EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Spins, Moments and Charge Radii Beyond ^{48}Ca

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Abstract

Laser spectroscopy of $^{49\text{-}54}$Ca is proposed as a continuation of the experimental theme initiated with IS484 *"Ground-state properties of K-isotopes from laser and β-NMR spectroscopy"* and expanded in I117 *"Moments, Spins and Charge Radii Beyond ^{48}Ca."* It is anticipated that the charge radii of these isotopes can show strong evidence for the existence of a sub-shell closure at N=32 and could provide a first tentative investigation into the existence of a shell effect at N=34. Furthermore the proposed experiments will simultaneously provide model independent measurements of the spins, magnetic moments and quadrupole moments of ^{51,53}Ca permitting existing and future excitation spectra to be pinned to firm unambiguous ground states.

Requested shifts: [36] shifts, (split into [2] runs of 18 shifts in 2012 and 2014)

Physics Case

The evolution of shell structure beyond *N*=28 is currently a topic of substantial experimental interest [1] and theoretical controversy [2]. Whilst β-decay spectroscopy, deep inelastic scattering and Coulomb-excitation experiments have all provided evidence for a sub-shell closure at *N*=32, no direct experimental evidence exists for such a closure at *N*=34. Indirect experimental evidence has recently been reported by Maierbeck *et al*. [3] who measured the ^{55}Ti ground state spin. This spin has been reproduced by shell model calculations which predict an *N*=34 shell gap but not by those indicating no such closure. Furthermore, since the first predictions of this closure by Beiner *et al.* more than 30 years ago [4], theoretical opinion has been strongly divided over its existence. As demonstrated in figure 1 [5] the 2^+ excitation energies of the Ca isotopes show a substantial rise at *N*=32 although the absence of data for *N*=34 limits the possibilities for a full and unambiguous understanding based on this fact alone.

High resolution laser spectroscopy is unique in its ability to provide critical, model independent information on both collective and single particle aspects of the structure of radioactive nuclei. The spin, magnetic-dipole and electrostatic-quadrupole moments may all be obtained, along with changes in the mean square charge radius $\delta\langle r^2\rangle$. In figure 2 the RMS charge radii of isotopes in the vicinity of the *N*=28 are shown [6,7]. The well known sensitivity of charge radii to shell closures can be seen by the systematic change of slope around *N*=28. In the proposed work we aim to use this sensitivity to examine the strength and extent of the *N*=32 sub-shell closure. The absence of charge radii data extending across *N*=28 is very apparent here. The preliminary results from our ongoing IS484 experiment on K isotopes are included, which for the first time have extended out from *N*=28 to *N*=32. Although the limited statistics on ^{51}K preclude a definitive answer, a comparison between this and the isotopic chain of Fe would suggest that at least normal odd-even staggering is overcome.

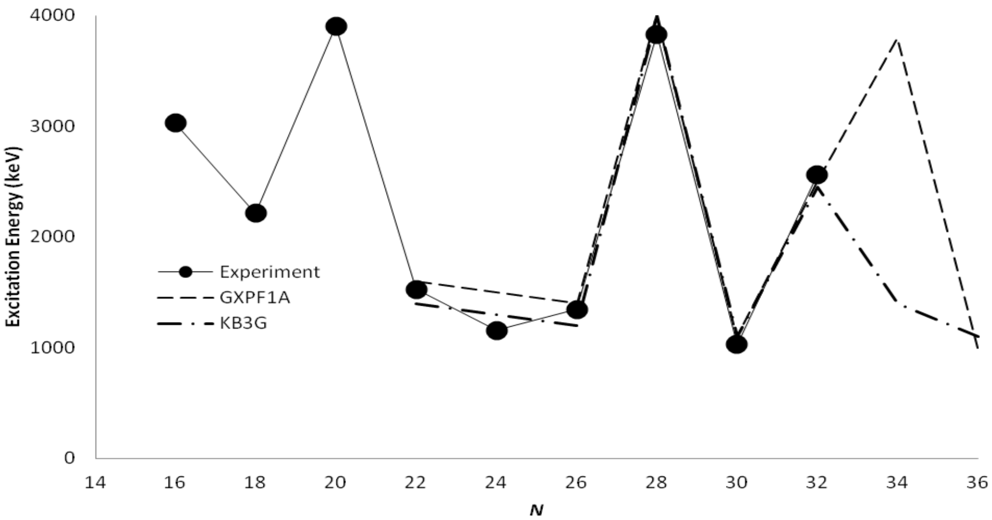

Figure 1: 2^+ excitation energies of Calcium isotopes compared with 2 theoretical predictions generated with the shell model interactions GXPF1A and KB3G [5].

