EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

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Single-particle structure study in neutron-rich Ca through ^{50}Ca(d,p)

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Abstract: We propose to measure the ^{50}Ca(d,p)^{51}Ca transfer reaction using the ISOLDE Solenoidal Spectrometer. This reaction will be carried out in inverse kinematics and allows to populate states in ^{51}Ca with a single-neutron character. This empirical information will help to evaluate the predicted new neutron magic numbers in calcium (N=32 & N=34) [1, 2] by evaluating the energy gaps between the $\nu 2p_{3/2}$, $\nu 2p_{1/2}$ and $\nu 1f_{5/2}$ orbitals. The proposed experiment can test the previously assigned configurations and spins of the states populated in a β-decay experiment [3] and a deep inelastic transfer reaction experiment [4].

Requested shifts: 15 shifts
Installation: HIE ISOLDE 2nd beamline (ISS)

1 Physics Case

Having protons only in the $\pi 1d_{3/2}$ orbital and not in the $\pi 1f_{7/2}$ orbital, the calcium isotopes are important for the study of the evolution of the neutron orbitals. It was theoretically predicted that the empty $\pi 1f_{7/2}$ orbital and its absent tensor force influence on the neutron $\nu 2p_{3/2}$, $\nu 2p_{1/2}$ and $\nu 1f_{5/2}$ orbitals gives rise to new neutron magic numbers 32 and 34. In contrast, the fully filled $\pi 1f_{7/2}$ orbital in Ni isotopes will substantially affect the position of those neutron orbitals, reducing their energy and placing the $\nu 1f_{5/2}$ orbital between $\nu 2p_{3/2}$ and $\nu 2p_{1/2}$ [5].

Various studies have pointed towards the existence of these two additional magic neutron numbers on the neutron-rich side, namely N=32,34 (corresponding to ^{52,54}Ca) [6, 7, 8]. Investigations have been performed to determine (among others) the masses [9], first 2^+ and 3^- energies [2] and charge radii of these nuclei [10]. The resulting observables give conflicting results about the magic character of these nuclei. For example the mass and 2^+ energy of ^{52}Ca point towards magicity, but its charge radius is much larger than expected for a doubly magic nucleus. However, by performing one-neutron knockout on ^{52}Ca, Enciu et al. [11] obtained a large root-mean-square radius of the $\nu 2p_{3/2}$ orbital which can serve as an explanation for the charge radius increase that is compatible with the magicity of ^{52}Ca. To clarify the shell migrations and appearance of the magic numbers, studies into the surrounding nuclei are needed.

The involved shell model orbitals are the $\nu 2p_{3/2}$, $\nu 2p_{1/2}$ and $\nu 1f_{5/2}$, situated directly above the N=28 shell gap. In the stable isotope ^{62}Ni (Z=28,N=34), the $\nu 1f_{5/2}$ orbital lies in between the $\nu 2p_{3/2}$ and the $\nu 2p_{1/2}$ orbitals, leaving no large gaps in between. However when going to lower Z isotopes, the $\nu 1f_{5/2}$ orbital migrates upwards due to the reduction of the tensor force, which is proportional to the occupation of the $\pi 1f_{7/2}$ orbital. In Ca the $\nu 1f_{5/2}$ appears above the $\nu 2p_{1/2}$ orbital, forming two new energy gaps at neutron numbers N = 32 and 34 [12]. This evolution is schematically shown in figure 1.

