EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Spins, moments and charge radii of $^{51-54}$Sc, crossing $N = 32$, measured with collinear resonance ionization laser spectroscopy at CRIS

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Abstract: Following on the proposal for the measurement of the charge radii and moments of $^{47-51}$Sc at COLLAPS, this proposal focuses on the studies of more exotic Sc ($Z = 21$) isotopes with collinear resonance ionization laser spectroscopy at CRIS. This experiment will provide the first experimental determination of nuclear spins and nuclear electromagnetic moments, as well as the changes in mean-square charge radii for $^{51-54}$Sc, across the suggested $N = 32$ shell gap. The new results will provide key information to test the magicity of the suggested new magic number $N = 32$, and allow the evolution of nuclear structure around $N = 32$ to be better understood.

Requested shifts: [21] shifts, (split into [2] runs over [2] years)

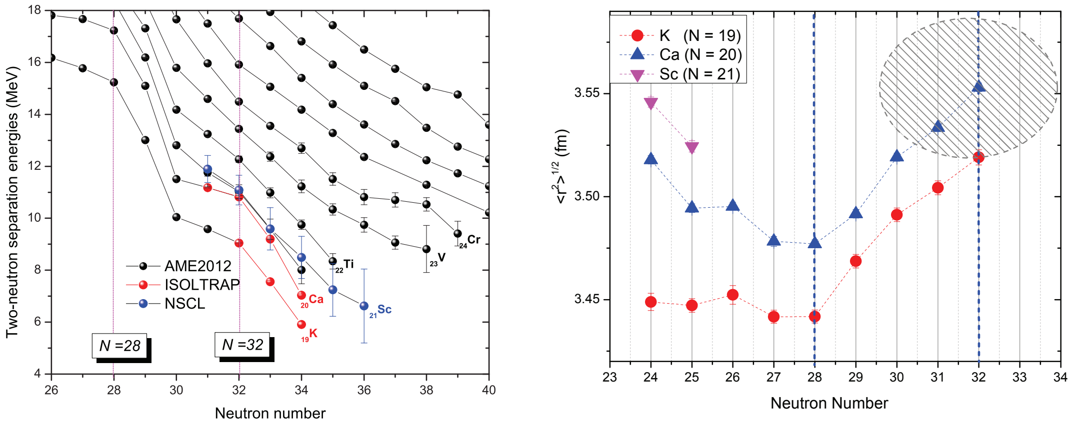
1 Introduction

Experimental indication of a subshell closure at $N = 32$ in isotopes of Ca ($Z = 20$), Ti ($Z = 22$) and Cr ($Z = 24$) has been found from the systematic behavior of the $E(2^+)$ energies of even-even nuclei in the Ca region [1-4]. Also recent mass measurements of neutron-rich Ca isotopes [5], as shown in Fig.1a, have provided evidence for magicity at $N = 32$, but no signature for magicity has been observed in the mean square charge radii of the Ca isotopes [6] (Fig.1b). In the shell model framework, a subshell closure at $N = 32$ can be explained by a shift of the $\nu f_{5/2}$ orbit when the $\pi f_{7/2}$ occupancy is changing. As protons are removed from the $\pi f_{7/2}$ when moving from Ni to Ca, the strong attractive interaction with the $\nu f_{5/2}$ is reduced, such that this level becomes less bound. In Ca, it is shifted above the $\nu p_{1/2}$ orbital, thus opening the $\nu p_{3/2}$ - $\nu p_{1/2}$ spin-orbit gap at $N = 32$ [7].

Below Ca, recent mass measurements of neutron-rich K ($Z = 19$) isotopes (Fig.1a) have observed a 3 MeV drop in S_{2n} from ^{51}K to ^{53}K, which also suggests a $N = 32$ shell effect in the K isotopic chain [8]. However, from the charge radii measured up to ^{51}K ($N = 32$), no evidence for magicity has been observed [9] (Fig.1 b). Above Ca, mass measurements up to $N = 35$ in Sc ($Z = 21$) isotope chain has been performed in NSCL of Michigan State University, recently. The new measured mass values are plotted in Fig. 1a together with the mass measurement of K and Ca performed with ISOLTRAP [5,8,10]. The strong drop in S_{2n} in the K and Ca isotopic chain at the crossing of $N = 32$, can not be clearly identified in the Sc chain due to the larger uncertainties of the measured masses. Therefore, precise mass measurements to investigate the possibility of this new “magic number”in the $Z = 21$ isotopes of Sc are planned at ISOLDE [11].

