TRIUMF - EEC SUBMISSION	TRIUMF	**Exp. No.**
EEC meeting: 201007S		S1283 - *Pending (Stage 1)*
Original Proposal		**Date Submitted:** 2010-06-28 10:06:53

Title of Experiment:

Precision Mass Measurements of the Halo Candidates ^{31}Ne and ^{22}C

Name of group:

TITAN

Spokesperson(s) for Group

S. Ettenauer

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

S. Ettenauer	University of British Columbia	Student (PhD)	100%
T. Brunner	T.U. Munich	Student (PhD)	50%
A. Gallant	University of British Columbia	Student (PhD)	50%
V. Simon	MPI-K Heidelberg	Student (Graduate)	50%
U. Chowdhury	University of Manitoba		50%
M. Simon	TRIUMF	PDF	30%
E. Mané	TRIUMF	PDF	30%
J. Dilling	TRIUMF	Research Scientist	20%
P.P.J. Delheij	TRIUMF	Research Scientist	10%
M.R. Pearson	TRIUMF	Research Scientist	10%
R. Kanungo	Saint Mary’s University	Research Associate	10%
G. Gwinner	University of Manitoba	Associate Professor	10%
M. Brodeur	University of British Columbia	Research Associate	10%

D. Lunney	Universite de Paris Sud	Senior Research	10%
R. Ringle	NSCL	Research Scientist	10%
B. Eberhardt	TRIUMF	Student (Graduate)	10%

Beam Shift Requests:

shifts on: TITAN

12 shifts

Basic Information:

Date submitted: 2010-06-28 10:06:53

Date experiment ready:

Summary:

Recently, a transmission experiment with ^{22}C and a Coulomb breakup reaction with ^{31}Ne, suggested (two-) neutron halo structures to explain the observed, unusually large cross sections. However, due to the large uncertainties on the (two-)neutron separation energies, the interpretation of the data by means of the halo-neutrons' orbitals and thus for ^{31}Ne also by means of the total spin-parity assignment remains ambiguous. We therefore propose precision mass measurements of ^{22}C and ^{20}C as well as ^{30}Ne and ^{31}Ne to extract the essential (two-)neutron separation energies.

Plain Text Summary: Recently, a transmission experiment with 22C and a Coulomb breakup reaction with 31Ne, suggested (two-) neutron halo structures to explain the observed, unusually large cross sections. However, due to the large uncertainties on the (two-)neutron separation energies, the interpretation of the data by means of the halo-neutrons' orbitals and thus for 31Ne also by means of the total spin-parity assignment remains ambiguous. We therefore propose precision mass measurements of 22C and 20C as well as 30Ne and 31Ne to extract the essential (two-)neutron separation energies.

Summary of Experiment Results:

Primary Beamline: isac2a

ISAC Facilities

ISAC Facility: TITAN Yield

ISAC-I Facility:

ISAC-II Facility:

Secondary Beam

Isotope: 20C,22C,31Ne

Energy: 20

Intensity Requested: >10^2(pps)

Minimum Intensity: 30

Maximum Intensity:

Energy Units:

Energy spread-maximum:

Time spread-maximum:

Angular Divergence:

Spot Size:

Charge Constraints:

Beam Purity:

Special Characteristics:

Experiment Support

Beam Diagnostics Required:

Signals for Beam Tuning:

DAQ Support:

TRIUMF Support:

All equipment is in place and running. Only normal operating support from TRIUMF is required

NSERC:

NSERC:

Other Funding:

Muon Justification:

Safety Issues:

Safety issues for the TITAN experiment have been already addressed in the required documents and have met approval. A safety request for the specific beams of this proposal will be made after the decision of the EEC.

TRIUMF EEC NEW RESEARCH PROPOSAL

Detailed Statement of Proposed Research for Experiment # S1283

Precision Mass Measurements of the Halo Candidates ^{31}Ne and ^{22}C

(a) **Scientific value of the experiment**: Describe the importance of the experiment and its relation to previous work and to theory. All competitive measurements at other laboratories should be mentioned. Include examples of the best available theoretical calculations with which the data will be compared.