As can be seen in the region between *N*=20 and *N*=28, the isotopic chain of Ca demonstrates a substantially larger odd-even staggering effect than that seen in K. This can be understood in terms on the blocking effect of the single unpaired proton. In the event that these characteristics are extended beyond the *N*=28 shell closure, the sensitivity to a shell effect at *N*=32 would be

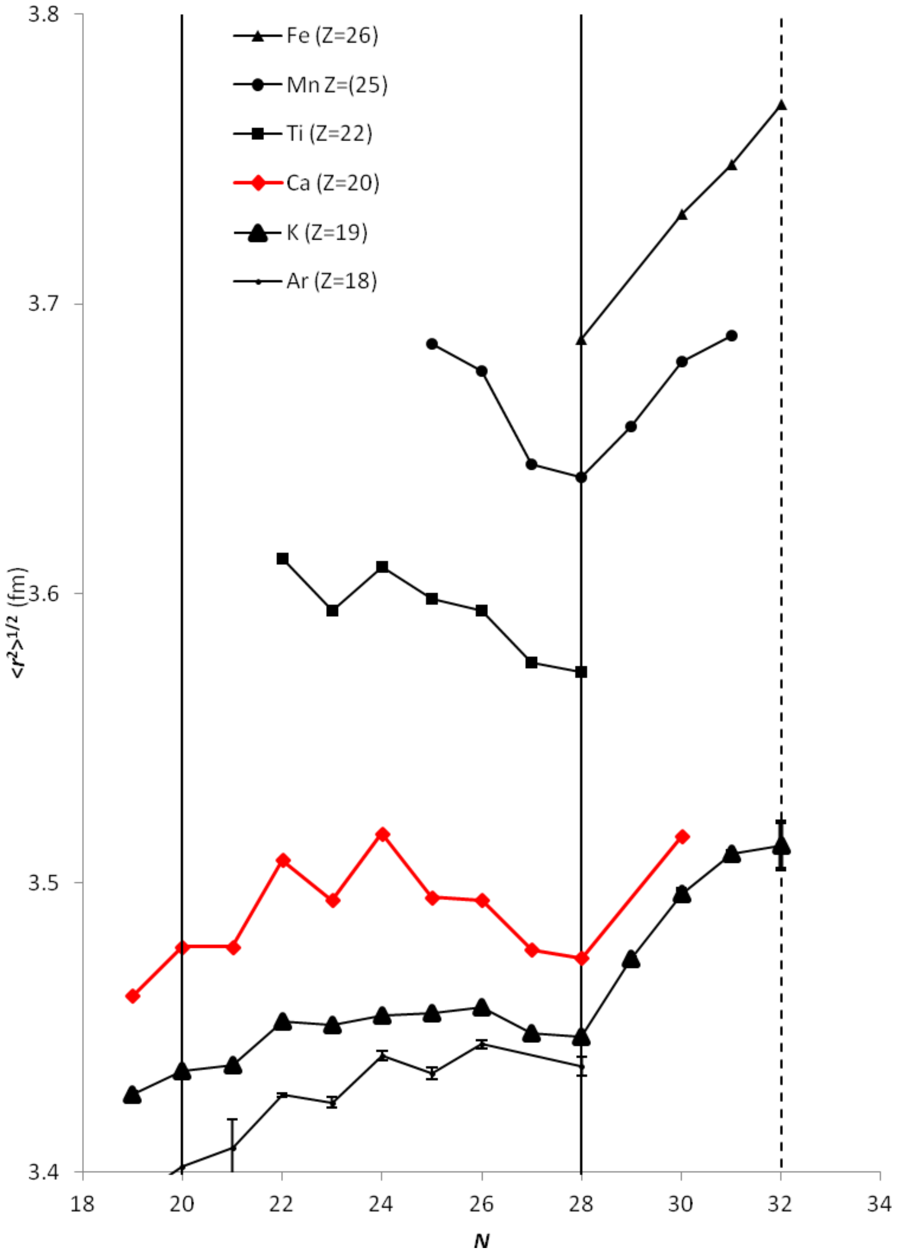

Figure 2: RMS Charge Radii around *N*=28 including *preliminary*, incomplete and unpublished values for neutron rich K. [6,7]

substantially enhanced in Ca due to the reduced rigidity of the proton distribution. In combination with both the full K measurements and the laser spectroscopy of Mn presented under IS508, the regional variation of the influence of *N*=32 can be explored.