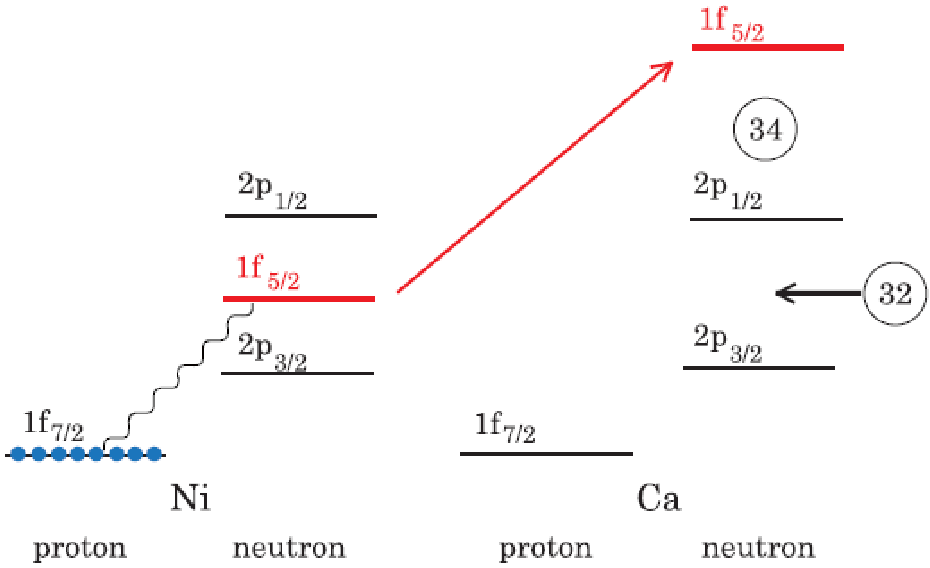

Figure 1: Shell evolution between Ni and Ca. Figure taken from [12]. The wavy line indicates the attractive force between the $\pi 1f_{7/2}$ and $\nu 1f_{5/2}$ orbitals, which is reduced when protons are removed from the $\pi 1f_{7/2}$.

As the ground state of ^{50}Ca contains two neutrons in the $\nu 2p_{3/2}$, the transferred neutron can enter in any of the three orbitals described above. This leads to the possibilities shown in figure 2.

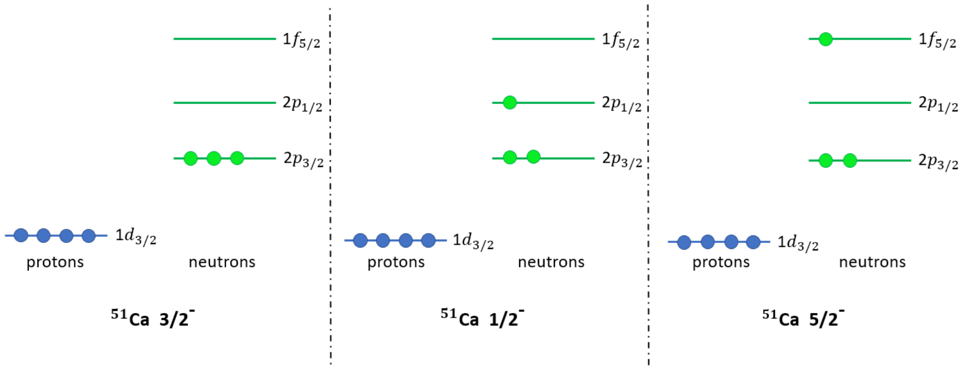

Figure 2: Assuming a pure configuration in ^{50}Ca, with two neutrons in the $\nu 2p_{3/2}$, the transferred neutron can end up in each of the three depicted shells, leading to different spin states.

The available data on ^{51}Ca only contains a firm spin assignment for the $3/2^-$ ground state [13], with other states either having a tentative spin assigned [14], or none at all. Therefore the other two displayed states are still open to investigation. Single-neutron transfer reactions on the stable ^{48}Ca have been performed in the past [15, 16] as well as one-neutron knockout on ^{48,50,52}Ca [11, 17] . Theoretical calculations performed Otsuka et al. [5] predict little change in the $\nu 1f_{5/2}$ effective single particle energy going from ^{48}Ca to ^{54}Ca. The evolution between ^{49}Ca and ^{51}Ca can be evaluated in the proposed experiment.

The N=34 gap can be evaluated by measuring the relative position of the $\nu 2p_{1/2}$ and $\nu 1f_{5/2}$ orbitals. In the deep inelastic transfer experiment [4], two states with a tentative spin assignment $5/2^-$ were observed at 2.4 MeV and 3.5 MeV in ^{51}Ca. The 2.4 MeV ($5/2^-$) state has no equivalent in ^{49}Ca, where two $5/2^-$ states appear at 3.6 and 4.0 MeV. Both of these states in ^{49}Ca were populated via (d,p) reactions in direct kinematics using a stable calcium target [15, 16]. The 2.4 MeV state in ^{51}Ca was interpreted as a ^{48}Ca core plus two neutrons in the $\nu 2p_{3/2}$ coupling to a 2^+ configuration with the last neutron in the $\nu 2p_{1/2}$ orbital [4, 14]. The proposed (d,p) reaction can be used to check this and other proposed configurations. In addition the obtained angular distributions can help to verify the assigned spins.

