TRIUMF - EEC SUBMISSION EEC meeting: 201007S *Original Proposal*	**Exp. No.** S1290 - *Pending (Stage 1)* **Date Submitted:** 2010-06-27 05:00:21

Title of Experiment:

Investigating the apparent disappearance of the N = 28 shell closure

Name of group:

TITAN

Spokesperson(s) for Group

J. Dilling, M. Brodeur, D. Lunney

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

J. Dilling	TRIUMF	Research Scientist	40%
M. Brodeur	University of British Columbia	PDF	30%
D. Lunney	Universite de Paris Sud	Senior Research	20%
P.P.J. Delheij	TRIUMF	Research Scientist	50%
V. Simon	MPI-K Heidelberg	Student (Graduate)	50%
A. Gallant	University of British Columbia	Student (PhD)	30%
S. Ettenauer	University of British Columbia	Student (PhD)	30%
G. Gwinner	University of Manitoba	Associate Professor	20%
T. Brunner	T.U. Munich	Student (PhD)	20%
P. Bricault	TRIUMF	Senior Research	10%
M. Dombsky	TRIUMF	Senior Research	10%
R. Ringle	NSCL	Research Scientist	10%
A. Lapierre	TRIUMF	Research Associate	10%

Beam Shift Requests:

8 shifts on: TITAN

Basic Information:

Date submitted: 2010-06-27 05:00:21

Date experiment ready: 2010-07-30 12:00:00

Summary:

Shell closures explain the exceptional relative stability of certain nuclides. However, the so-called “magic” numbers have been shown to lose their supernatural powers in extreme situations of isospin imbalance. Na (Z = 11) and Mg (Z = 12) nuclides with N = 20 are the benchmark of such disappearance and now, the case of N = 28 has fallen under suspicion. We propose measuring the binding energy of exotic argon isotopes in order to determine whether the N = 28 shell closure erodes for these nuclides. The masses will be measured using the TITAN spectrometer at TRIUMF-ISAC. We request 8 shifts of beam time for mass measurements of $^{46\text{-}48}$Ar to unambiguously determine the N = 28 shell gap.

Plain Text Summary: Shell closures explain the exceptional relative stability of certain nuclides. However, the so-called “magic” numbers have been shown to lose their supernatural powers in extreme situations of isospin imbalance. Na (Z = 11) and Mg (Z = 12) nuclides with N = 20 are the benchmark of such disappearance and now, the case of N = 28 has fallen under suspicion. We propose measuring the binding energy of exotic argon isotopes in order to determine whether the N = 28 shell closure erodes for these nuclides. The masses will be measured using the TITAN spectrometer at TRIUMF-ISAC. We request 8 shifts of beam time for mass measurements of 46-48Ar to unambiguously determine the N = 28 shell gap.

Primary Beamline: isac2a

ISAC Facilities

ISAC Facility: TITAN

ISAC-I Facility:

ISAC-II Facility:

Secondary Beam

Isotope(s): 46Ar, 47Ar, 48Ar

Energy: 30

Energy Units:

Energy spread-maximum:

Time spread-maximum:

Angular Divergence:

Spot Size: 5

Intensity Requested: 1000

Minimum Intensity: 300

Maximum Intensity: 3000

Charge Constraints: none

Beam Purity:

Special Characteristics:

Experiment Support

Beam Diagnostics Required:

Signals for Beam Tuning:

DAQ Support:

TRIUMF Support:

NSERC:

NSERC:

Other Funding:

Muon Justification:

Safety Issues:

TRIUMF SUB-ATOMIC PHYSICS EEC NEW RESEARCH PROPOSAL

Detailed Statement of Proposed Research for Experiment # S1290

Title: Investigating the apparent disappearance of the $N = 28$ shell closure

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

Abstract: Shell closures explain the exceptional relative stability of certain nuclides. However, the so-called "magic" numbers have been shown to lose their supernatural powers in extreme situations of isospin imbalance. Na ($Z = 11$) and Mg ($Z = 12$) nuclides with $N = 20$ are the benchmark of such disappearance and now, the case of $N = 28$ has fallen under suspicion. We propose measuring the binding energy of exotic argon isotopes in order to determine whether the $N = 28$ shell closure erodes for these nuclides. The masses will be measured using the TITAN spectrometer at TRIUMF-ISAC. We request 8 shifts of beam time for mass measurements of $^{46\text{-}48}$Ar to unambiguously determine the $N = 28$ shell gap.