With measurements beyond ^{52}Ca one can start to explore the influence of the *N*=34 sub-shell closure. As was noted by Gade and Glasmacher [1], ^{54}Ca is “the key nucleus for a search for the new magic number *N*=34.” From reference 5 it is found that whilst the shell model interaction GXPF1A predicts an increase in the $\nu f_{5/2}$- $\nu p_{1/2}$ gap with neutron number up to *N*=34 in Ca, the interaction KB3G demonstrates no such effect. Both interactions differ little in predicted 2^+ energies for Cr and Ti and agreement with measurement is good. From this it becomes apparent that discerning between these two interactions hinges on the observation of a strong shell effect in ^{54}Ca.

In a parallel submission to this committee “Seeking the Purported Magic Number N=32 with High-Precision Mass Spectrometry” ISOLTRAP will approach this problem from the complementary perspective of masses. These measurements will not only address the underlying physics case but will be beneficial in reducing the uncertainty associated with extracting $\delta<r^2>$ from the observed isotope shifts.

In addition to providing a sharp test of the proton-neutron component of effective shell model interactions all isotopes proposed here are accessible with *ab-initio* coupled-cluster calculations [8]. Given the small range of isotopes which may be calculated with such methods, charge radii, magnetic dipole moments and quadrupole moments will constitute a significant test of this approach. The high quality and abundance of the data already available for $\delta<r^2>$ in the region between ^{40}Ca and ^{48}Ca has already resulted in this isotopic chain becoming arguably the most theoretically studied in terms of $\delta<r^2>$ [9 to 13]. The extent and detail of these theoretical investigations can only heighten our ability to draw significant conclusions from the measurements proposed here.

Experimental Techniques

Optical Detection

At present no information is available for Ca yields at the PSB on the ISOLDE database. In a private communication from T. Stora, the production of ^{52}Ca from a UCx target with a surface ion source has been measured and is found to be 1000 ions/μC.

Considering the tabulated yields for SC-ISOLDE and scaling to account for the ^{52}Ca yield measurement, the neutron rich isotopes $^{49-52}$Ca are immediately accessible with bunched beam fluorescence spectroscopy [14]. For the primary stage of this investigation it is proposed to use the optical detection station developed in conjunction with the K experiments. With this system one can conservatively estimate an optical detection efficiency in the region of 1 photon in 4000 ions for the 393.4 nm 4s $^2S_{1/2}$ to 4p $^2P_{3/2}$ ionic transition. With this transition optimal access to the magnetic moment, quadrupole moment, $\delta<r^2>$ and spin will be obtained. Using background assumptions based on recent Ga [15] and Cd [16] experiments and similar ISCOOL ion bunch lengths, a ^{52}Ca spectrum of the quality shown in figure 3 should be achievable within 4 shifts. This time includes 40 minutes per 2 hour period for the measurement of a stable reference isotope. Given the need to reduce systematic effects associated with this relatively long scanning time, it would be desirable to record 3 such spectra within the running period. With the extrapolated yields ^{51}Ca should be achievable within 5 shifts and ^{49}Ca in less than 1 shift. As the total acceleration of the ion beam is of critical

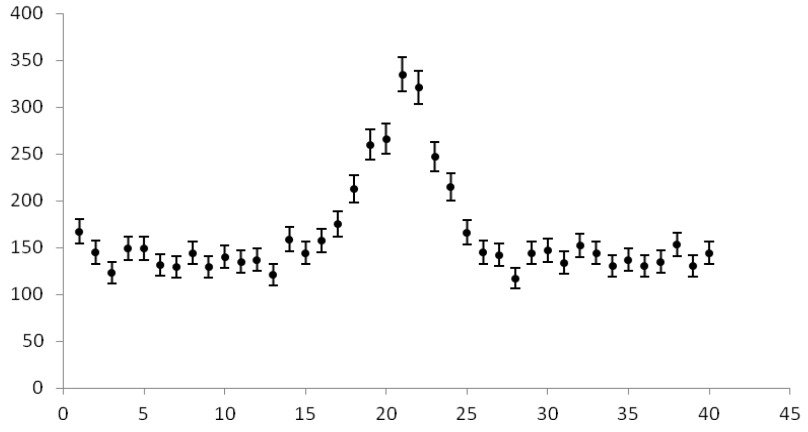

Figure 3: Simulated ^{52}Ca spectrum with 1000 ions/μC

importance for isotope shift measurements an additional 3 shifts of stable beam should also be added directly before the run. This time is necessary for both the optimization of detection efficiency and the re-measurement of the isotope shift between ^{40}Ca and ^{48}Ca in order to provide the best possible voltage calibration of ISCOOL.

