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The mean square nuclear charge radius of ^{39}Ca

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ABSTRACT : We report on a collinear laser spectroscopy measurement of the nuclear charge radius of ^{39}Ca (I=3/2), yielding $\delta\langle r^2\rangle^{40,39} = -0.127(16)$ fm^2. Within the experimental accuracy, the N=20 neutron shell closure has no influence on the charge radii of the calcium isotopes.

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The nuclear structure of the calcium isotopes having a closed proton shell (Z=20) and reaching two neutron shell closures (N=20,28) with the naturally occurring isotopes, has been studied extensively for many years. The nuclear charge distribution of the isotopes with neutrons in the fp-shell (N>20) has been investigated by muonic x-ray spectroscopy [1], electron scattering [2] and optical spectroscopy [3-8]. A parabolic behaviour of the mean square charge radii between N=20 and N=28 is the essence of the results. Several theoretical approaches were proposed to reproduce the data [9-12], and it was found that an essential role is played by the contribution of higher-order collective vibrations. For isotopes above the N=28 shell closure, the only experimental information on the nuclear charge distribution was obtained by a collinear laser spectroscopy measurement of the mean square charge radius of ^{50}Ca [13]. At N=28, the shell closure is prominently reflected in the minimum value of the charge radius occurring for ^{48}Ca as compared to the neighbouring isotopes. From ^{48}Ca, which has nearly the same radius as ^{40}Ca, the radii increase steeply with a ^{50}Ca value close to the one of ^{44}Ca. In this report we discuss the extension of collinear laser spectroscopy to an isotope below the N=20 shell closure and present the measurement of the ^{39}Ca (I=3/2) nuclear charge radius with respect to the one of ^{40}Ca.

This change in mean square charge radius between ^{39}Ca and ^{40}Ca is deduced from the measurement of the isotope shift $IS^{40,39}$ in the transition 4s $^2S_{1/2} \rightarrow$ 4p $^2P_{1/2}$ (λ=397.0 nm) of singly ionized calcium. The method is basically the one described in ref. [14], but it makes use of radioactivity detection in order to discriminate the weak beam of ^{39}Ca from the huge background of stable ^{39}K. Here the experimental procedure will be sketched only briefly. After the impact of the pulsed 1 GeV proton beam of the CERN PS-BOOSTER (seven 2.4μs long pulses with 2-3 x 10^{13} protons per 14.4s supercycle) on a titanium target, neutron-deficient calcium isotopes are evaporated, ionized by surface ionization on tungsten, accelerated to 33 kV and transmitted through the ISOLDE on-line mass separator [15]. The yield for ^{39}Ca is a few times 10^4 ions per proton pulse, and the stable ^{39}K ion beam has an intensity of about 5 x 10^{10} ions/s. In an optical pumping zone of about 1.5m length the ^{39}Ca beam is merged with a cw dye laser beam. The interaction frequency between the ions and the laser light is Doppler-tuned across the resonances by varying the electrical potential applied to this optical pumping zone. At resonance, the ground-state population is transferred to the low-lying metastable 3d $^2D_{3/2}$ state by repeated excitation to the 4p $^2P_{1/2}$ state which partially decays into the metastable state. Further downstream the ion beam is decelerated to a residual energy of 5 keV and guided through an open sodium vapour cell, where it is partially neutralized. Since at this low energy the neutralization cross section for the ground state is about 3 times lower than for the metastable state [16], the change in atomic state of the ions at resonance is efficiently transformed into a change in charge state. Finally the remaining ions are deflected and the neutral atoms are implanted into a tape. The emitted β-radiation is detected using a scintillator, surrounding the tape with a total solid angle of 70 % ($T_{1/2}(^{39}Ca)$ = 860 ms). The spectrum of the reference isotope ^{40}Ca was recorded before and after each measurement on ^{39}Ca by detecting the fluorescence photons (λ=866 nm) from the decay of the 4p $^2P_{1/2}$ to the metastable 3d $^2D_{3/2}$ state. This detection scheme allowed to block the 397 nm stray laser light by an optical filter. As an additional consistency check, the spectrum of ^{44}Ca was recorded in the same way.