2 Experimental Setup

The ISS is well-suited for (d,p) reaction studies, where the low energy protons are going backwards in the laboratory frame. These protons are detected with the hexagonal silicon array. In addition, the recoils can be detected and identified using the Bragg chamber mounted at the end of the ISS setup. The elastically scattered deuterons are focused in the forward lab angles and can be detected by a luminosity detector to monitor the incoming beam rates.

The requested energy of the ^{50}Ca beam is 7 MeV/u. This energy strikes a balance between the reaction cross-section (lower energy provides better Q-value matching) and the detection efficiency of protons for excited states. This beam energy allows us to observe protons for excitation energies up to 4 MeV in ^{51}Ca. Based on the yield of 2.50e5 particles/μC (listed in the ISOLDE yield database) and an estimated transmission efficiency of 5% (at a charge state of 17+, maximal energy 9.4MeV/u, private communication with A.Rodriguez), the total yield will be approximately 1.25e4 particles/μC at the setup. However, higher yields for neutron-rich calcium isotopes were measured by ISOLTRAP [18] , with a yield of approximately 8.00e5 particles/μC for ^{50}Ca, which corresponds to 4.00e4 particles/μC at ISS considering 5% transmission efficiency from ISOLTRAP to ISS. The estimates described below are made using the yield from the ISOLDE database.

The nuclear reactions will take place inside the ISS magnet operating at a field strength of 2 T. The beam of ^{50}Ca will be focused at a CD_2 target with thickness of ∼200 µg/cm^2. The low energy protons will be detected by placing the silicon array upstream (backward lab angles). The expected angular distributions were obtained using the FRESCO code [19] and are shown in figure 3. The calculations include five energy states with a spin assignment [20] (assuming that they correspond to a pure single neutron added to ^{50}Ca

Table 1: Expected counts and total integrated cross sections

State	Total 4π Integrated Cross Section [mb]	Expected Number of Reactions over 4π	Expected Proton Counts in Array
$2p_{3/2}$ GS	56.49	3436	1617
$2p_{1/2}$ 1.7MeV	29.13	1772	876
$1f_{5/2}$ 2.4MeV	24.73	1504	673
$2p_{3/2}$ 2.9MeV	62.06	3775	1761
$1f_{5/2}$ 3.5MeV	32.36	1968	841

configuration). The optical model parameters used are taken from Daehnick [21] for the deuterons and Koning-Delaroche [22] for the protons.

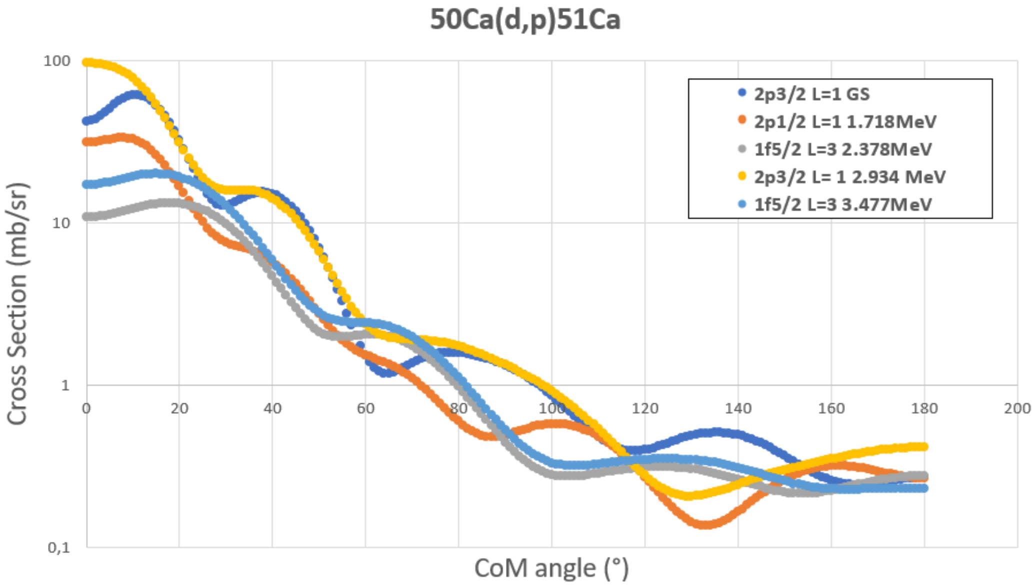

Figure 3: Calculated cross section for five states with spin-parity assignments. All spectroscopic factors are taken equal to one.

