TRIUMF - EEC SUBMISSION Draft Submission *Progress Report*		**Exp. No.** S1240 - *In Preparation* **Date Created:** 2009-06-04 08:19:31

Title of Experiment:

Precision mass cartography of the island of inversion

Name of group:

Spokesperson(s) for Group

D. Lunney, J. Dilling

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

D. Lunney	Universite de Paris Sud	Senior Research	%
J. Dilling	TRIUMF	Research Scientist	%
A. Lapierre	TRIUMF	Research Associate	%
C. Andreoiu	Simon Fraser University	Assistant Professor	%
F. Ames	TRIUMF	Research Scientist	%
G. Gwinner	University of Manitoba	Associate Professor	%
J. Lassen	TRIUMF	Research Scientist	%
M. Brodeur	University of British Columbia	Student (PhD)	%
M. Dombsky	TRIUMF	Senior Research	%
M.R. Pearson	TRIUMF	Research Scientist	%
P. Bricault	TRIUMF	Senior Research	%
P.P.J. Delheij	TRIUMF	Research Scientist	%

R. Ringle	NSCL	Research Scientist	%
S. Ettenauer	University of British Columbia	Student (PhD)	%
T. Brunner	T.U. Munich	Student (PhD)	%

New Beam Requests:

32 shifts with: TITAN

Beam Shifts Used:

Beam Shifts Remaining:

Basic Information:

Date Created: 2009-06-04 08:19:31

Date Experiment Ready: 0000-00-00

Summary:

We propose a detailed binding-energy survey of the famous “island of inversion.” This area is now a benchmark case for the disappearance of the normally- stabilizing effect of a closed shell on the binding energy. The newly-commissioned TITAN setup at TRIUMF-ISAC is the only Penning-trap capable of carrying out such a study, due to the very short half-lives. We request 32 shifts of beam time for mass measurements of neon, sodium, magnesium and aluminum nuclides around $N = 20$.

Plain Text Summary: The nuclear binding energy is determined by weighing exotic nuclides produced at ISAC in a Penning trap, thanks to the celebrated relation of mass and energy (E=mc2). The binding energy reflects the variations in nuclear structure along rows of neighboring isotopes. In one particular region, encircling neon, sodium and magnesium, an oddity of nuclear structure manifests itself, relegating a stabilizing magic neutron number (N=20) into something less so. This experiment will probe this curious effect with unprecedented precision in order to find suble effects that may be at the origin.

Primary Beam Line: isac2a

ISAC Facilities

ISAC Facility: TITAN

ISAC-I Facility:

ISAC-II Facility:

Secondary Beam

Isotope(s):

Energy:

Energy Units:

Energy spread - maximum :

Time spread - maximum :

Angular Divergence :

Spot Size:

Intensity Requested:

Minimum Intensity:

Maximum Intensity:

Charge Constraints:

Beam Purity:

Special Characteristics:

Experiment Support

Beam Diagnostics Required:

Signals for Beam Tuning:

DAQ Support
(Summary of Requirements):

TRIUMF Support (Resources Needed):

NSERC:

Other Funding:

Safety Issues:

Full suite of TITAN safety reports exists.

EEC Reader:

TRIUMF SUB-ATOMIC PHYSICS EEC NEW RESEARCH PROPOSAL

Detailed Statement of Proposed Research for Experiment # S1240

Title: Precision mass cartography of the island of inversion

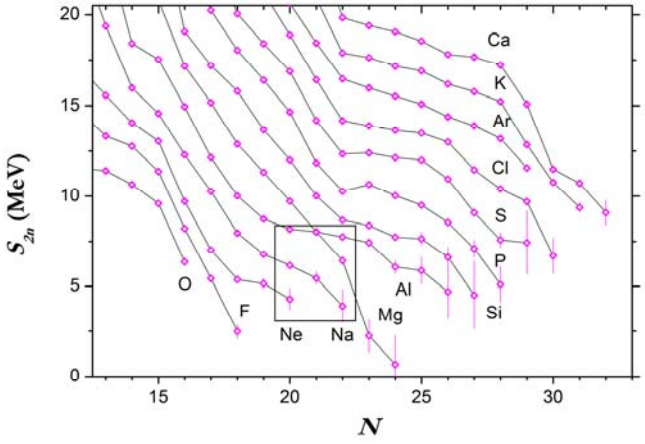
Spokespersons: D. Lunney and J. Dilling, for the TITAN collaboration