(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 cornerstone of nuclear structure shell model, in which nucleons occupy orbitals akin to the atomic system, was derived from observations of particularly strong binding energies for filled shells . 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 reordering of the nuclear quantum states unveils 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 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 $S_{2n} = BE(Z,N) - BE(Z,N2)$ exhibited an anomaly: while a "normal" shell closure shows a kink at the magic number $N = 20$, the Na and Mg isotopes show no such kink. Nuclear spectroscopy later revealed that the extra binding was 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 was illustrated by [Otsuka02] who showed how the "normal" orbital occupation for $N = 20$ isotones close to stability 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.

Naturally, attention was directed at the N = 28 shell closure to see if another occurrence of the shell erosion might be present. Mass measurements were performed at GANIL using the SPEG spectrometer combined with time-of-flight measurements, by Sarazin et al. [Sara00]. Those results were included in the 2003 atomic-mass evaluation [Aud03] and can be seen in Figure 1.

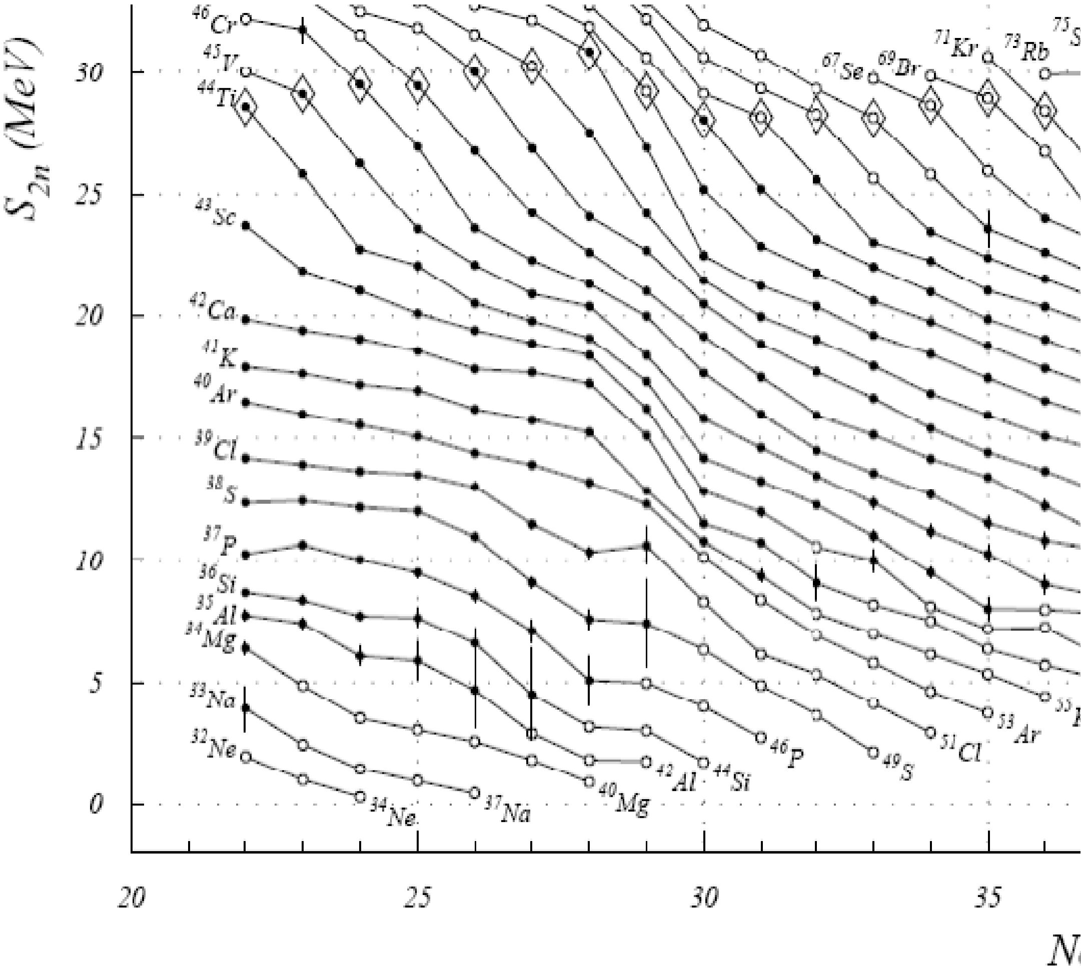


Figure 1: Two-neutron separation energies in the region of ^{48}Ar (from [Aud03]). The kink at N = 28 is clearly visible for Ti, Sc, Ca and K but is less pronounced for Ar. As the mass of ^{48}Ar is unknown, it is difficult to say with certainty that the shell closure is really quenched.

In particular, the mass for ^{39}Cl (at N = 29) showed a similar upward trend as in the $N = 20$ case for Na, however more recent measurements with the same instrument (by Jurado et al. 2007 [Jura07]) but with better calibration data, made this effect less impressive.