Previous laser spectroscopy measurements performed on neutron-rich K and Ca isotopes at the COLLAPS experiment have also elucidated important aspects of nuclear structure in the Ca region, through the measurement of nuclear moments and spins [12-14]. The trend in the magnetic moments provides evidence for rather pure proton configurations in the ground state wave function of $^{38-47}$K as well as in ^{50,51}K (at $N = 31, 32$), while a very mixed wave function appears in ^{48,49}K (at $N = 29, 30$) [13]. The magnetic moment of ^{51}Ca, having a single neutron-hole with respect to the suggested $N = 32$ subshell closure, indicates mixing with configurations involving neutron excitations above $N = 32$ [14]. However, due to the nature of these neutron excitations (of $M1$ type between the $p_{3/2}$ and $p_{1/2}$ spin-orbit partners), just a few percent of mixing is sufficient to reproduce the experimental value, and therefore a strong conclusion on the strength of the $N = 32$ shell gap cannot be made. The extension of these studies in the Sc ($Z = 21$) isotopic chain, where the $\pi f_{7/2}$ orbit is active, will provide new insights into the main mechanism that drives the nuclear structure evolution in the neighborhood of $Z = 20$, and will allow the investigation of the nuclear structure around $N = 32$ and $N = 34$.

As summarized in Table 1 of Ref.[15], isotope shifts, nuclear magnetic and quadrupole moments have been measured relative to ^{45}Sc for ^{42m,43,44g,44m,45g,45m,46}Sc at Jyvaskyla [16]. Following the measurement of the nuclear moments and charge radii of $^{47-51}$Sc in proposal [15], here we propose to measure the nuclear spin, moments and isotopes shifts



(a) (b)

Figure 1: (a): Two neutron separation energy in the Ca region [5,8,10]. (b): RMS nuclear charge radii around $N = 32$ versus neutron number for the ground state of isotopes of K, Ca [6,9].

of $^{51-54}$Sc isotopes using the CRIS setup, thus extending the laser spectroscopy studies up to $N = 33$.

One valence proton in the $\pi f_{7/2}$ orbit gives a $7/2^-$ spin/parity for the ground state of odd-mass Sc (Table 1). Therefore, the spins of ^{51,53}Sc are assumed to be $7/2^-$ following the systematic trend of other odd$-A$ Sc isotopes. For the odd-odd Sc isotopes, the coupling between the proton in the $\pi f_{7/2}$ orbit and the neutron in the $\nu p_{3/2}$ ($^{50-52}$Sc) or $\nu p_{1/2}$ (^{54}Sc) gives several possible spins for the ground state, for instance, $(3,4)^+$ for ^{54}Sc [17]. Based on beta-decay spectroscopy, nuclear spins has been only tentatively assigned for ground and isomeric states (^{50m,52,54}Sc) [18]. Laser spectroscopy measurements will allow an unambiguous assignment for the spins of these isotopes, which are of important for interpreting the nuclear structure data obtained by previous decay spectroscopy experiments [18].

A comparison of available nuclear moments from literatures [16,19-22] and the Schmidt limit is shown in Fig.2. As expected, the measured magnetic moments of ^{41}Sc and ^{49}Sc are close to the single-particle value (Schmidt value) of the $\pi f_{7/2}$ orbit, as deviations due to configuration mixing are minimal for isotopes that have a single odd nucleon outside a double-magic core. The parabolic curve between two single-magic isotopes is a signature for more configuration mixing in the ^{43,45,47}Sc wave functions. A similar parabolic curve of magnetic moments would be expected with increasing neutron occupation in the $\nu p_{3/2}$ orbit (the shaded area of Fig.2), assuming $N = 32$ represents a true shell gap. Therefore, the measurements of the unknown magnetic moments of the Sc isotopes will allow quantification of the mixing of configurations in neutron-rich Sc isotopes around $N = 32$. In case of the presence of a shell closure at $N = 32$, we would expect a bigger magnetic moment for ^{53}Sc than for ^{51}Sc.