Abstract: We propose a detailed binding-energy survey of the famous "island of inversion." This area is now a benchmark for the disappearance of the normally-stabilizing effect of a closed shell on the binding energy. The newly-commissioned TITAN setup at TRIUMF-ISAC is the only Penning-trap capable of carrying out such a study, due to the short half-lives involved. We request 32 shifts of beam time for mass measurements of Ne, Na, Mg and Al nuclides around $N = 20$.

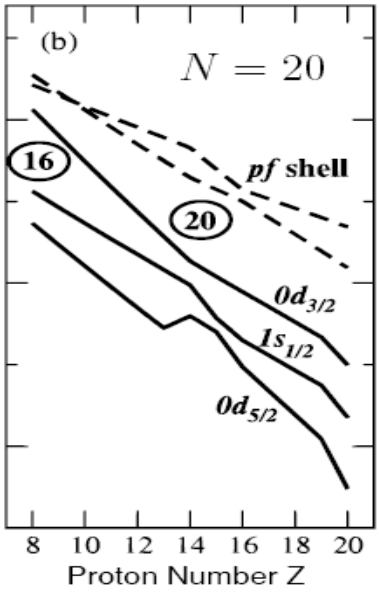
(a) **Scientific value of the experiment**: Describe the importance of the experiment and its relation to previous work and to theory. All competitive measurements at other laboratories should be mentioned. Include examples of the best available theoretical calculations with which the data will be compared.

The nuclear shell model, in which nucleons occupy orbitals akin to the atomic system, was derived from observations of particularly strong binding energies for filled shells and is a cornerstone of nuclear structure. Aptly enough, not only have these so-called "magic" numbers been found to exhibit disappearing acts far from the valley of stability, new magic numbers have also made apparitions. This isospin-dependent re-ordering of the nuclear quantum states now points us to the improvements needed for a better theory of the nuclear interaction. As such, magic-number migration is a major axis of research in nuclear structure. A recent review article [SorPor2008] summarizes the copious collection of experimental and theoretical work and attests to the continued importance of tracking the (dis)appearances of closed-shell effects for exotic nuclides.

The original case study for the disappearance of a magic number was that of $N = 20$ and the now-famous island of inversion, discovered from pioneering on-line mass spectrometry studies of sodium isotopes at CERN [Thib75]. Instead of the increased binding energy (BE) normally associated with a closed shell, the derived two-neutron separation energies $S_{2n} = BE(Z,N) - BE(Z,N-2)$ exhibited an anomaly, visible in the figure (right). A "normal" shell closure shows a kink at the magic number, as seen for Ca and K, whereas the Na and Mg isotopes show no such kink at $N = 20$.



Following the mass measurements, nuclear spectroscopy[1] revealed the extra binding to be due to deformation brought on by the inversion of so-called "intruding" *pf* orbitals that offered themselves for occupation. Shell model calculations using only the *sd* orbitals (following the "normal" quantum sequence) did not correctly account for the experimental results. This concept is illustrated (right) by a calculation taken from [Otsuka02] that shows how the "normal" orbital occupation for $N = 20$ isotones close to stability ($Z = 20$ and lower) has a large energy gap whereas for exotic nuclides ($Z = 12$ and below) the orbital spacing changes and the new magic number $N = 16$ emerges. These results were obtained by including a spin-isospin dependence in the nuclear interaction.



