TRIUMF – EEC NEW RESEARCH PROPOSAL		Exp. No: S1124 Date: 27/10/06

TITLE OF EXPERIMENT

Mass measurements for the supernova νp-process

Name of group	**S-nu-p**

Spokesperson(s) for Group **C. Ruiz, J. Dilling**	**Email address(es)** ruiz@triumf.ca, jdilling@triumf.ca

Current Members of Group: (name, institution, status, % of research time devoted to experiment)

C. Ruiz	TRIUMF/U. York	Research Associate	40 %
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A.M. Laird	U. York	Lecturer	10 %
B.R. Fulton	U. York	Full Professor	5 %
C. Vockenhuber	TRIUMF	Research Associate	15 %
M. Pearson	TRIUMF	Research Scientist	5 %
J.M. D'Auria	SFU	Full Professor	10 %
J. Pearson	U. McMaster	Research Associate	15 %
M. Trinczek	TRIUMF/SFU	Research Associate	15 %
P. Delheij	TRIUMF	Research Scientist	10 %
G. Gwinner	U. Manitoba	Assistant Professor	10 %

Date for Start of Preparations: Now	**Beam time requested (# of 12-hr shifts): 9**
Date Ready: Fall 2007	**Experimental Area: TITAN** **Base (1A, 2C, 2C4, 1B) or ISAC (2A)** **(Place response here): ISAC (2A)**
Completion Date: 2007/2008	

SUMMARY

The νp-process is a newly proposed nucleosynthesis process expected to occur in the explosions of core-collapse supernovae. It arises as the result of a new paradigm in supernova neutrino transport theory, where conditions in the neutrino driven winds blowing from a nascent neutron star at early times are proton-rich [1,2]. Due to a small but persistent neutron flux, maintained by the $p(\bar{\nu}_e, e^+)n$ reaction, nucleosynthesis via an rp-process involving proton-capture on seed nuclei can carry the synthesis up a path on the proton-rich side of stability. The neutron flux assists this process via (n,p) reactions, thus bypassing the β^+ decays that would otherwise be waiting points. The process can synthesize the well-known p-nuclei from Se to Pd, whose exact origin is still unclear. Some s- and r-process nuclei can also be produced if reasonable modifications to the entropy in the wind are made.

One problem identified with this process is that it under-produces the most abundant p-nucleus, ^{92}Mo. Its synthesis depends sensitively upon the population of radioactive progenitors which are governed by specifics of nuclear reaction flows through the N=46,47,48 isotones around A=92. Since many of these flows are in near equilibrium, their exact path is principally due to nuclear masses, and therefore Q-values, of the relevant (p,γ) reactions, many of which are unknown experimentally and highly uncertain.

We propose a set of mass measurements on the N=46,47,48 isotones around the A=92 region using the TITAN facility to experimentally fix the νp-process flow in this region and remove the nuclear uncertainties which the synthesis of ^{92}Mo depends on.

BEAM AND SUPPORT REQUIREMENTS

PROTON BEAM/ TARGET: (energy, intensity, pulse characteristics, ion source)

Energy (in MeV): 500

Intensity (in μA): 75

Pulse Width (in nanoseconds): N/A

Rep Rate: Choose one of: normal; 1/5; other (Place response here): N/A

PRODUCTION TARGET:

$1AT_1$: 1cmC; 1cmBe or $1AT_2$: 10cmBe (Place response here): HP-Ta or HP-LaC

ISAC: Ion Source: SURFACE; FEBIAD; LASER; ECR; OLIS

(Place response here): LASER

SECONDARY CHANNEL/ISAC BEAMLINE (Place response in the space below):

TITAN

SECONDARY BEAM (particle type/isotope, energy, energy width, solid angle, spot size, intensity, beam purity, target, special characteristics)

Please list all isotopes: ^{90,91,92}Ru,^{91,92,93}Rh, >100/s, isobaric contaminants below this level.

EXPERIMENTAL FACILITY(IES) TO BE USED: TITAN

TRIUMF RESOURCES REQUESTED:
(Summarize the expected TRIUMF resources needed for the experiment. Identify major capital items and other costs that will be requested from TRIUMF. Note: Technical Review Forms must be provided before allocation of beam time.)