Halo nuclei are of prime interest for current nuclear structure research. Due to their small separation energy of the valence nucleon(s), quantum mechanics allows these nucleons to deeply tunnel into the classically forbidden regions leading to extended tails in a valence nucleon's wave-function. As a result, halo nuclei have, compared to non-halo systems, large matter radii, and they generally can be viewed as a core plus the respective halo nucleon(s).

From a theoretical perspective, the exotic features of halo nuclei pose a real challenge for models of nuclear structure, especially due to the extended wave-function of the halo nucleon(s). Well established light halo systems, such as ^{6,8}He, ^{11}Li, or ^{11}Be, are of particular interest as the mass region with A up to around 16 has recently become accessible by a variety of theoretical descriptions including ab-initio methods (see for instance [GEIT08],[FOR09], [BAC09], or [HAG10] for some recent developments). Due to their exotic features, halo nuclei are important benchmarks for these models.

Because of the centrifugal barrier halo nuclei can only form with valence nucleons in the low orbital angular momentum configurations s and p, where the centrifugal barrier is either absent or low enough [JEN04]. It is thought that a more abundant appearance of halo nuclei could thus be limited to lighter masses because the condition of low orbital angular momentum would not generally occur along the drip line of heavier systems. But since in many cases shell structures and magic numbers at the limits of nuclear existence develop differently than expected from the well studied behaviors at or near stability (e.g. [SOR08], [JAN09], [OTS10]), halo nuclei might in fact be more common than expected. Halo nuclei could also be important for the location of the drip-line itself as their formation mechanism might add extra stability and thereby extend the limits of nuclear existence.

Indeed, very recently halo structures have been proposed for heavier systems: in the drip-line nuclide ^{22}C [TAN10] and in ^{31}Ne [NAK09] located in the island of inversion. If confirmed, these would be the heaviest halos known to date. In both cases, the atomic masses and, thus, the (two) neutron separation energies are either unknown or measured only with very poor precision. This situation leads to ambiguities in the interpretation of the experimental data in [TAN10] and [NAK09].

The case of ^{22}C

First suggested in [HOR06], experimental evidence for a (two neutron) halo structure in ^{22}C was recently found in reaction cross section σ_R measurements of $^{19,20,22}C$ at RIKEN by Tanaka and collaborators [TAN10]. The neutron rich carbon isotopes bombarded a liquid hydrogen target at ~40 MeV/A providing a determination of the reaction cross section by the transmission method. The results of the measurement are plotted in Figure 1a, which shows a significantly larger σ_R for ^{22}C. The Glauber model in the optical-limit approach and in a finite range treatment was applied to extract the rms matter radius. As shown in Figure 1b, the trend of the rms matter radii of other carbon isotopes is not continued by the larger rms radius of ^{22}C which is suggesting a halo structure in this nucleus.

The reaction cross section for the lighter $^{19,20}C$ are well predicted by a Glauber type calculation, i.e. in a few-body approach for ^{19}C (assumed as ^{18}C+n) and in the optical limit approach for ^{20}C [ABU08]. The same few body calculation for ^{22}C underestimates the experimental reaction cross section σ_R (see Table 1). Here, ^{22}C was treated as a s-wave two-neutron halo ^{20}C+n+n. However, the theoretical result for σ_R strongly depends on the two neutron separation energy S_{2n}, which is unknown experimentally. In the Atomic Mass Evaluation of 2003 (AME'03) [AUD03], the currently adapted value of S_{2n}=420(940) keV is based on an extrapolated mass for ^{22}C.

In [TAN10], a Glauber calculation (in a few body approach and the finite range treatment) for σ_R was performed in which the relative ratio of the wave function $(0d_{5/2})^2_{J=0}$ and $(1s_{1/2})^2_{J=0}$ of the two-valence neutrons was varied. Results are also plotted in Figure 1a assuming the valence neutrons to either only occupy the $1s_{1/2}$ (red) or the $0d_{5/2}$ orbital (blue). Solid symbols indicate an assumed S_{2n} of 10 keV while open symbols are based on