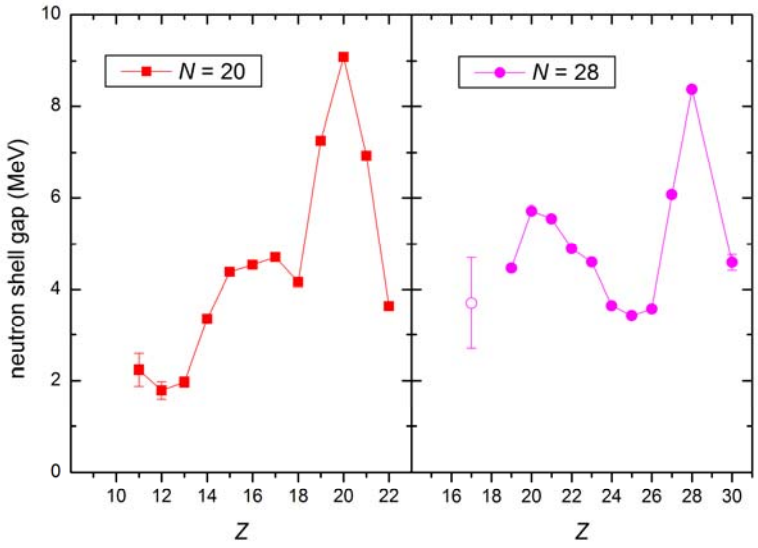
While mass measurements can very nicely illustrate eventual disappearances, they do not give sufficient information for their explanation since the mass is the net effect of all forces acting inside the nucleus. Therefore, the arsenal of post-accelerated radioactive beams has now been brought to bear on this problem. A recent example was published by Hurst *et al.* [Hurst09] where the process of Coulomb excitation was used to probe the single-particle properties of the ^{29}Na nucleus. While this nuclide is not considered as a *de facto* resident of the island of inversion, the results are interesting since they show strong mixing of the intruder orbitals. Thus, the understanding of the island itself, requires some snorkeling in its littoral shallows. This was the case for the southern coast of the island where the role of intruder states was further elaborated using Coulomb excitation studies of ^{26,28}Ne [Pri99].

Complementing reactions and spectroscopy studies is the low-energy technique of β-NMR coupled with laser spectroscopy, recently used at ISOLDE to decisively nail the spin of the ^{33}Mg ground state [Yord07]. The mass is also necessary for complementary laser spectroscopy experiments dedicated to the measurement of the mean-square charge radius. The charge radius is extracted from the measured isotope shift, the two components of which include a mass shift.

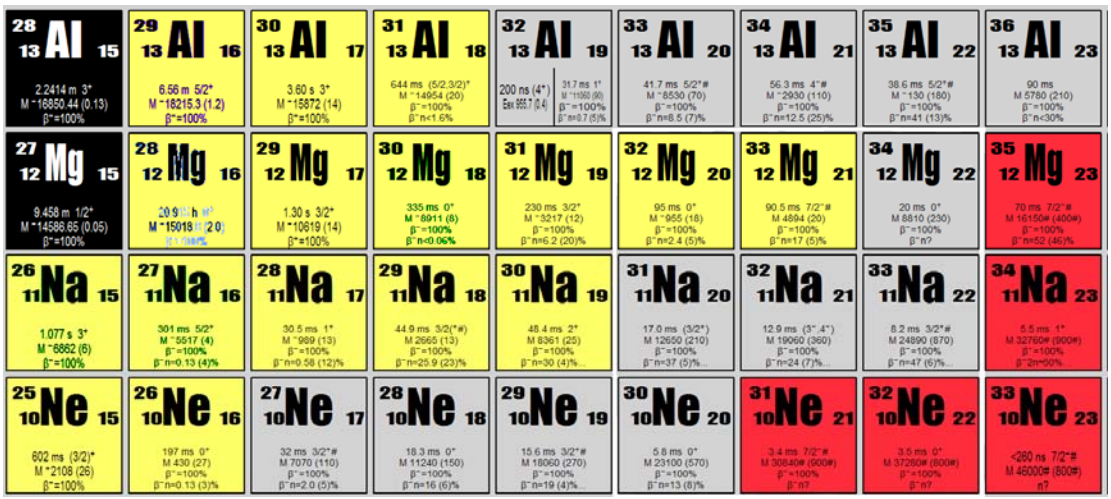
The reader is referred to a recent review article [SorPor08] for the whole picture.

[1] The same group, from Orsay, published nuclear spectroscopy results for ^{32}Mg [Detraz79] in which they reported a particularly low 2^+ level and interpreted it as the onset of deformation that overpowered the effect of the erstwhile closed shell. In subsequent work [Detraz83], they derived masses for $^{31\text{-}32}$Mg from the decay-energies, which also confirmed the $N = 20$ disappearance for $Z = 12$.