A (*d,p*) reaction experiment performed on ^{46}Ar ($N = 28$) by Gaudefroy et al. [Gaud06] likewise indicated failing shell strength. Moreover, from the reaction Q value, Gaudefroy et al. derived a new mass value for ^{47}Ar, which was 700 keV less bound. The disadvantage of such a reaction is that spectroscopic factors are also required in order to correctly interpret the data, which is also model dependent. The advantage of a mass measurement is that the data are model independent. However, the mass is the net effect of all interacting forces in the nucleus. As such, it is impossible to disentangle the one element of physics that may be affecting the shell strength.

A more direct study was performed [Gaud2009] by measuring the quadrupole moment of an intruder isomeric state in ^{46}Ar compared to ^{48}Ca. Here, more concrete evidence for the disappearance of the shell exists. It is quite important to be able to compare difference types of observables in order to extract a maximum of information concerning the interactions responsible to this magic-number-migration phenomenon.

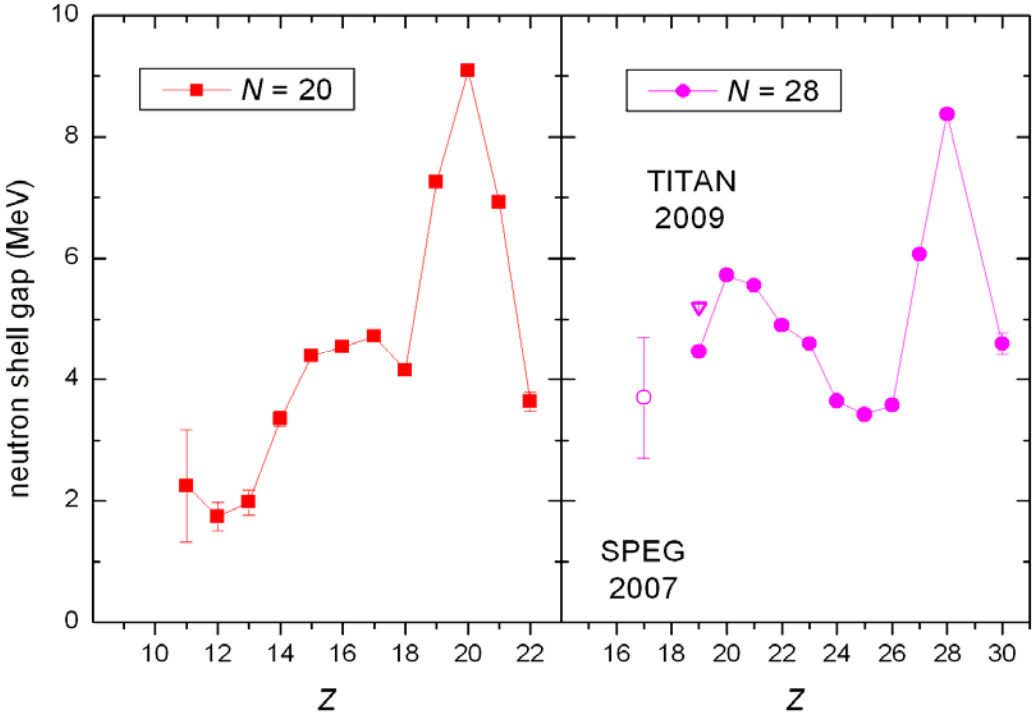
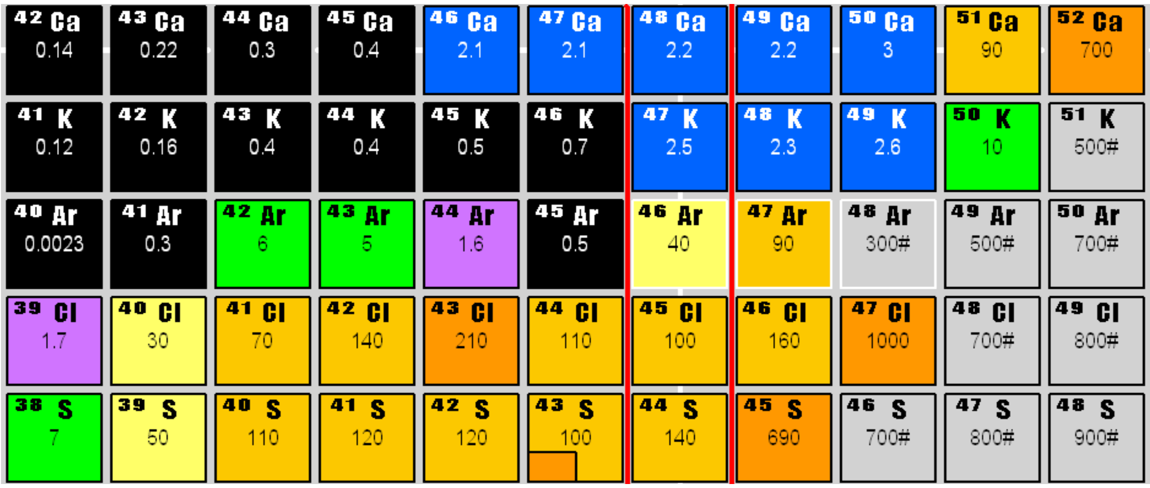


Figure 2: The N = 20 and N = 28 shell gaps as a function of proton number. (The dripline is approached from the left.)