TITAN operational grant, TRIUMF DAQ support, TRIUMF beam development (targets and TRILIS)

EXTERNAL FUNDING SOURCES (Summarize expected non-TRIUMF sources of funding for the experiment.)

1. NSERC: Canadian participants will be funded from their respective NSERC grants

2. OTHER (Please describe): Participants from the UK and US will be funded by their respective grants (EPSRC and DOE)

SAFETY

(Summarize possible hazards associated with the experimental apparatus, precautions to be taken, and other matters that should be brought to the notice of the Safety Officer. Details must be provided separately in a safety report to be prepared by the spokesperson under the guidance of the Safety Report Guide available from the Science Division Office.)

DETAILED STATEMENT OF PROPOSED RESEARCH

Production of ^{92}Mo in the νp-process

The paper of Pruet *et al.* details the particular net nuclear flows involved in the νp-process. The path proceeds far from stability, so ^{92}Mo arises from radioactive decay of species populated along the flow path. One such path that lead to co-production of many p-nuclei from Sr to Pd is illustrated in Fig. 1 (wind trajectory 6 in Pruet *et al*), indicating the dominant net nuclear flows that bypass the proton-unbound (white) nuclei above ^{64}Ge, and in the regions of 90<A<94, the dominant flows that produced the radioactive progenitors responsible for ^{92}Mo synthesis. The dominant flow through ^{90}Ru proceeds mainly by the (n,p) reaction to ^{90}Tc because of an impedance due to the small proton-separation energy of ^{91}Rh, hence the path detours and flows up the N=47 and N=48 isotones, unhindered because of the relatively large proton-separation energies encountered there, until ^{93}Pd and ^{94}Pd are reached and again the path is diverted to a greater line of isotones because of the small proton-separation energies of ^{94}Ag and ^{95}Ag. The N=46 isotone is the first place where the pattern of encountering proton-unbound nuclei along the Z=N=Even nuclei is broken. If this were not the case, and the flow were to carry on up to ^{92}Pd before diverting, Pruet *et al.* suggested this might contribute to ^{92}Mo co-production. They also suggested it might occur at later times as the wind transitioned to a neutron-rich character.