Returning to the S_{2n} plot, it is interesting to examine the case of N = 28 for more exotic nuclides. While the case of Ar is still not determined, Cl would appear to fall victim to the disappearance of the N = 28 shell. These masses were obtained from measurements made at GANIL using the SPEG energy-loss spectrometer [Sara00]. The relative strength of the difference in binding energy before and after a purported magic number can be quantified by a quantity defined as the shell gap $\Delta = S_{2n}(Z,N) - S_{2n}(Z,N+2)$.



In the figure (left) the shell gap is plotted versus Z for the cases of N = 20 and 28. The prominent features of this plot are the peaks for nuclides having $N = Z$. This shows the exceptional binding of such nuclides due to proton-neutron pairing (sometimes called the Wigner effect). Another peak can be seen for N = 28 and Z = 20 (the doubly-magic nuclide ^{48}Ca). The shell gap nicely illustrates the magic number disappearance for N = 20, being greatly diminished below Z = 15 (to the point of being "quenched" at Z = 13) from its nominal value of 4-5 MeV. The unfilled N = 28 shell-gap point for Z = 17 was obtained from recent mass measurements with SPEG using fragmentation [Jura07]. Such measurements so far from stability are indeed impressive, however the uncertainty associated with the results is unfortunately too large to report the disappearance of the N = 28 shell. In fact, the error bars of the N = 20 shell gap values for sodium and magnesium do not rule out the possibility of a reincarnation of this magic number! It may well be within the possibilities of nature for the doubly magic ^{26}O nuclide to exist. A recent reaction mass measurement was performed at MSU for ^{25}O that highlights the emergence of an N = 16 shell [Hoff08] and shows that important theoretical work remains to be done to explain the nuclear binding of this region. It is therefore of great interest to complement this work by a more refined mapping of the shell gap behavior to help further understand the delicate properties on which shell structure rests.



The light nuclides and island of inversion. The color code is for binding-energy uncertainty with shaded (gray) nuclides > 100 keV. In yellow are nuclides measured by MISTRAL [Lunn01a,Lunn01b,Lunn06]. Nuclides marked with # (red) are derived from extrapolation [Aud03]. The key nuclides for this proposal are: $^{28\text{-}30}$*Ne,* $^{31\text{-}33}$*Na,* ^{34}*Mg and* $^{32\text{-}35}$*Al.*

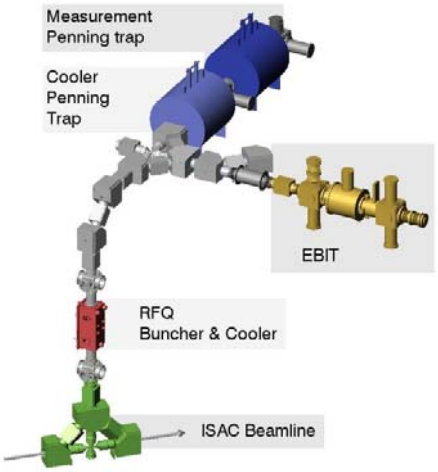
The case of the neon isotopes is particularly interesting. Reducing the rather large uncertainty (almost 0.9 MeV) on the mass of ^{33}Na and adding a shell-gap value for Ne would give information of unprecedented detail concerning the behavior of an "opened" nuclear shell.

Another important topographical anomaly is found for the aluminum isotopes crossing $N = 20$. There the S_{2n} values overlap which is something that happens nowhere on the nuclear chart. This situation is most probably due to a wrongly-determined mass value. This is frequently the case with masses derived from beta-decay spectra so a direct measurement of high precision is important here.

The instrument of choice for precision mass measurements is now the Penning trap. No less than six Penning-trap mass measurement programs now exist worldwide, thanks to the pioneering work of ISOLTRAP at CERN-ISOLDE. Despite the number of Penning-trap programs, only one is capable of measuring masses of nuclides with half-lives shorter than 50 ms: TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN).

(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.