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: $S_{2n}(Z,N) - S_{2n}(Z,N+2)$. In the figure (above) 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 the 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.

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). Indeed, TITAN has turned its focus to the case of the N = 28 shell gap. By measuring the masses of $^{46\text{-}50}$Kr, a new value for the K shell gap has been obtained [Lapierre10] and is shown in Fig. 3 (as an hollow triangle). The new value is more precise and differs with the previously accepted one by several standard deviations. The new TITAN result shows that the $N = 28$ shell gap is still in very good shape for $Z = 19$.

Here, we propose going farther from stability to see if $N = 28$ withstands a greater surplus of neutrons in the case of $Z = 18$ (Ar). A precise measurement for $Z = 18$, though less exotic, will give a tighter constraint than the large uncertainty for $Z = 17$. To obtain a new point for Fig. 2, mass measurements of ^{46,48}Ar are required. We also propose a direct mass measurement of ^{47}Ar to confirm the deviating value of Gaudefroy et al., obtained from a (d,p) reaction.

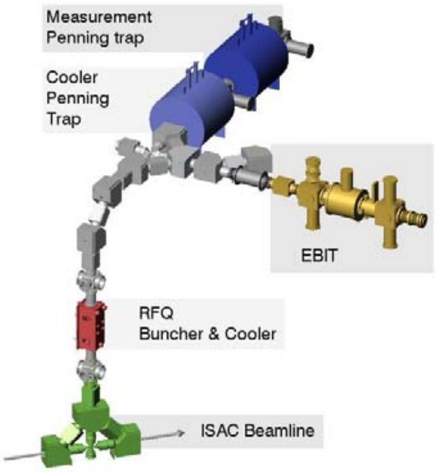


42 Ca 0.14	43 Ca 0.22	44 Ca 0.3	45 Ca 0.4	46 Ca 2.1	47 Ca 2.1	48 Ca 2.2	49 Ca 2.2	50 Ca 3	51 Ca 90	52 Ca 700
41 K 0.12	42 K 0.16	43 K 0.4	44 K 0.4	45 K 0.5	46 K 0.7	47 K 2.5	48 K 2.3	49 K 2.6	50 K 10	51 K 500#
40 Ar 0.0023	41 Ar 0.3	42 Ar 6	43 Ar 5	44 Ar 1.6	45 Ar 0.5	46 Ar 40	47 Ar 90	48 Ar 300#	49 Ar 500#	50 Ar 700#
39 Cl 1.7	40 Cl 30	41 Cl 70	42 Cl 140	43 Cl 210	44 Cl 110	45 Cl 100	46 Cl 160	47 Cl 1000	48 Cl 700#	49 Cl 800#
38 S 7	39 S 50	40 S 110	41 S 120	42 S 120	43 S 100	44 S 140	45 S 690	46 S 700#	47 S 800#	48 S 900#

The nuclides around the $N = 28$ shell closure (vertical solid lines). The numbers indicate the binding energy uncertainties (in keV). Nuclides marked with # are extrapolated [Aud03]. The nuclides for this proposal are: $^{46\text{-}48}$Ar. The masses of $^{44\text{-}45}$Ar were measured by ISOLTRAP [Bla03]. In 2009, TITAN measured the masses of $^{47\text{-}50}$K.

(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, TITAN has the capability to tackle the shortest-lived cases. Although the nuclides of this proposal have longer half-lives, TITAN has proved also to be a very efficient instrument, allowing measurements of very weakly produced species. We request the FEBIAD source with cooled line for Ar.



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 [Kon95]. 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]. A relative mass uncertainty of better than 10^{-7} is possible, given statistics. In a recent study of ^{6}Li, TITAN demonstrated a thorough systematic error exploration [Bro10].

(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 produced by the FEBIAD source.

(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 the FEBIAD ion source, measuring neutron-rich helium masses. **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 8 shifts using the UC target. After a shift of setting up and reference/cross-check measurements, the case of ^{46}Ar would require 1 shift, ^{47}Ar 2 shifts, and ^{48}Ar 4 shifts. Reference masses could be ^{40}Ar, ^{41}K, ^{44}Ca, or even ^{48}Ti from OLIS.

(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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