The total integrated cross-section and the expected counts for a 200 μg/cm^2 target after 15 shifts at an average proton current of 1.5 μA can be found in table 1.

2.1 ISS silicon array

The ISS silicon array is used to detect protons produced in the (d,p) reaction. The protons emitted from the reaction have a minimum energy of 2.02 MeV if the ^{51}Ca is produced in the ground state (down to 606keV at the neutron separation treshold). The reaction was simulated using the NPTool package [23] using the cross sections (shown in figure 3) and states (as listed in table 1) for a magnetic field of 2 T and a distance of 100 mm between the target and the array. The silicon array covers the z range of -100 mm to -600 mm (distance to target along beam direction, negative means upstream). In this configuration protons with $11° < \theta_{cm} < 36°$ can be detected on the array for states with excitation energy up to 4 MeV. The requested number of shifts allows for a minimum of 500 expected proton counts in each of the states.

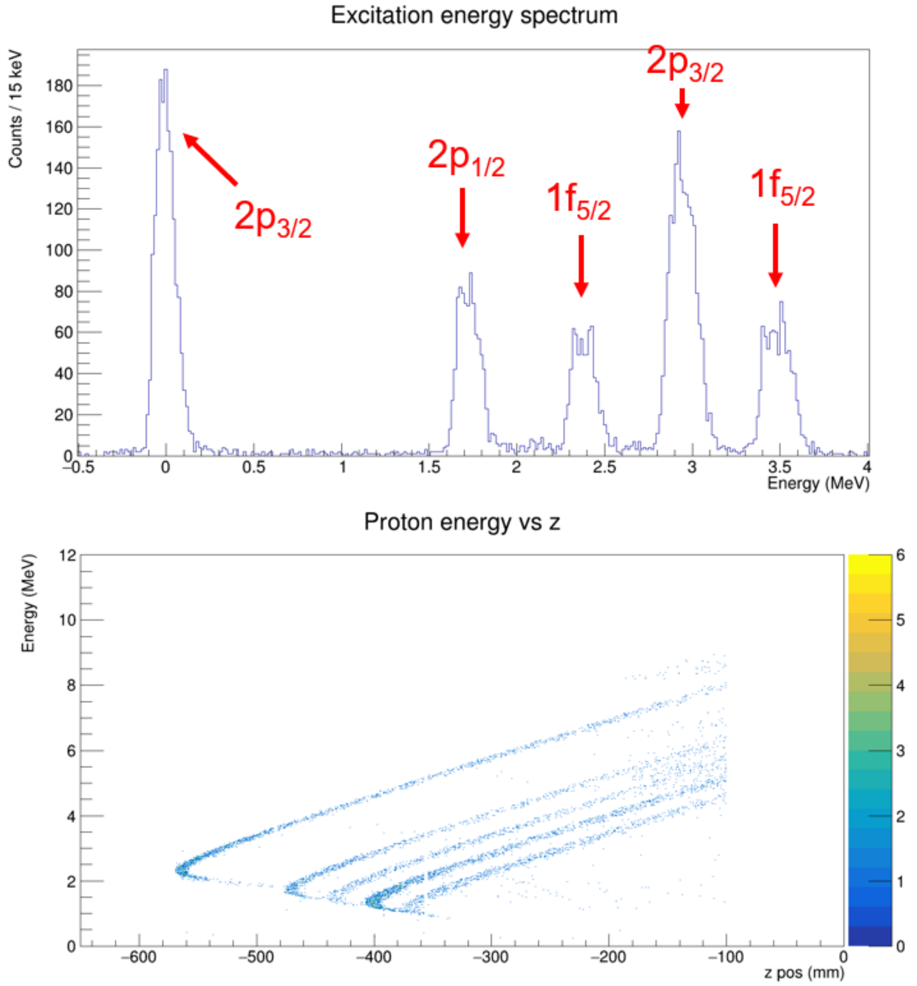

Figure 4: Simulation of the reaction performed using the NPTool code. Top: reconstructed excitation energy spectrum. Bottom: Energy vs z-position of detected proton in the silicon array. The highest kinematics line corresponds to the ground state.