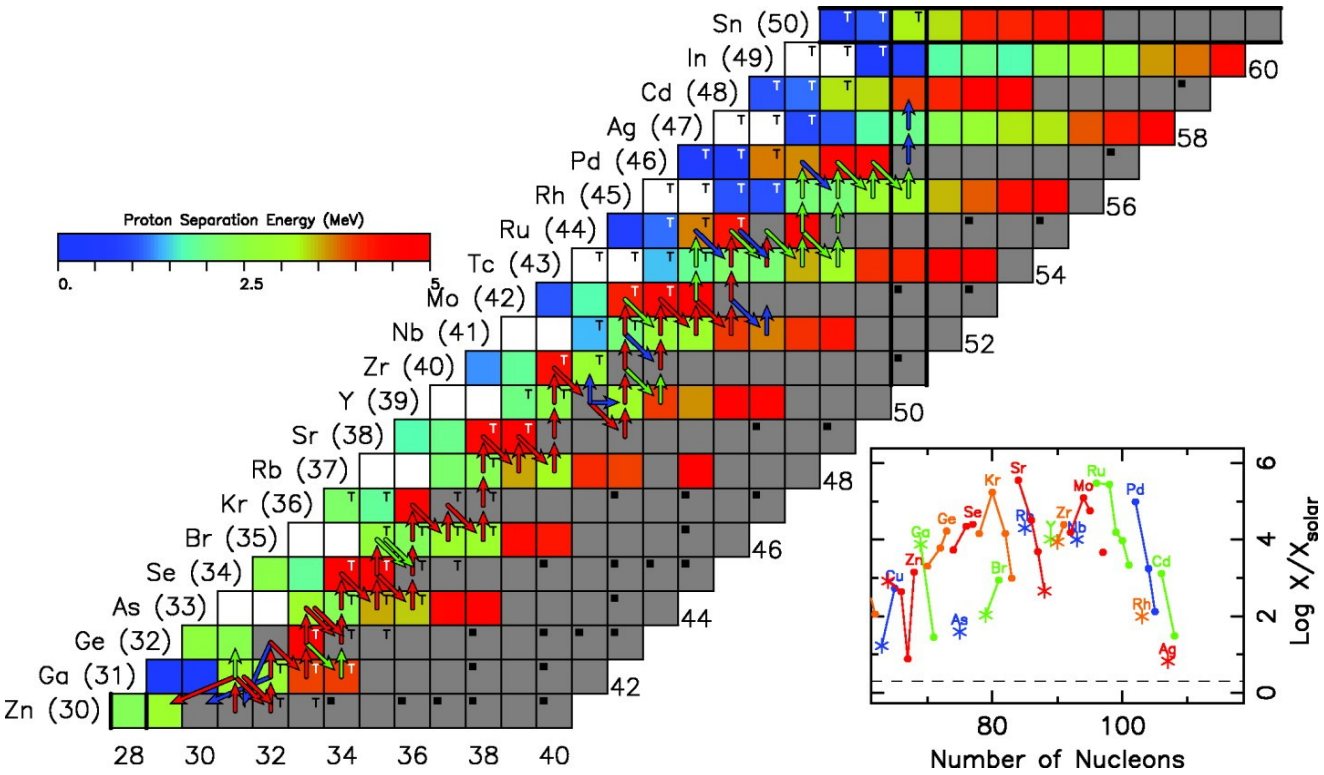

Figure 1: Pruet *et al* [2] figure showing the net nuclear flows in νp-process for wind trajectory 6 in a 15 solar mass supernova explosion (T_9=2.05).

DETAILED STATEMENT OF PROPOSED RESEARCH

Subsequent investigation of the nucleosynthesis in wind trajectory 6 of Pruet *et al*. has determined the sensitivity of ^{92}Mo production to individual quantities within the reaction network for species with 90 < A < 95 in the N=46,47,48 isotones (Hoffman *et al.* – private communication). The intent was to address the question: can ^{92}Mo be co-produced with the other p-nuclei from Sr – Pd? Co-production means relative production with respect to solar abundances, assessed using the production factors, defined for an isotope (Z,A) as its mass fraction at the end of the simulation divided by its mass fraction in the sun. Successful co-production would mean relative production within a factor of 2-4 of the dominant species produced, in this case ^{96,98}Ru. The inset production factor diagram in Fig. 1 indicates ^{92}Mo is under-produced compared to the other p-nuclei ^{84}Sr, ^{96,96}Ru, and ^{102}Pd by a factor of 20. Of less concern but still a question is ^{94}Mo, which is co-produced to within a factor 5.

Since many of the dominant species are produced in a state of (p,γ)-(γ,p) equilibrium, where reaction rates are nearly balanced by their inverses, the important quantities affecting production are those involved in calculation of the reverse rates which are determined through detailed balance. Thus, uncertainties in nuclear partition functions, statistical weight factors, and especially Q-values (*i.e.* nuclear masses) will dominate the nuclear flows and hence production of these rare species.

The first investigation studied the neutron-rich outflows recently extracted from [1], finding insufficient ^{92}Mo production compared to that found in Pruet *et al*. In that paper, the first attempt at a sensitivity study in trajectory 6 was attempted by making a 1 MeV increase to the ^{91}Rh proton separation energy, which resulted in an increase in ^{92}Mo synthesis, now co-produced to within a factor of 12. Although promising, this fell far short of what is needed. A further 1 MeV increase in the ^{91}Rh proton separation energy yielded no further increase in ^{92}Mo, because the production of ^{92}Pd is essentially saturated at the temperatures where it was made ($T_9 \sim 2$). Also, modification of the ground-state spins of several nuclei in the region showed only mild influence (< few %) on ^{92}Mo production, since they enter the calculations as a linear term in the calculation of the reverse rates (whereas the Q-values are part of an exponential term).

Next, a 1 MeV decrease in the proton separation energy of ^{93}Rh was made (keeping the $S_p(^{91}Rh)$ as the original value) to impede the flow of the ^{92}Ru(p,γ)^{93}Rh reaction. In this case, ^{92}Mo was co-produced within a very respectable factor 3 of ^{96}Ru. However, ^{94}Mo was badly affected, resulting in a shortfall of a factor 20; effectively switching the co-production problems of the p-isotopes of Mo.