Quadrupole moment measurements offer an additional probe to investigate nuclear structure, since they are very sensitive to the nuclear matter distribution. Especially for the isotopes near a closed shell, the quadrupole moments reflect the radial and angular

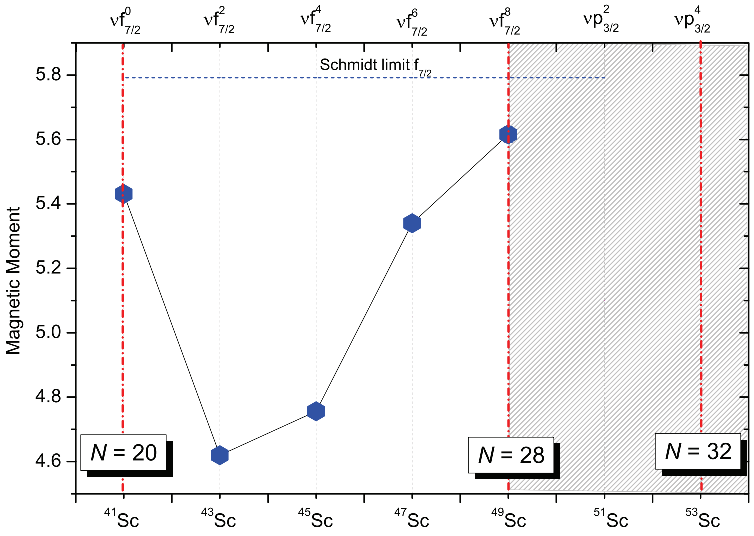


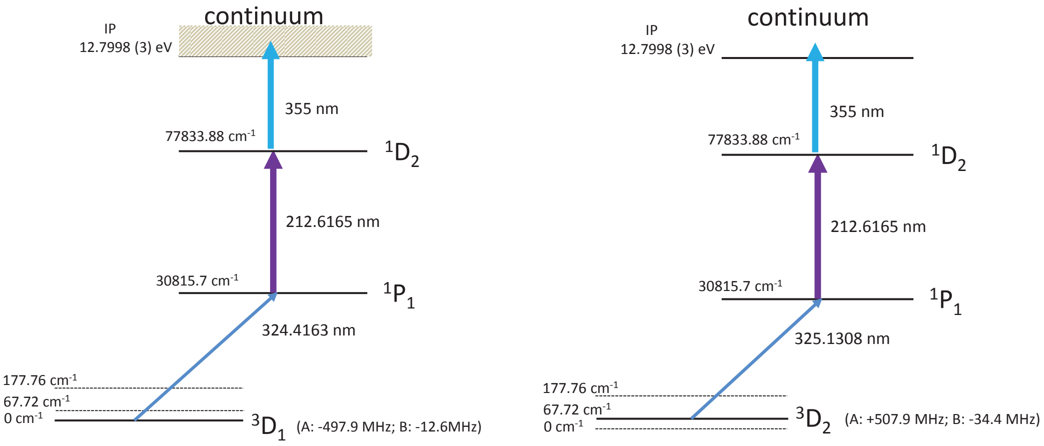
Figure 2: Experimental ground state magnetic moments (blue dots) compared to the Schmidt limit (blue dash line) of single proton in $f_{7/2}$ orbit, calculated with $\mu = (g_l l + g_s s)\ \mu_N$.

distributions of valence particles of a spherical nucleus. If $N = 32$ is a true closed shell as suggested, measurement of the quadrupole moment of isotopes near $N = 32$ (e.g ^{53}Sc) will allow investigation of the properties of the doubly-magic nuclei ^{52}Ca. Note that no quadrupole moments could be measured in the K-isotopes, because the studied laser transition was not sensitive enough to this observable. This would be the first study of quadrupole moments to probe the sub-shell effect at $N = 32$.

As shown in fig.1b, measurements of charge radii above $N = 32$ have not yet been performed, but the present data for the K and Ca isotope chains seem not to support a shell closure at $N = 32$, as the radii of both ^{51}K and ^{52}Ca are increasing with a similar trend for Mn or Fe (as shown in Fig.7 of Ref. [9] and Fig.2 of Ref. [23]) where no subshell closure is predicted. As proposed in IS529 (Ref. [24]), the measurement of mean-square charge radii beyond $N = 32$ in the Ca isotopes, should provide further evidence on whether or not $N = 32$ appears as a sub-shell closure in the Ca chain. Therefore, together with the measurement of charge radii for $^{47-51}$Sc around $N = 28$ in Ref. [15], the measurement of the charge radii of $^{51-54}$Sc across $N = 32$ (as indicated in the shaded area of Fig.1b), has the potential to probe two shell closures and allow the effect at the $N = 28$ closed shell to be directly compared to $N = 32$. Measuring the charge radius of ^{54}Sc is the key to understanding the nature of $N = 32$ with one probe proton.