These measurements would be performed with the TITAN setup (left), requiring only the RFQ buncher and the measurement Penning trap [Dil06]. Among the six Penning-trap mass-measurement facilities currently in operation, only TITAN has the capability to tackle the short-lived cases in this proposal. Different ionization schemes will maximize the yields of the different species: the FEBIAD source with cooled line for Ne; surface ionization for Na; laser ionization for Mg; surface or (preferably) laser ionization for Al.



To make a mass measurement, an ion is injected into the homogeneous field of the TITAN Measurement Penning Trap (MPET) where its cyclotron frequency $f_c = qB/2\pi m$ is probed and determined using a time-of-flight detection of the ejected ions. The cyclotron frequency is compared to that of a well-known reference mass (generally, a stable species of similar mass) to provide a measurement. TITAN was commissioned in August, 2007 at which point the masses of the short-lived radioactive nuclides ^{8}Li and ^{9}Li were measured. Since then, several high-quality measurements have been published: ^{8}He [Ryjkov08]; ^{11}Li [Smith08]; ^{11}Be [Ringle09]. From efficiencies derived from these measurements, yields of less than 100/s are sufficient to measure the nuclides in this proposal. Given the short half-lives, a relative mass uncertainty of better than 10^{-7} is possible in all cases, given statistics.

(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.

Aside from the TITAN setup itself, the only TRIUMF equipment necessary could be the yield station in order to map out the magnetic profile of some of the isobaric contamination in the case of the FEBIAD source. For example at $A = 28$, in addition to ^{28}Ne, there would be ^{14}N^{14}N and ^{12}C^{16}O but the large mass difference will enable separation using the mass separator with a resolving power of about 5000 (and less for the $A = 29$ and 30 cases).

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

The TITAN setup is currently in running mode. TITAN has already run using all three types of ion sources, measuring masses in the same region. **Since the proposed measurements can be made as of today, we request stage-two approval at this time.**

(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 request a total of 32 shifts with the breakdown shown below. Reference masses would be ^{22}Ne, ^{26}Mg, ^{27}Al and ^{36}Ar, depending on which ion source is used. The most exotic nuclides require the UO target however some of the nuclides could be reached using the Ta-foil target. The shifts would be divided over three or four runs as follows:

Ne run (FEBIAD source):

^{20}Ne pilot beam	**0.5**	**UO/Ta**
^{24}Ne beam	**0.5**	**UO/Ta**
^{25}Ne beam	**0.5**	**UO/Ta**
^{26}Ne beam	**0.5**	**UO/Ta**
^{27}Ne beam	**1.0**	**UO/Ta**
^{28}Ne beam	**1.0**	**UO/Ta**
^{29}Ne beam	**1.5**	**UO**
^{30}Ne beam	**2.5**	**UO**
Total	**8 shifts**	

Mg run (TRILIS source):

^{26}Mg pilot beam	**0.5**	**Ta**
^{31}Mg beam	**0.5**	**Ta**
^{32}Mg beam	**1.0**	**Ta**
^{33}Mg beam	**1.5**	**Ta**
^{34}Mg beam	**2.5**	**Ta**
Total	**6 shifts**	

Na run (surface source):

^{23}Na pilot beam	**0.5**	**UO/Ta**
^{26}Na beam	**0.5**	**UO/Ta**
^{28}Na beam	**0.5**	**UO/Ta**
^{29}Na beam	**1.0**	**UO/Ta**
^{30}Na beam	**1.0**	**UO/Ta**
^{31}Na beam	**1.5**	**UO/Ta**
^{32}Na beam	**2.5**	**UO**
^{33}Na beam	**2.5**	**UO**
Total	**10 shifts**	

Al run (TRILIS source):

^{20}Ne pilot beam	**0.5**	**UO/Ta**
^{24}Ne beam	**0.5**	**UO/Ta**
^{30}Al beam	**0.5**	**UO/Ta**
^{31}Al beam	**0.5**	**UO/Ta**
^{32}Al beam	**1.0**	**UO/Ta**
^{33}Al beam	**1.0**	**UO**
^{34}Al beam	**1.5**	**UO**
^{35}Al beam	**2.5**	**UO**
Total	**8 shifts**	

with reference scans performed every 3-4 hours for all runs

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

All the necessary software tools are now operational for analyzing TITAN data.

References

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