In the end, it was possible to get close to equal co-production of ^{92}Mo and ^{94}Mo compared to ^{96}Ru by making a 0.76 MeV increase in $S_p(^{91}Rh)$, and a 0.5 MeV decrease in $S_p(^{93}Rh)$. These are the suggested errors to which each is known in the recent mass evaluation of Audi and Wapstra (2003). With this change both ^{92}Mo and ^{94}Mo we co-produced with ^{96,98}Ru to within factors of 4 and 7 respectively.

It has been shown therefore that according to network calculations, high sensitivity exists to the Q-values of certain reactions which affect ^{92}Mo production, and that adjusting these values within their accepted errors can co-produce all the p-nuclei between Sr-Pd in solar proportions. This evidence alone is compelling, in that this new nucleosynthetic process now does not seem to have any glaring shortfall, and for the first time ever can co-produce the Mo and Ru p-nuclei in a consistent way.

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Known masses in A=92, N=46,47,48 region

From the AME2003 atomic mass evaluation [6], the proton separation energies of some of the relevant nuclei to ^{92}Mo synthesis are given as:

Nucleus	Proton separation energy	Source
^{90}Ru	4.75 ± 0.36 MeV	Extrapolation
^{91}Ru	4.74 ± 0.76 MeV	Extrapolation
^{92}Ru	5.71 ± 0.36 MeV	Extrapolation
^{91}Rh	1.09 ± 0.50 MeV	Extrapolation
^{92}Rh	1.99 ± 0.71 MeV	Extrapolation
^{93}Rh	2.05 ± 0.50 MeV	Extrapolation
^{92}Pd	3.68 ± 0.64 MeV	Extrapolation
^{93}Pd	3.63 ± 0.57 MeV	Extrapolation
^{94}Pd	4.47 ± 0.57 MeV	Extrapolation

Since the above uncertainties are assumed to be 1σ errors, changes of 1 MeV in certain nuclei are not unreasonable. The proton separation energies of the Ru isotopes are large enough that changes of the order 1 MeV in these values are not likely to affect the nucleosynthesis flow for the temperatures where ^{92}Mo and other p-nuclei are synthesized. However the relatively low values for the Rh isotopes are a different matter; it is here where changes could make a large difference to the final ^{92}Mo abundances, as we have seen from the calculations mentioned above. Thus in order to know the proton separation energies for Rh isotopes, we would like to be able to measure the masses of the Ru and Rh nuclei tabulated above.

The separation energies of the Pd isotopes are not strictly important to know, having extrapolated values almost as high as the Ru values, and therefore not potentially affecting the flow much. Not shown in the table are the Ag isotopes, which have low extrapolated proton separation energies and therefore impede the forward flow. These would be interesting nuclei to measure in order to determine the true nucleosynthesis path, although because of the stability afforded by the adjacent closed proton and neutron shells above this region, the abundances of the p-nuclei are unlikely to be affected drastically by changes in this path. Thus the measurement of Ag separation energies will possibly be considered in a future proposal but are considered less important for the apparent ^{92}Mo production discrepancy.

We therefore propose to measure the masses of ^{90,91,92}Ru and ^{91,92,93}Rh using the TITAN facility, with an accuracy of ±5 keV, in order to determine the Q-values that most sensitively affect ^{92}Mo production.

Mass measurements using TITAN

Beams of Ru and Rh may be made using a high-mass production target such as lanthanum-carbide (LaC). A high-power LaC target exists at ISAC currently, as an analogue for the proposed future uranium-carbide target, and is due to be tested at some point even though no experiments are presently scheduled for this target. With ionization potentials of 7.37 and 7.46 eV respectively, these elements may be candidates for ionization using the Triumf Resonant Ionization Laser Ion Source (TRILIS).

DETAILED STATEMENT OF PROPOSED RESEARCH

The experiment will be carried out with the TITAN facility. The isotopes from ISAC will be delivered to the experiment located in the low-energy area of ISAC I. The continuous beam will be brought into the linear cooler and buncher RFQ (RFCT), where it will be cooled via interactions with buffer gas, followed by bunched extraction. The kinetic energy of the beam extracted from this device can be adjusted and will be ~ 2-4 keV.