2 Experimental technique

We propose to measure the hyperfine structure (HFS) spectra and the isotope shift (IS) of Sc isotopes by collinear resonance ionisation laser spectroscopy (CRIS) at ISOLDE [25-28]. This technique combines the advantages of the high sensitivity and selectivity obtained by particle detection of resonantly ionized isotopes, with the high resolution of collinear laser spectroscopy. An efficiency of 1 % has been achieved during the Fr experiment in 2012, allowing the measurement on radioactive Fr beams down to 100



(a)

(b)

Figure 3: RIS schemes, starting from the ionic ground state/first excited state of Sc, to be used for this experiment: the hyperfine structure will be scanned in the first step using a chopped CW laser, while ionization is achieved by two pulsed lasers. The hyperfine parameters A and B factors are known for both initial states of the proposed schemes, which are suitable for the moment measurements.

ions/s in the low resolution HFS measurements [25]. Last year, using a chopped high resolution cw laser beam, the resolution of the collinear resonance ionization technique was improved and reached 20 MHz FWHM [27]. It has been applied on-line to the Fr isotopes, allowing the upper-state hyperfine structure to be resolved, from which quadrupole moments can be deduced [27].

Spectroscopy scheme

In most cases, the the alkali vapour charge-exchange cell (CEC), can be expected to neutralize 50 % of ions. However, in the case of Sc, due to the existence of several metastable states in the atom, only a small fraction of the ions will be converted into the ground state of Sc I. Therefore, to avoid a low neutralization efficiency in the desired level and thus a low experimental efficiency, the laser spectroscopy measurement will be applied to the Sc ion (Sc II). Furthermore, the high ionization potential (IP) of ions will reduce the collisional re-ionization rate, which will further suppress the associated background in the doubly-ionized (Sc III) ion spectra. Additional improvement in transmission efficiency and thus the overall efficiency will also be expected when we remove the charge exchange cell. In order to achieve high efficiency resonance ionization, the ionization scheme needs to be chosen such that it matches our available laser systems (wavelength, power) and has the appropriate hyperfine parameters (sensitive to magnetic moment and quadrupole moment).

Two optional three-step ionization schemes are proposed in this experiment, as shown in Fig.3. The hyperfine A and B factors known for both initial states of the proposed schemes are suitable for the moment measurements. The HFS of the first step can be measured by scanning a frequency-doubled continuous-wave dye laser. High power broadband frequency quadrupled Ti:Sa lasers (10 kHz) or a frequency tripled pulsed dye laser, which will be available soon in the CRIS laser laboratory, will be used for the second step. Finally, the ionization into the continuum (Sc III) will be achieved by a 355 nm Nd:YAG

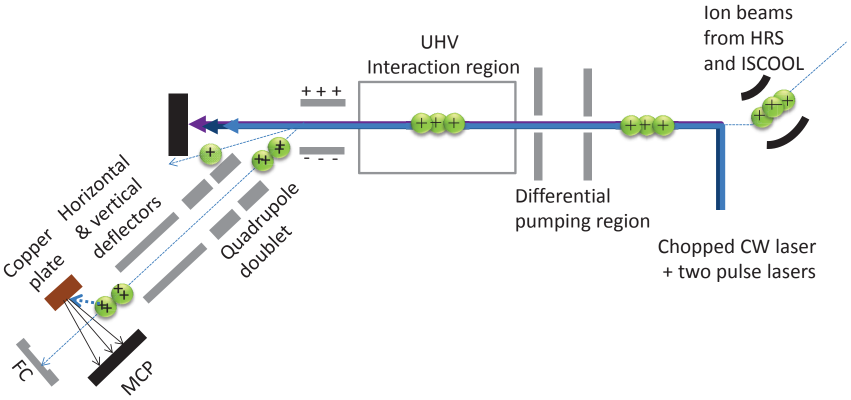


Figure 4: Schematic diagram of the CRIS beam line used for this experiment. The resonantly ionized ions (SC III) will be deflected onto a copper plate and the secondary electrons from the copper plate are collected by the MCP [28].

laser (200 Hz) also available in the coming months in the CRIS laser lab.

