, spins and widths of resonances that might contribute. This would again be conducted with the TUDA facility, and apart from the new beam species, will be very similar in nature to previous experiments performed by the TUDA collaboration such as $^{21}$Na($p,p$)$^{21}$Na and $^{20}$Na($p,p$)$^{20}$Na. In conjunction with this, collaboration with the DRAGON group will be sought so as to conduct the direct measurement in a coordinated effort. The astrophysical energies to be
explored are all consistent with ISAC-I beam energies, though the CSB and the laser ion source will of course be required.

In summary, I would like to inform the EEC that I intend to undertake a series of measurements utilising the TUDA and DRAGON facilities in order to study key reactions of relevance to $^{44}$Ti production in core collapse supernovae. All necessary equipment either currently exists or is under development. Timescales for these studies are therefore determined by beam availability.