The ion bunch is transferred to the Electron Beam Ion Trap (EBIT) for charge breeding. The ions will be stored and charge bred for a specific time and the electron beam energy can be adjusted. Then the ion bunch is mass-to-charge selected employing two Wien filters (WIFI 1&2). This provides a beam of only one charge state, and eliminates possible isobaric contamination. The final step is the mass measurement in a Penning trap (MPET) employing a time-of-flight method. A description of the system can be found in [7] and a schematic is shown in figure 4. Some of the properties of the nuclei to be measured and their charge states in the TITAN apparatus are listed in the table below.

Nucleus	**$T_{1/2}$**	**Proton separation energy /MeV**	**TITAN mass uncertainty /keV**	**Charge state /e**
^{90}Ru	11 ± 3 s	4.75 ± 0.36	0.1	42
^{91}Ru	9 ± 1 s	4.74 ± 0.76	0.1	42
^{92}Ru	3.65 ± 0.05 m	5.71 ± 0.36	0.1	42
^{91}Rh	1.74 ± 0.14 s	1.09 ± 0.50	0.1	43
^{92}Rh	4.3 ±1.3 s	1.99 ± 0.71	0.1	43
^{93}Rh	13.9 ± 1.6 s	2.05 ± 0.50	0.1	43

The actual mass measurement is done in the following way using the Penning trap mass spectrometer. Penning traps are the most precise devices to measure masses and our system is designed to carry out measurements of atomic masses with an accuracy of $\delta m/m < 1 \cdot 10^{-8}$, even for radioactive isotopes with half-lives well below 100 ms. In the center of such a spectrometer is the set of hyperbolic electrodes placed in the strong magnetic field, schematically shown in figure 5.

The measurement consists of the following steps.

1. Ion injection. The electrostatic potential is removed and a few ions are allowed to drift into the trap. When the ions are in the trap, the potential is raised to confine them. The closing time should be optimized so that the energy of the resulting axial oscillations is minimal. The ion motion after injection is mostly magnetron and axial oscillation, with minimal cyclotron motion.

2. Quadrupole RF excitation. An external RF field of the form $V_Q = V_Q^{(0)}(x^2 - y^2) \times \cos(\omega_Q t)$ is overlapped onto the electrostatic trapping potential for the measurement time interval T_{RF}. It converts the magnetron motion into the cyclotron motion of the same amplitude if the resonant condition

$$\omega_Q = \omega_+ + \omega_- = \omega_c = \frac{qB}{m}$$

is satisfied. The width of this resonance is given by the inverse of the excitation time T_{RF}, which determines the resolving power of this measurement method

$$\frac{m}{\delta m} \propto \omega_c T_{RF} \sqrt{N} = \frac{qB}{m} T_{RF} \sqrt{N} \quad ,$$

where *N* is the statistical improvement factor.

3. Ejection and TOF measurement. After RF excitation the ions are released from the trap by gradually lowering the electrostatic potential along *z*-axis. The resonantly created cyclotron motion has the same amplitude as the initial magnetron motion. Since $\omega_+/\omega_- >> 1$ (typically by several orders of magnitude) the energy and magnetic moment of the ion are drastically increased during the RF excitation. Upon ejection, the ion drifts outside the magnetic field region. On its way it passes through the region with the high gradient of the magnetic field. Here, the ions are accelerated proportionally to their magnetic moment. Thus the ions with high magnetic moment will have a shorter time-of-flight (TOF). This allows one to unambiguously detect the resonant conversion of the magnetron motion into the cyclotron motion, hence the resonant frequency, which is directly proportional to the mass. The schematic and an example is depicted in figure 6.