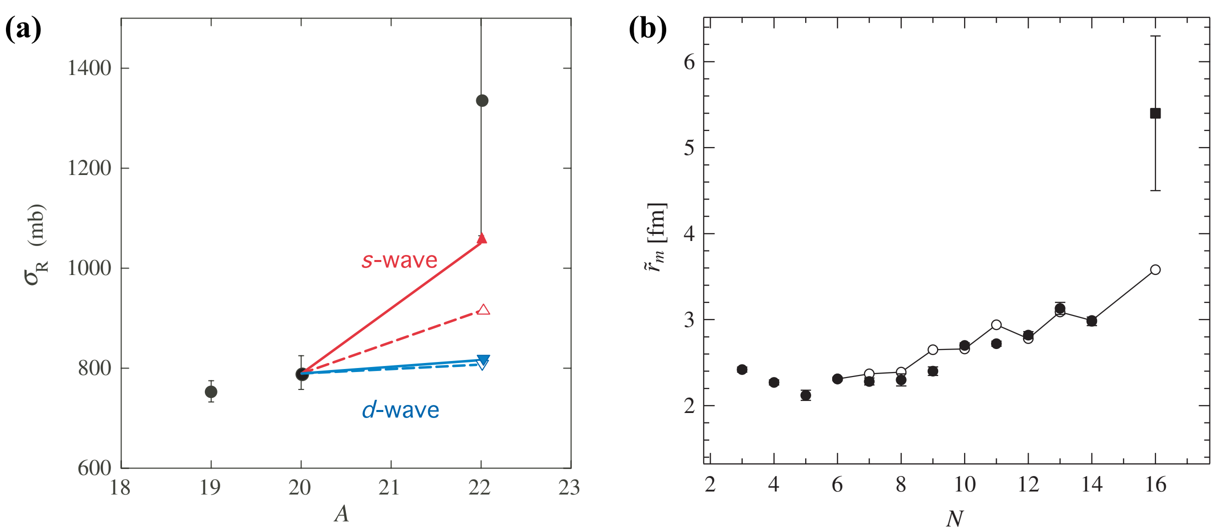

Figure 1:

(a) Measured reaction cross sections for $^{19,20,22}C$ at ~40 MeV/A onto a liquid hydrogen target. Coloured lines are to guide the eye. See text for details.

(b) rms matter radius for carbon isotopes. Filled circles and squares are determined from experiment ([OZA01] and [TAN10]. Open circles are the results of calculations in [ABU08].

(both figures from [TAN10])

__Table 1:__ Calculated reaction cross sections σ_R for ^{22}C at 40 MeV/A impinging on a proton target for different two neutron separation energies S_{2n} [ABU08] in comparison to the experimental value.

S_{2n} [keV]	σ_R [mb]	
489	957	
361	969	
232	985	
122	1005	
420(940)	1338(274)	experiment

S_{2n} =420 keV. The comparison of this calculation with the experimental data would favor a predominate occupation of $(1s_{1/2})^2_{J=0}$ as already predicted in [HOR06]. The s-wave configuration shows a stronger dependence on the two-neutron separation energy suggesting a lower S_{2n} since S_{2n}=10 keV reproduces the experimental result best.

The loose end of all existing calculations to either predict the reaction cross section or to extract spectroscopic information from the measured σ_R is the lack of (independent) experimental knowledge of S_{2n} and, thus, the mass of ^{22}C. Eliminating S_{2n} as a source of uncertainty is furthermore essential since the applicability of the Glauber model itself is questioned at lower energies and thus also at the 40 MeV/A of the existing measurement. If S_{2n} was much larger than the reaction cross section data indicates, none of the current calculations would be able to reproduce the measured σ_R, and the validity of the Glauber model at lower energies would require further investigation.

Additionally, a direct mass measurement of ^{22}C could serve to benchmark recent shell model calculations with a chiral nucleon-nucleon potential which (among others) provides results for energies of neutron rich carbon isotope ground states [COR10]. It should be noted that in this calculation the two neutron separation energy for ^{22}C is given relatively large with S_{2n}=601 keV. When downshifting the single-particle energies (s.p.e.) to reproduce the experimental difference in ground state energies for ^{14}C and ^{15}C, the even-even ground state energies of $^{16-20}C$ are very well reproduced (see Figure 2), but S_{2n} for ^{22}C becomes even larger.