CRIS experiment
The radioactive ion beams separated by the high-resolution HRS separator, will be cooled and bunched by ISCOOL. The bunched beam at 30-40 keV will be deflected into the CRIS beam line where it will be spatially overlapped and time-synchronized with the narrow-band chopped cw laser and the two broadband pulsed lasers. The resonantly ionized ions (Sc III) are subsequently deflected onto a copper dynode, while the remaining singly−charged ions (Sc II, including potential isobaric contaminants) are deflected by a smaller angle compared with the doubly-ionized signal. The secondary electrons from the copper dynode, induced by the Sc III impact, are collected by a micro channel plate (MCP), as shown in Fig.4. Recording the ion counts by the MCP as a function of the scanned laser wavelength, the HFS of Sc isotopes will be measured, which allows the ground state nuclear spins, nuclear moments and changes in the RMS charge radii to be deduced [25,28,29]. Recently, a second MCP has been installed in our beam line just after the interaction region, which should provide us with better detection efficiency than before.

3 Production yields and beam time estimate

The neutron-rich radioactive Sc ion beams will be produced with a UC$_x$ target. From the ISOLDE yield database, only the yield of 13 ion/μC for ^{52}Sc is reported with 0.6 GeV proton energy on a UC$_x$ target and a tungsten surface ioniser [30]. However, the development of the ionization scheme of Sc in RILIS has demonstrated that a factor of 400 enhancement of Sc production yield can be obtained with respect to the surface-ionized yield [31,32]. Therefore, on the basis of the ISOLDE yield database and the development of Sc ionization scheme from RILIS, the production yield for the neutron-rich Sc can be estimated as listed in Table 2 (Ref. [11]). However, due to the uncertainty of the estimated yield and that the radioactive Sc isotopes were not produced during ISOLTRAP run in 2014, a yield check prior to scheduling the experiment will be requested.

Table 1: Estimated production yield.

Isotopes	half life	yield	Target/ion source	shifts (Run1)	shifts (Run2)
^{51}Sc	12.4 s	$> 5 \times 10^3$	UC$_x$ /RILIS	2	
^{52}Sc	8.2 s	$\sim 5 \times 10^3$	UC$_x$ /RILIS	3	
^{53}Sc	2.6 s	$\sim 5 \times 10^2$	UC$_x$ /RILIS	5	
^{54}Sc	0.526 s	$\sim 5 \times 10^1$	UC$_x$ /RILIS		11

The estimated yields in Table 1 indicate that measurements of the isotopes up to ^{53}Sc ($N = 32$) (with a predicted yield of > 100/s) should be feasible by using the CRIS setup. Therefore, to study the neutron-rich isotopes $^{51-53}$Sc, we request a total of 12 shifts, including 2 shifts with stable beam immediately before the run for optimizing the experimental set-up and laser scheme (transmission, ion-laser spatial and time overlap, etc.).

In the mean time, the offline test experiments using a new plasma ion source at CRIS will allow to optimize the laser scheme for Sc II. With the measurement of $^{51-53}$Sc and off-line development of an optimized laser scheme, we should able to reach ^{54}Sc (and thus cross $N = 32$), assuming the estimated yield are correct. Therefore, an additional 12 shifts (including one shift of stable beam) is requested to focus on the measurement of ^{54}Sc. Note that a dedicated highly sensitivity beta-detector array is being developed for the Ga experiment (Laser Assisted Nuclear Decay Spectroscopy (LANDS) technique [33]). It will be installed at the end of CRIS beam line next year. In case that some isomers in the very exotic Sc isotopes needed to be studied, this new technique LANDS can also be used. This will allow beta-gamma decay spectroscopy on very pure isomeric beams of Sc (e.g. ^{46m}Sc, ^{50m}Sc).

Summary of requested shifts: 21 shifts of radioactive beam time and 3 shifts of stable beam are requested, separated in two runs with 10 and 11 shifts respectively, as summarized in Table 2.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: CRIS

Part of the	Availability	Design and manufacturing
(CRIS)	☒ Existing	☒ To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT

Hazards named in the document relevant for the fixed CRIS installation.

Additional hazards: None