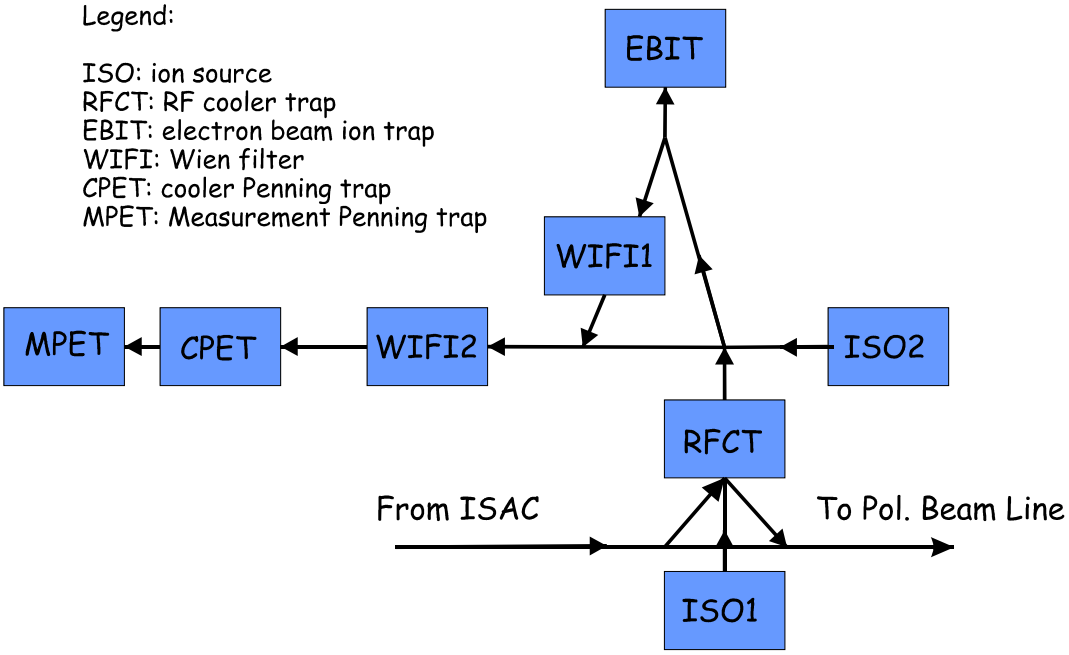

Fig. 4 Schematic of the final layout of TITAN.

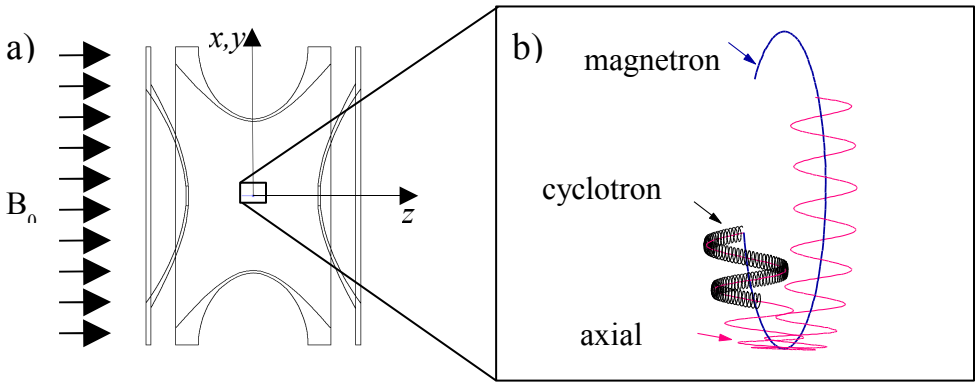

Figure 5. Typical Penning trap a) the geometry and coordinate system; the hyperbolic electrodes create harmonic potential of the form $V(x,y,z) = A(z^2 - (x^2+y^2)/2)$; uniform magnetic field is directed along z-axis $\vec{B} = B_0\hat{z}$. b) ion motion inside the Penning trap consists of three characteristic modes. Along z-axis ion oscillates with axial frequency ω_z. In the x,y-plane the ion motion is a combination of two circular motions with fast modified cyclotron frequency ω_+ and slow magnetron frequency ω_-.