Remark concerning the low intensity of the requested ^{50}Ca beam: The resulting intensity of the ^{50}Ca beam on the CD_2 target most likely will be the lowest among the all experiments conducted with ISS so far. However, an experiment with a similarly low beam intensity was successfully run with ISS in November of 2022. The measurement of the excited states in ^{69}Ni with a ^{68}Ni(d,p) reaction (IS587 experiment) demonstrated the feasibility of conducting an experiment with ISS using low intensity beams of $\sim 3 \times 10^4$ pps at the setup. A preliminary energy spectrum obtained after this experiment is shown in figure 5.

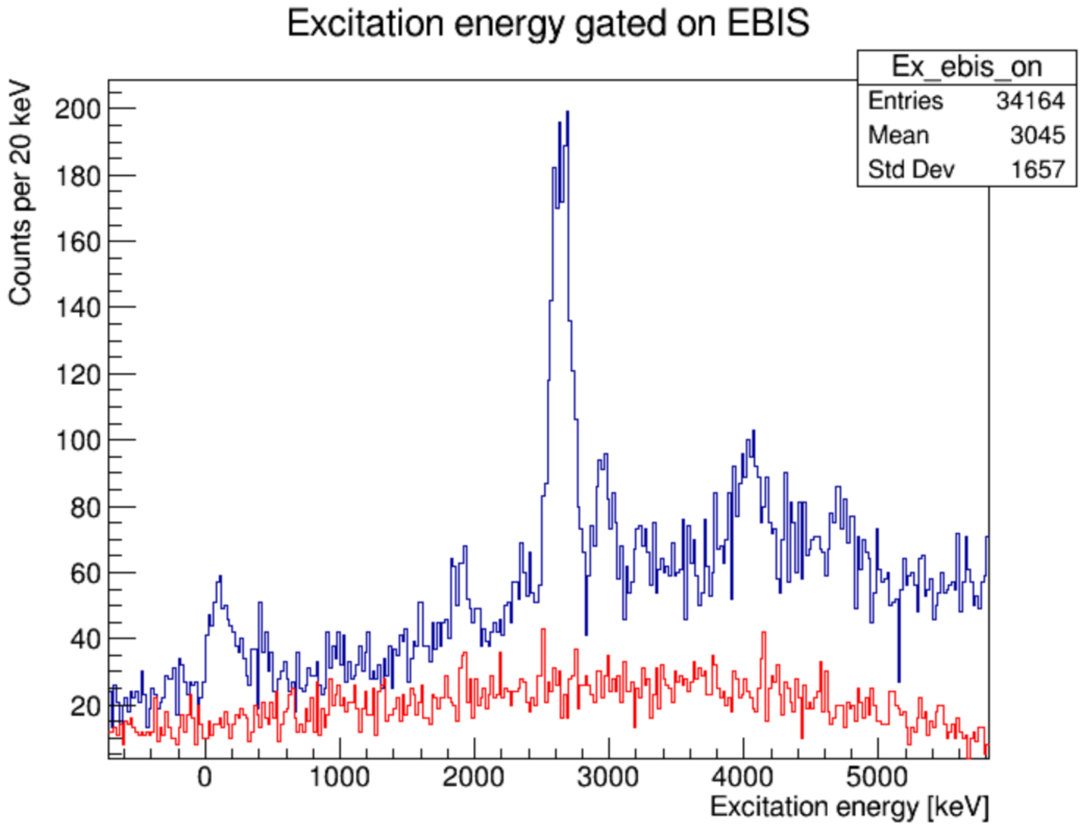

Figure 5: Preliminary energy spectrum obtained during the IS587 experiment (^{68}Ni(d,p)^{69}Ni). Blue: Data (laser on + 3s beamgate). Red: Background (laser off + no beamgate).