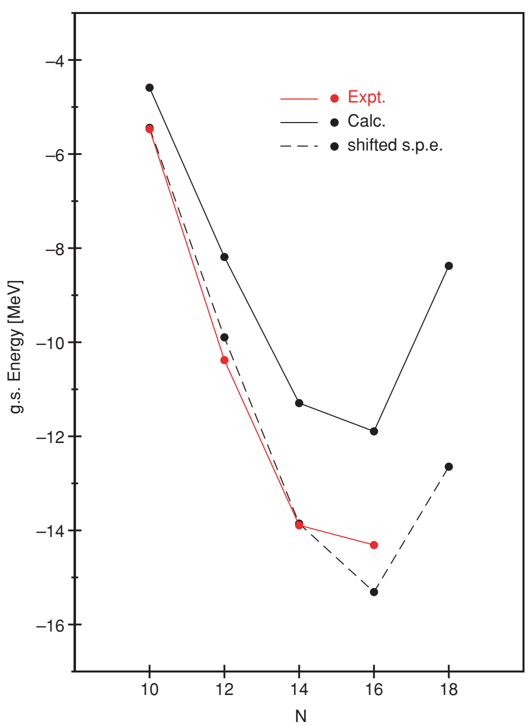

__Figure 2:__ Experimental and calculated ground-state energies for even-even carbon isotopes. The experimental value for A=16 (^{22}C) is an extrapolation in the AME'03.
Figure from [COR10].

The case of ^{31}Ne

A measurement of the (inclusive) Coulomb breakup cross section σ_{-1n}(E1) is a probe for the low-lying electric dipole, E1, strength. According to

$$\sigma_{-1n}(E1) = \int_{Sn}^{\infty} \frac{16\pi^3}{9\hbar c} N_{E1}(E_x) \frac{dB(E1)}{dE_x} dEx$$

σ_{-1n}(E1) is the convolution of the exponentially decreasing E1 virtual photon number, $N_{E1}(E_x)$, with the energy-differential reduced matrix E1 element dB(E1)/dE_x. In contrast to higher orbital angular moment configurations, dB(E1)/dE_x peaks at low energies E_x for s and p waves leading to larger σ_{-1n}(E1). Hence, halo nuclei are expected to exhibit enhanced σ_{-1n}(E1).

In [NAK09], the one-neutron removal cross section of ^{31}Ne on C and Pb targets was studied to deduce the Coulomb breakup cross section σ_{-1n}(E1). At ~230 MeV/A, Nakamura and collaborators extracted a Coulomb breakup cross section of 540(70) mb for ^{31}Ne which is comparable to 690(70) mb for the well established halo ^{19}C. Together with the low neutron separation energy S_n=0.3(1.6) MeV [JUR07], this result is consistent with the formation of a halo in ^{31}Ne. Of course, the current low precision of S_n requires improvement to strengthen such an interpretation.

Additionally, dB(E1)/dE_x was calculated in [NAK09] in a ^{30}Ne+n model for different possible core-valence neutron configurations. In the reaction process itself, the core was treated as a spectator. The deduced Coulomb breakup cross sections are compared to the the experimental result in Figure 3. Each calculated line represents the maximal possible spectroscopic factor C^2S; σ_{-1n}(E1) would be reduced for smaller C^2S. In this analysis, the $f_{7/2}$ orbit, which is expected from the conventional shell model, cannot account for the enhanced σ_{-1n}(E1). For S_n<800 keV, s or p waves would be compatible with the observed large Coulomb breakup cross section allowing a halo structure.

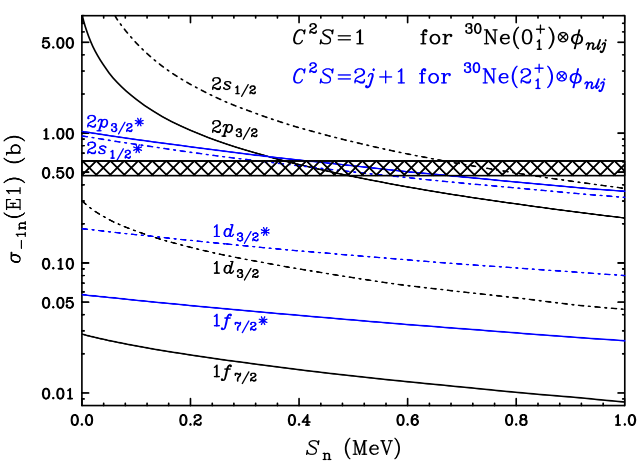

Figure 3: *Calculated Coulomb breakup cross section of ^{31}Ne for different valence neutron configurations as a function of the separation energy S_n. The shaded band represents the experimental value.*
Note the different orbital notation in this figure compared to the rest of this document.
(figure from [NAK09])