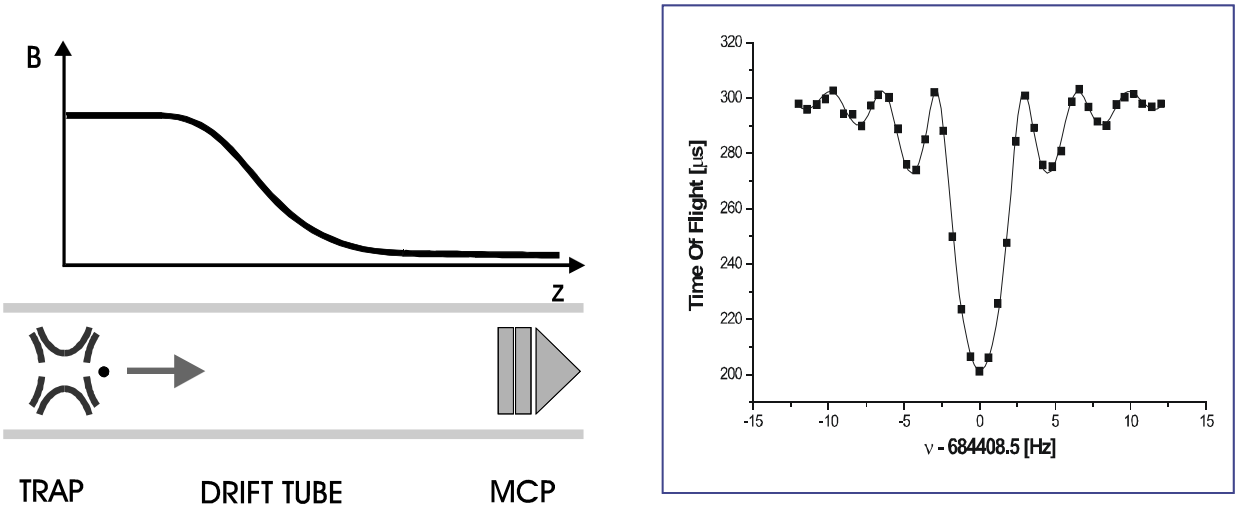

Fig. 6 Left: schematic of the TOF method, where the released ions move through the inhomogeneous magnetic field; right: TOF spectrum, shown is the excitation frequency versus the TOF. The minimum resonance corresponds to the cyclotron frequency, and hence allows the mass determination.

3. Requested beam time

The requested beam time is based on the assumed efficiency (60% for cooling, 60% for breeding, and 50% for measuring), a reasonable constant radioactive beam current, required time for magnetic field calibrations for the measurement magnet, and optimization procedures for the EBIT.

For some example nuclei, the following estimations can be made:
For ^{90}Ru (11(3)s), a production rate of 3.2 $\times 10^4$ ions/s is expected from a high power Ta target. If one assumes a bad ionization efficiency of 1% 320 ions/s are expected. The measurement will be carried out by breeding the Ru to charge state q = 42 (breeding time ~ 40 ms), corresponding to the closed He-shell structure. At a Penning trap excitation time of 1 s and N=3000 a theoretical resolution of $\delta m/m = 3 \times 10^{-10}$ can be reached, which has to convoluted with the systematic uncertainty of the system. This is at present estimated to be on order 1×10^{-9}.

For ^{91}Ru (9(1)s), 4.3 $\times 10^5$ ions/s are expected (same ionization efficiency). For this isotope an isomeric state is known with an expected excitation energy of 80 (300) keV. For the isomer the $T_{1/2}$ = 7.6 (0.8) s. The production is assumed to be symmetric for gs and isomer. The measurement will be carried out by breeding the Ru to charge state q = 42. At a Penning trap excitation time of 1 s and N=3000 a resolution can be reached that allows to clearly separate ground and isomeric state.

For ^{92}Rh (1.74(0.14)s) a production n of 8 $\times 10^3$ is expected for a LaC_2 target. An assumed ionization efficiency of 1% results in a beam of 80 ions/s.. The measurement will be carried out by breeding the Rh to charge state q = 43 (breeding time about 35 ms at 7300 eV electron beam energy), corresponding to the closed He-shell structure only for Rh, excluding heavier isobar contamination. At a Penning trap excitation time of 1 s and N=3000 the required resolution of $\delta m/m = 1 \times 10^{-8}$ can be reached.

Summarizing the duty cycle in the case of ^{90}Ru and for 320 incoming ions /s,
- 100 ms cooling × 60% efficiency and no decay losses = 19 ions
- 35 ms breeding × 60% efficiency = 11 ions
- 1000 ms measuring × 50% efficiency and decay losses = 3 ions
we obtain an average of 5 ions per cycle in the measurement Penning trap.

We request a total of 9 shifts. 1 shift will be allotted for the set-up of each of the elements (Ru, Rh) and 1 shift for each isotope measurement. This time estimate could be adjusted, within the 9 shifts, according to each isotope. The measurements do not need to be allocated in a single experiment but could be broken up to allow for more flexibility and additional off-line optimization.

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PUBLICATION LIST OF SPOKESPERSON(S) (2001-2006)

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