Altough data analysis is still ongoing, the preliminary spectrum shows clearly separable energy states with sufficient statistics in the peaks of interest.

Summary of requested shifts: A total of 15 shifts in a single run are requested.

References

[1] A. Huck, G. Klotz, A. Knipper, C. Miehé, C. Richard-Serre, G. Walter, A. Poves, H. L. Ravn, and G. Marguier. Beta decay of the new isotopes ^{52}K, ^{52}Ca, and ^{52}Sc; a test of the shell model far from stability. *Phys. Rev. C*, 31:2226–2237, 1985.

[2] D. Steppenbeck, S. Takeuchi, J. Lee, K. Matsui, S. Michimasa, T. Motobayashi, D. Nishimura, T. Otsuka, H. Sakurai, Y. Shiga, P.-A. Söderström, T. Sumikama, N. Aoi, H. Suzuki, R. Taniuchi, Y. Utsuno, J. J. Valiente-Dobon, K. Yoneda, P. Doornenbal, M. Matsushita, H. Wang, H. Baba, N. Fukuda, S. Go, and M. Honma. Evidence for a new nuclear 'magic number' from the level structure of 54ca. *Nature (London)*, 502(7470):207–210, 2013.

[3] F. Perrot, F. Maréchal, C. Jollet, Ph. Dessagne, J.-C. Angélique, G. Ban, P. Baumann, F. Benrachi, U. Bergmann, C. Borcea, A. Buţă, J. Cederkall, S. Courtin, J.-M. Daugas, L. M. Fraile, S. Grévy, A. Jokinen, F. R. Lecolley, E. Liénard, G. Le Scornet, V. Méot, Ch. Miehé, F. Negoiţă, N. A. Orr, S. Pietri, E. Poirier, M. Ramdhane, O. Roig, I. Stefan, and W. Wang. β-decay studies of neutron-rich k isotopes. *Phys. Rev. C*, 74:014313, Jul 2006.

[4] M. Rejmund, S. Bhattacharyya, A. Navin, W. Mittig, L. Gaudefroy, M. Gelin, G. Mukherjee, F. Rejmund, P. Roussel-Chomaz, and Ch. Theisen. Shell evolution and the $n = 34$ "magic number". *Phys. Rev. C*, 76:021304, Aug 2007.

[5] Takaharu Otsuka, Alexandra Gade, Olivier Sorlin, Toshio Suzuki, and Yutaka Utsuno. Evolution of shell structure in exotic nuclei. *Rev. Mod. Phys.*, 92:015002, Mar 2020.

[6] T. Otsuka, R. Fujimoto, Y. Utsuno, B. A. Brown, M. Honma, and T. Mizusaki. Magic numbers in exotic nuclei and spin-isospin properties of the *NN* interaction. *Phys. Rev. Lett.*, 87:082502, 2001.

[7] J.I. Prisciandaro, P.F. Mantica, B.A. Brown, D.W. Anthony, M.W. Cooper, A. Garcia, D.E. Groh, A. Komives, W. Kumarasiri, P.A. Lofy, A.M. Oros-Peusquens, S.L. Tabor, and M. Wiedeking. New evidence for a subshell gap at n=32. *Physics Letters B*, 510(1):17–23, 2001.

[8] L. Coraggio, A. Covello, A. Gargano, and N. Itaco. Spectroscopic study of neutron-rich calcium isotopes with a realistic shell-model interaction. *Phys. Rev. C*, 80:044311, 2009.

[9] F. Wienholtz, D. Beck, K. Blaum, Ch Borgmann, M. Breitenfeldt, R.B. Cakirli, S. George, F. Herfurth, J.D. Holt, M. Kowalska, S. Kreim, D. Lunney, V. Manea, J. Menéndez, D. Neidherr, M. Rosenbusch, L. Schweikhard, A. Schwenk, J. Simonis, J. Stanja, R.N. Wolf, and K. Zuber. Masses of exotic calcium isotopes pin down nuclear forces. *Nature (London)*, 498(7454):346–349, 2013.