A theoretical description of the breakup channel of ^{31}Ne has recently been published in [HAM10] which interprets the data in means of deformation. As the neighboring nuclides ^{32}Na [THI75], ^{30}Ne [YAN03], and ^{32}Ne [DOO09] lie within the island of inversion, deformation is likely to play an important role for ^{31}Ne. [HAM10] follows previous studies on

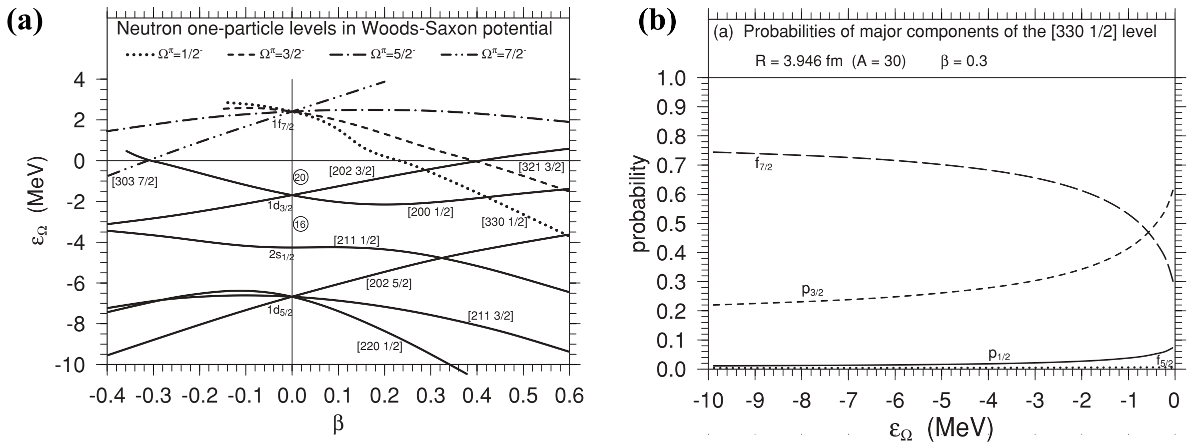

Figure 4:

(a) Nilson diagram for neutron one-particle levles as a function of the deformation parameter adjusted to the ^{30}Ne+n system.

(b) Calculated probablities of the major componetns of the [330 1/2] level with β=0.3 as a function of the energy eigenvalue.

(both figures from [HAM10])

weakly bound deformed single-neutron orbits [HAM07], [HAM04], which had shown that the lower angular moment components in a deformed potential start to dominate for small binding energies. This statement is valid independently of the size of deformation or the type of orbital. In Figure 4a the development of the neutron one particle levels over the deformation parameter are shown. The increasing dominance of the p-waves over the $f_{7/2}$ orbital for decreasing energy eigenvalues is illustrated in Figure 4b for a fixed β=0.3. [HAM10] concludes the following:

- For neutron separation energies S_n>500 keV the deformation would be large with β>0.6 and the ground state of ^{31}Ne would be $I^\pi=1/2^+$ from the Nilson level [200 1/2].
- For S_n<500 keV the ground state's spin parity could be $I^\pi=3/2^-$ and a p-wave neutron halo coming from either
    - [330 1/2] for 200 keV < S_n <500 keV or
    - [321 3/2] for 200 keV > S_n
- It is also argued that a clarification of the spin-parity is best achieved experimentally by an improvement of the neutron separation energy. For instance, a magnetic moment measurement may not be conclusive as the valence neutron in a deformed core will always be negative and its value will be similar for all possible configurations listed above.