In a second private communication with V. Fedosseev he noted that we may obtain a further order of magnitude increase in ionisation efficiency if we were to use a new efficient laser scheme instead of surface ionization. Whilst we have not accounted for this untested potential gain in calculating the time required, in the event that the yield is an order of magnitude higher we would use the remaining time to attempt a measurement of ^{53}Ca.

In total, a run with bunched beam optical detection would require 18 shifts + 3 offline shifts directly prior to the run for calibration and optimisation with stable isotopes.

Radioactive detection of optically pumped ions after state selective charge exchange (ROC)

To go beyond ^{52}Ca will most likely require a non-optical detection technique. For these cases it is proposed to implement and enhance the ROC technique [17,18] pioneered at SC-ISOLDE. In this approach an extended optical pumping region is used in which the Ca ions may undergo multiple laser induced excitations and decays. Using the scheme demonstrated in figure 4 the ions may be transferred into the $^2D_{3/2}$ state after multiple excitations only when the laser frequency is such that it corresponds to the Doppler shifted transition frequency of the 4s $^2S_{1/2}$ to 4p $^2P_{1/2}$ transition. Subsequently, the ions are decelerated to 5kV and passed into a charge exchange cell.

At this energy the $^2D_{3/2}$ neutralisation cross-section is a factor of 3 larger than the $^2S_{1/2}$ [19] and thus the amount of neutralisation will depend on the excitation of the pumping transition. After the charge exchange cell the ions are deflected away and the beam can be implanted into a tape station. By detecting the subsequent β decays one has a highly efficient, low background method of observing hyperfine structure and isotope shifts. Whilst this technique could offer ultimately the best sensitivity for Ca isotopes, the development time required is not negligible. For this reason we propose that initial measurements are conducted with optical detection and subsequently the CERN shutdown period is used for development and testing of this setup. Prior to this development we would estimate an additional 18 shifts for the measurement of ^{53,54}Ca.

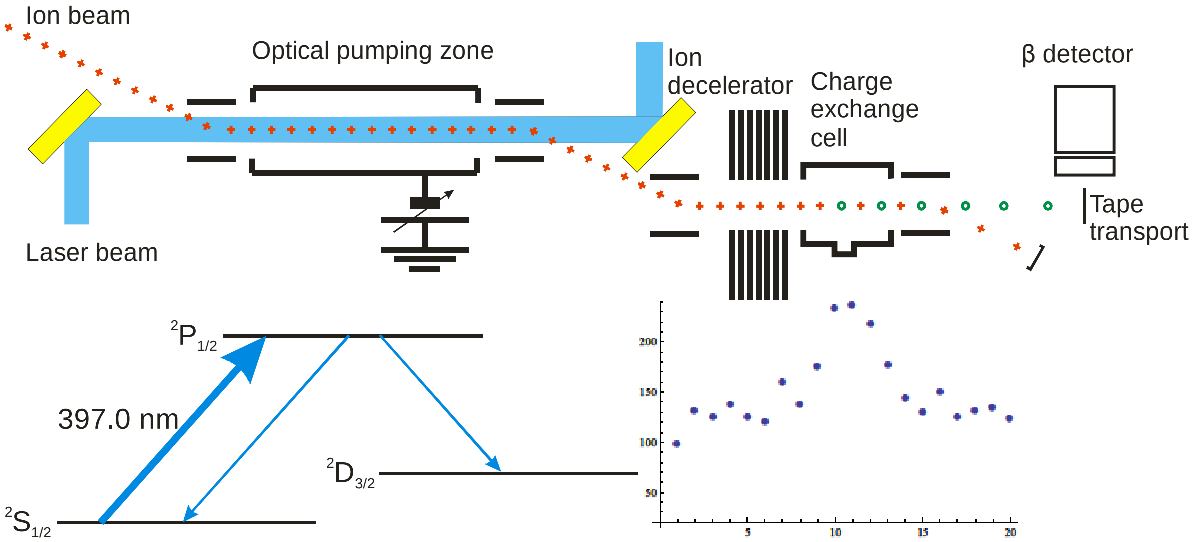

Figure 4: ROC setup, optical scheme and predicted results for 1 ^{54}Ca ion/s with 5 shifts.