[10] R.F. Garcia Ruiz, M.L. Bissell, K. Blaum, A. Ekström, N. Frömmgen, G. Hagen, M. Hammen, K. Hebeler, J.D. Holt, G.R. Jansen, M. Kowalska, K. Kreim, W. Nazarewicz, R. Neugart, G. Neyens, W. Nörtershäuser, T. Papenbrock, J. Papuga, A. Schwenk, J. Simonis, K.A. Wendt, and D.T. Yordanov. Unexpectedly large charge radii of neutron-rich calcium isotopes. *Nature physics*, 12(6):594–598, 2016.

[11] M. Enciu, H. N. Liu, A. Obertelli, P. Doornenbal, F. Nowacki, K. Ogata, A. Poves, K. Yoshida, N. L. Achouri, H. Baba, F. Browne, D. Calvet, F. Château, S. Chen, N. Chiga, A. Corsi, M. L. Cortés, A. Delbart, J-M. Gheller, A. Giganon, A. Gillibert, C. Hilaire, T. Isobe, T. Kobayashi, Y. Kubota, V. Lapoux, T. Motobayashi, I. Murray, H. Otsu, V. Panin, N. Paul, W. Rodriguez, H. Sakurai, M. Sasano, D. Steppenbeck, L. Stuhl, Y. L. Sun, Y. Togano, T. Uesaka, K. Wimmer, K. Yoneda, O. Aktas, T. Aumann, L. X. Chung, F. Flavigny, S. Franchoo, I. Gasparic, R.-B.

Gerst, J. Gibelin, K. I. Hahn, D. Kim, Y. Kondo, P. Koseoglou, J. Lee, C. Lehr, P. J. Li, B. D. Linh, T. Lokotko, M. MacCormick, K. Moschner, T. Nakamura, S. Y. Park, D. Rossi, E. Sahin, P.-A. Söderström, D. Sohler, S. Takeuchi, H. Toernqvist, V. Vaquero, V. Wagner, S. Wang, V. Werner, X. Xu, H. Yamada, D. Yan, Z. Yang, M. Yasuda, and L. Zanetti. Extended p 3 / 2 neutron orbital and the n = 32 shell closure in ca 52. *Physical review letters*, 129(26), 2022.

[12] T. Otsuka and Y. Tsunoda. The role of shell evolution in shape coexistence. *Journal of Physics G: Nuclear and Particle Physics*, 43(2):024009, 2016.

[13] R. F. Garcia Ruiz, M. L. Bissell, K. Blaum, N. Frömmgen, M. Hammen, J. D. Holt, M. Kowalska, K. Kreim, J. Menéndez, R. Neugart, G. Neyens, W. Nörtershäuser, F. Nowacki, J. Papuga, A. Poves, A. Schwenk, J. Simonis, and D. T. Yordanov. Ground-state electromagnetic moments of calcium isotopes. *Phys. Rev. C*, 91:041304, Apr 2015.

[14] B. Fornal, R. V. F. Janssens, R. Broda, N. Marginean, S. Beghini, L. Corradi, M. P. Carpenter, G. De Angelis, F. Della Vedova, E. Farnea, E. Fioretto, A. Gadea, B. Guiot, M. Honma, W. Królas, T. Lauritsen, S. Lunardi, P. F. Mantica, P. Mason, G. Montagnoli, D. R. Napoli, T. Otsuka, T. Pawłat, G. Pollarolo, F. Scarlassara, A. M. Stefanini, D. Seweryniak, S. Szilner, C. A. Ur, M. Trotta, J. J. Valiente-Dobón, J. Wrzesiński, and S. Zhu. Yrast structure of the neutron-rich $n = 31$ isotones ^{51}Ca and ^{52}Sc. *Phys. Rev. C*, 77:014304, Jan 2008.

[15] N Taccetti, P A Mando, P Sona, and K P Lieb. Lifetime measurements in 49ca and 51ti. *Journal of Physics G: Nuclear Physics*, 13(3):393, mar 1987.

[16] Y. Uozumi, O. Iwamoto, S. Widodo, A. Nohtomi, T. Sakae, M. Matoba, M. Nakano, T. Maki, and N. Koori. Single-particle strengths measured with 48ca(d, p)49ca reaction at 56 mev. *Nuclear Physics A*, 576(1):123–137, 1994.