Finally, a Glauber calculation to describe the Coulomb breakup of ^{31}Ne has been performed in [HOR10]. It assumes the ^{30}Ne core to be in the 0^+ ground state and compares the $0f_{7/2}$ to the $1p_{3/2}$ configuration of the valence neutron. The experimental data cannot be reproduced by the $f_{7/2}$ orbital of the valence neutron while the $p_{3/2}$ orbital yields a slightly overestimated $\sigma_{-1n}(E1)$.

Again, the result depends on S_n and it is suggested that S_n might be larger then 0.33 MeV[1] because a calculation with 0.6 MeV obtains a $\sigma_{-1n}(E1)$ value closer to experiment.

In summary, recent experiments on ^{22}C and ^{31}Ne provide evidence for the formation of halo structures. However, the interpretation of the experimental results depends on the two or one neutron separation energies, which are either based on AME03 extrapolations or only known with poor precision. We thus propose direct mass measurements of $^{20,22}C$ and $^{30,31}Ne$ with the TITAN mass spectrometer to determine S_{2n} and S_n, respectively.

(b) **Description of the experiment**: Techniques to be used, scale drawing of the apparatus, measurements to be made, data rates and background expected, sources of systematic error, results and precision anticipated. Compare this precision with that obtained in previous work and discuss its significance in regard to constraining theory. Give a precise list of targets to be used in order of their priority.

Penning traps dedicated to mass measurements of radioactive ions are now coupled to many radioactive beam facilities. Despite their supremacy in terms of the achieved precision, mass measurements on nuclides further away from stability pose a real challenge for Penning traps due to short half-lives. TITAN is uniquely capable to perform precision mass measurements on nuclides with half-lives even below 10 ms as demonstrated with ^{11}Li ($T_{1/2}$=8.6 ms) [SMI08]. It is thus the only Penning trap facility where a mass measurement on the even shorter lived ^{22}C and ^{31}Ne can be proposed.
Currently, the TITAN facility (see Figure 1a) consists of three ion traps: a radiofrequency quadrupole (RFQ) cooler and buncher [SMI06], an electron beam ion trap (EBIT) [FRO07], and a precision measurement Penning trap. The EBIT can be used to charge breed radioactive ions which boosts the precision of a mass measurement by a factor identical to the charge

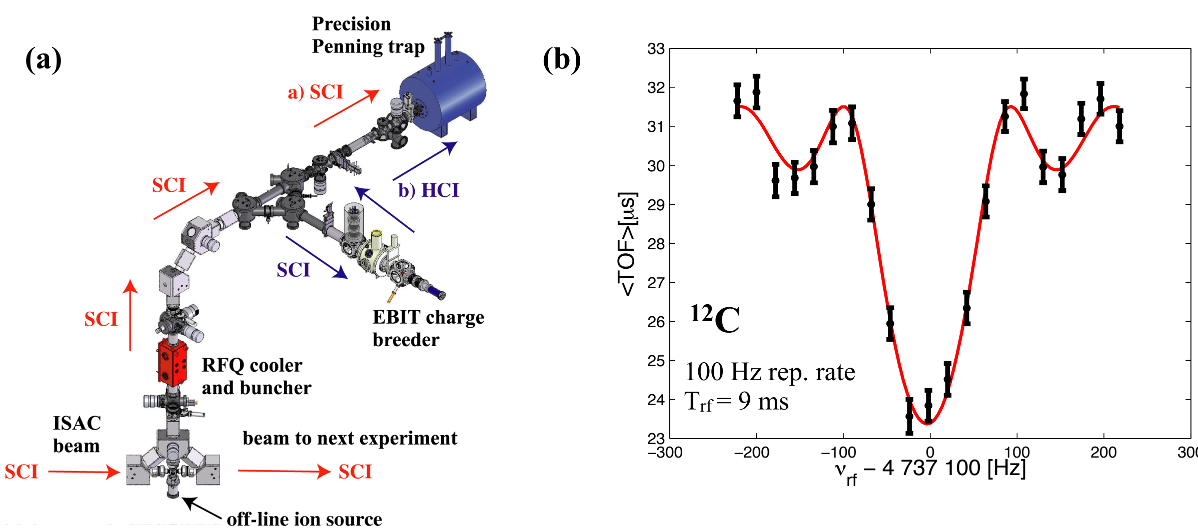

Figure 5:
(a) TITAN setup with the respective pathways for singly (SCI) and highly charged ions (HCI).
(b) Resonance for ^{12}C with a repetition rate of 100 Hz.