Summary of requested shifts:

For the first optically detected experiment we request-

^{49}Ca	***1 Shift***	UCx (with option of RILIS)
^{51}Ca	***5 Shifts***	UCx (with option of RILIS)
^{52}Ca	***12 Shifts***	UCx (with option of RILIS)

+ <u>3 off-line shifts</u> directly before the online run.

We also request a subsequent run after the shutdown with a total of ***<u>18 shifts</u>*** for the measurement of ^{53}Ca and ^{54}Ca.

References:

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises:

Part of the Choose an item.	**Availability**	**Design and manufacturing**
COLLAPS	☒ Existing	☒ To be used without any modification
	COLLAPS	
[Part 1 of experiment/ equipment] ***Bunched beam optical detection***	☒ Existing	☒ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[Part 2 experiment/ equipment] ***Radioactive detection after state selective charge exchange***	☒ Existing	☐ To be used without any modification ☒ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[insert lines if needed]		

HAZARDS GENERATED BY THE EXPERIMENT

(if using fixed installation) Hazards named in the document relevant for the fixed [COLLAPS, CRIS, ISOLTRAP, MINIBALL + only CD, MINIBALL + T-REX, NICOLE, SSP-GLM chamber, SSP-GHM chamber, or WITCH] installation.

For bunched beam optical detection see the COLLAPS safety file.

The developments for radioactive detection after state selective charge exchange will take place during the CERN shutdown and a preliminary identification of hazards is given below:

Additional hazards:

Hazards	*[Part 1 of the experiment/equipment]* ***See COLLAPS FILE***	***ROC***	*[Part 3 of the experiment/equipment]*
Thermodynamic and fluidic			
Pressure	[pressure][Bar], [volume][l]		
Vacuum		10^-7mbar	
Temperature	[temperature] [K]	CEC ~200°C in centre of cell located in vacuum and thermally isolated from outside.	
Heat transfer		Hot oil pump to cool ends of	

		Charge exchange cell ~100^{o}C	
Thermal properties of materials			
Cryogenic fluid	[fluid], [pressure][Bar], [volume][l]		
Electrical and electromagnetic			
Electricity	[voltage] [V], [current][A]	High voltage platform required to decelerate the ion beam to 5kV (Minimum 25kV)	
Static electricity			
Magnetic field	[magnetic field] [T]		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material	[material]	2 Tape Stations in which ion beam and atom beam are implanted	
Beam particle type (e, p, ions, etc)		Ca 1+ ions and atoms	
Beam intensity		10^5/s to 0.1/s	
Beam energy		>30keV and<60keV	
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☐		
• Open source	☐		
• Sealed source	☐ [ISO standard]		
• Isotope			
• Activity			
Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			
Non-ionizing radiation			
Laser		Same as COLLAPS	
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chemical agent], [quantity]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chemical agent], [quantity]		
Corrosive	[chemical agent], [quantity]		
Irritant	[chemical agent], [quantity]		
Flammable	[chemical agent], [quantity]		
Oxidizing	[chemical agent], [quantity]		
Explosiveness	[chemical agent], [quantity]		
Asphyxiant	[chemical agent], [quantity]		
Dangerous for the environment	[chemical agent], [quantity]		
Mechanical			
Physical impact or mechanical energy (moving	[location]		

parts)			
Mechanical properties (Sharp, rough, slippery)	[location]		
Vibration	[location]		
Vehicles and Means of Transport	[location]		
Noise			
Frequency	[frequency],[Hz]		
Intensity			
Physical			
Confined spaces	[location]		
High workplaces	[location]		
Access to high workplaces	[location]		
Obstructions in passageways	[location]		
Manual handling	[location]		
Poor ergonomics	[location]		

0.1 Hazard identification

Part 1 –As normal

Part 2 - Full risk assessment to be undertaken upon completion of the design of the modified ROC setup.

The major additional risk associated with high voltage will be mitigated with the addition of a fully interlocked Faraday cage around the high voltage part of the ROC setup.

3.2 Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): *(make a rough estimate of the total power consumption of the additional equipment used in the experiment)*

-Similar to as collaps