[17] H. L. Crawford, A. O. Macchiavelli, P. Fallon, M. Albers, V. M. Bader, D. Bazin, C. M. Campbell, R. M. Clark, M. Cromaz, J. Dilling, A. Gade, A. Gallant, J. D. Holt, R. V. F. Janssens, R. Krücken, C. Langer, T. Lauritsen, I. Y. Lee, J. Menéndez, S. Noji, S. Paschalis, F. Recchia, J. Rissanen, A. Schwenk, M. Scott, J. Simonis, S. R. Stroberg, J. A. Tostevin, C. Walz, D. Weisshaar, A. Wiens, K. Wimmer, and S. Zhu. Unexpected distribution of $\nu 1 f_{7/2}$ strength in ^{49}**Ca**. *Phys. Rev. C*, 95:064317, Jun 2017.

[18] Wienholtz, F. High-precision mass measurements on neutron-rich radionuclides with isoltrap for nuclear astrophysics studies. `theorie.ikp.physik.tu-darmstadt.de/hirschegg/2015/talks/Tue/Wienholtz.pdf`. Accessed: 2023-01-02.

[19] I. J. Thompson. Coupled reaction channels calculations in nuclear physics. *Computer physics reports*, 7(4):167–212, 1988.

[20] National nuclear data center. website, 2022. URL: `https://www.nndc.bnl.gov`.

[21] W. W. Daehnick et al. Global optical model potential for elastic deuteron scattering from 12 to 90 mev. *Phys. Rev. C*, 21:2253–2274, Jun 1980.

[22] A.J. Koning and J.P. Delaroche. Local and global nucleon optical models from 1 kev to 200 mev. *Nuclear Physics A*, 713(3):231–310, 2003.

[23] A Matta, P Morfouace, N de Séréville, F Flavigny, M Labiche, and R Shearman. Nptool: a simulation and analysis framework for low-energy nuclear physics experiments. *Journal of physics. G, Nuclear and particle physics*, 43(4):45113–, 2016.

Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: The ISOLDE Solenoidal Spectrometer (ISS)

<table>
<tr><td>Part of the</td><td>Availability</td><td>Design and manufacturing</td></tr>
<tr><td rowspan="2">ISS</td><td>☒ Existing</td><td>☒ To be used without any modification
☐ To be modified</td></tr>
<tr><td>☐ New</td><td>☐ Standard equipment supplied by a manufacturer
☐ CERN/collaboration responsible for the design and/or manufacturing</td></tr>
</table>

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed ISS installation.

Additional hazards:

Hazards	
Thermodynamic and fluidic	
Pressure	
Vacuum	10^{-6} mbar
Temperature	293 K
Heat transfer	
Thermal properties of materials	
Cryogenic fluid	
Electrical and electromagnetic	
Electricity	
Static electricity	
Magnetic field	2 T
Batteries	
Capacitors	
Ionizing radiation	
Target material [material]	CD_2
Beam particle type (e, p, ions, etc)	^{50}Ca
Beam intensity	
Beam energy	7 MeV/u
Cooling liquids	
Gases	
Calibration sources:	☒
• Open source	☒

• Sealed source	☒
• Isotope	α: ^{148}Gd, ^{239}Pu, ^{241}Am and ^{244}Cm
• Activity	α: 1 kBq/isotope
Use of activated material:	
• Description	
• Dose rate on contact and in 10 cm distance	
• Isotope	
• Activity	
Non-ionizing radiation	
Laser	
UV light	
Microwaves (300MHz-30 GHz)	
Radiofrequency (1-300 MHz)	
Chemical	
Toxic	
Harmful	
CMR (carcinogens, mutagens and substances toxic to reproduction)	
Corrosive	
Irritant	
Flammable	
Oxidizing	
Explosiveness	
Asphyxiant	
Dangerous for the environment	
Mechanical	
Physical impact or mechanical energy (moving parts)	
Mechanical properties (Sharp, rough, slippery)	
Vibration	
Vehicles and Means of Transport	
Noise	
Frequency	
Intensity	
Physical	

Confined spaces	
High workplaces	
Access to high workplaces	
Obstructions in passageways	
Manual handling	
Poor ergonomics	

Hazard identification:

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): N/A