1 S_n=0.33 MeV was taken from an extrapolation in the Atomic Mass Evaluation 2003 [AUD03], and not from the more recent TOF measurement in [JUR07].

state. However, due to the very short half-lives and the relatively modest required precision the EBIT will not be used in this measurement.

To capture the incoming beam, the RFQ is floated to high voltage. The ions are confined in the radial direction by an electric quadrupolar rf field and axially by a potential minimum formed by a dc gradient. Through collision with a He buffer gas, the ions are cooled before they are extracted in bunches from the RFQ. A pulsed drift tube brings the ions to ground potential with a kinetic energy of 2 keV. The cooled and bunched ions are transferred directly from the RFQ to the measurement Penning trap. A homogeneous, axial 3.7 T magnetic field and a harmonic potential from a hyperbolic electrode structure establish the confinement in the Penning trap, resulting in three ion eigenmotions ([BRO86] [BOL90] [KOE95]). The magnetron and reduced cyclotron motions with respective frequencies ν_- and ν_+ are in the radial direction and are related to the cyclotron frequency $\nu_c=(1/2\pi)(q/m)B$ via $\nu_c=\nu_+ + \nu_-$. Through the application of an electric quadrupolar rf field at the frequency ν_{rf} the radial eigenmotions can be coupled. By applying $\nu_{rf} = \nu_c$ at a constant product of amplitude A_{rf} and excitation time T_{rf} of the rf, an initial magnetron motion can be fully converted into a reduced cyclotron motion and vice versa. According to $\nu_+ \gg \nu_-$, this results in a significant change in an ion's kinetic energy. In the time-of-flight resonance detection technique ions initially on magnetron motion trajectories are excited by such an rf field. Changes in the kinetic energy are observed by a reduction of the time of flight (TOF) to a microchannel plate (MCP) detector after the ions are ejected from the trap. For each ion bunch, a fixed ν_{rf} is applied. By scanning through ν_{rf} a resonance with a minimum in TOF at $\nu_{rf} = \nu_c$ is obtained (see Figure 5b). At TITAN, the initial magnetron motion is induced using a Lorentz-steerer [RIN07], which allows fast and precise ion preparation during the injection of the ion bunch into the trap.

For short lived isotopes the optimal excitation time T_{rf} for a given half-life $T_{1/2}$ is $T_{rf} \approx 2.9\cdot T_{1/2}$. A 100 Hz repetition cycle can hence deal with the half-life of 3.4(8) ms for ^{31}Ne and 6.1 ms +1.4-1.2 ms for ^{22}C. The feasibility of such a measurement cycle has been tested: a resonance of ^{12}C delivered from OLIS and measured at a repetition rate of 100 Hz is plotted in Figure 5b.

At TITAN it is possible to perform measurements even at very low yields. As soon as the respective nuclides are detectable at the yield station, we will be able to perform the measurements. We are aiming for a precision of $\delta m/m \approx 5\cdot 10^{-7}$. This allows the extraction of the (two) neutron separation energies well below 100 keV which is required to put the interpretation of the recent reaction measurements on ^{22}C and ^{31}Ne on solid ground. Systematic effects at TITAN have been studied in detail in [BRO09] and are expected to be well below the precision of the proposed measurements.

(c) **Experimental equipment**: Describe the purpose of all major equipment to be used.
Details of all equipment and services to be supplied by TRIUMF must be provided separately on the Technical Review Form available from the Science Division Office.

In addition to the TITAN facility, the ISAC yield station will be needed to determine the yields, isobaric contaminants and their suppression by the mass separator. A quadrupole ion guide under development at ISAC could be involved at the later stage of the proposed experiment to help reduce isobaric contamination.

(d) **Readiness**: Provide a schedule for assembly, construction and testing of equipment. Include equipment to be provided by TRIUMF.

The TITAN setup is operational and ready to perform the measurements outlined above. TITAN was proven to be in a position to handle short-lived isotopes at low rates.

(e) **Beam time required**: State in terms of number of 12-hour shifts. Show details of the beam time estimates, indicate whether prime-user or parasitic time is involved, and distinguish time required for test and adjustment of apparatus.

We thus request 3 shifts for each nuclide, ^{20,22}C and ^{31}Ne plus one shift for setup in each case, summing to 12 shifts in total. ^{30}Ne is already part of the approved TITAN proposal S1240. ^{31}Ne will require an UO-target or UC-target coupled to the FEBIAD source. ^{20,22}C beams can be produced from an oxide target. Tests of an oxide target are underway.
Since all of the requested nuclides require beam developments, we request stage 1 approval at this time.

(f) **Data analysis**: Give details and state what data processing facilities are to be provided by TRIUMF.

The data evaluation methods are well developed for the TITAN mass spectrometer system, and all the necessary software tools are available.

References:

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Publication List

Name: Stephan Ettenauer

Precision ground state mass of ^{12}Be and an isobaric multiplet mass equation (IMME) extrapolation for 2^+ and 0^{+2} states in the T=2, A=12 multiplet
S. Ettenauer, M. Brodeur, T. Brunner, A. T. Gallant, A. Lapierre, R. Ringle, M. R. Pearson, P. Delheij, J. Lassen, D. Lunney and J. Dilling
Phys. Rev. C 81, 024314 (2010)

In-Trap Decay Spectroscopy of Radioactive Nuclei at TITAN/TRIUMF for a Determination of 2νββ Matrix Elements
S. Ettenauer, T. Brunner, M. Brodeur, A. T. Gallant, A. Lapierre, R. Ringle, M. Good, C. Andreoiu, R Delheij, D. Frekers, R. Kriicken, and J. Dilling
AIP Conf. Proc. -- December 17, 2009 -- Volume 1182, pp. 100-103 10TH CONFERENCE ON THE INTERSECTIONS OF PARTICLE AND NUCLEAR PHYSICS

Gamma-Ray Spectroscopy at TRIUMF-ISAC: the New Frontier of Radioactive Ion Beam Research
G. C. Ball, C. Andreoiu, R. A. E. Austin, D. Bandyopadhyay, J. A. Becker, P. Bricault, N. Brown, S. Chan, R. Churchman, S. Colosimo, H. Coombes, D. Cross, G. Demand, T. E. Drake, M. Dombsky, **S. Ettenauer**, P. Finlay, D. Furse, A. Garnsworthy, P. E. Garrett, K. L. Green, G. F. Grinyer, B. Hyland, G. Hackman, R. Kanungo, W. D. Kulp, J. Lassen, K. G. Leach, J. R. Leslie, C. Mattoon, D. Melconian, A. C. Morton, C. J. Pearson, A. A. Phillips, E. Rand, F. Sarazin, C. E. Svensson, S. Sumithrarachchi, M. A. Schumaker, S. Triambak, J. C. Waddington, P. M. Walker, S. J. Williams, J. L. Wood, J. Wong, and E. F. Zganjarp
AIP Conf. Proc. -- March 31, 2009 -- Volume 1109, pp. 19-26 NUCLEAR PHYSICS AND APPLICATIONS: Proceedings of the First Ulaanbaatar Conference on Nuclear Physics and Applications; doi:10.1063/1.3122255

New mass measurement of ^{6}Li and ppb-level systematic studies of the Penning trap mass spectrometer TITAN
M. Brodeur, T. Brunner, C. Champagne, **S. Ettenauer**, M. Smith, A. Lapierre, R. Ringle, V. L. Ryjkov, G. Audi, P. Delheij, D. Lunney, and J. Dilling
Phys. Rev. C 80, 044318 (2009)

High-Precision Penning-Trap Mass Measurements of ^{9,10}Be and the One-Neutron Halo Nuclide ^{11}Be
R. Ringle, M. Brodeur, T. Brunner, **S. Ettenauer**, M. Smith, A. Lapierre, V.L. Ryjkov, P. Delheij, G.W.F. Drake, J. Lassen, D. Lunney, J. Dilling
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First Penning-trap mass measurement in the millisecond half-life range: the exotic halo nucleus ^{11}Li
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