The voltages applied to the optical pumping zone are converted into frequencies relative to the resonance position of ^{40}Ca. The final spectrum for ^{39}Ca is shown in figure 1. The total measuring time for the low frequency doublet was 32s (corresponding to 16 proton pulses) per channel. Only the stronger of the high-frequency hyperfine components (the other one is expected to be about 5 times weaker) was detected by accumulating data during 200s (98 proton pulses) per channel. The fitted line positions of these three hyperfine components yield the magnetic dipole hyperfine interaction constants A_{4s} and A_{4p} as well as the isotope shift $IS^{40,39}$. The value deduced for the ratio A_{4s}/A_{4p} (5.53(11)) coincides with the more accurate value known from the study of the stable isotope ^{43}Ca (5.53(4)) [17]. Moreover, the value for the nuclear magnetic moment ($\mu(^{39}\mathrm{Ca})=1.022(4)\mu_N$) deduced from $A_{4s}(^{39}\mathrm{Ca})$ in combination with the A_{4s} factor and the magnetic moment of ^{43}Ca [18] agrees perfectly with the literature value : $\mu(^{39}\mathrm{Ca}) = 1.0216(2)\mu_N$ [19]. Advantage was taken from this indirect, but more accurate information about the A-factors, in order to reduce the statistical uncertainty of the isotope shift from 4.0 to 3.0 MHz. To account for the relative voltage measurement uncertainty of 10^{-4}, a systematic error of 2.3 MHz is included in the final result for the isotope shift :

$$IS^{40,39} = -222.2(3.0)[2.3]\ \mathrm{MHz}$$

Following the procedure described in refs. [8,13], the change in the nuclear mean square charge radius between ^{40}Ca and ^{39}Ca is deduced from the isotope shift according to :

$$IS^{A,A'} = K^{NMS} \cdot \frac{m(A')-m(A)}{m(A')m(A)} + K^{SMS} \cdot \frac{m(A')-m(A)}{m(A')m(A)} + F \cdot \delta\langle r^2\rangle^{A,A'}$$

For the transition studied, the normal mass shift constant is K^{NMS} = 414.3 GHz amu, the specific mass shift constant K^{SMS} = -9.2(3.8) GHz amu, and the field shift factor F = -283(6) MHz/fm^2 [8]. This yields the difference of the radii :

$$\delta<r^2>^{40,39} = <r^2>^{39} - <r^2>^{40} = -0.127(16)\ \mathrm{fm}^2 .$$

This new result is incorporated in figure 2 where the changes in mean square charge radii within the calcium isotopic series are plotted. The behaviour at the shell closure at N=20 is smooth, similar to earlier observations on the potassium radii ($19 \leq N \leq 28$) [20] and very recently also for an extended series of sd-shell isotopes of argon ($15 \leq A \leq 28$) [21]. This is in qualitative agreement with recent investigations of ground-state properties of Z=14-20 nuclei [22] where for different microscopic approaches a smooth behaviour of charge radii at the neutron shell closure N=20 was calculated. The disappearance of the shell effect at N=20 is discussed in detail in our recent paper on the argon isotopes [21], where physics arguments are given for the results of microscopic and semi-empirical calculations. Quantitative information about the shell-closure effect in calcium can only be obtained by comparing the odd-N ^{39}Ca radius with odd-N values within the fp-shell. In this way the odd-even staggering does not influence the conclusions. Combining our data with those from [5], we find : $\delta\langle r^2\rangle^{41,39} = -0.115(18)\ \mathrm{fm}^2$ and $\delta\langle r^2\rangle^{43,41} = -0.129(9)\ \mathrm{fm}^2$. Within the error limits, these differential radii are the same, meaning that the effect of the neutron shell closure at N=20 on the mean square radius is very small, in contrast to the striking shell effect at N=28.

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Figure Captions

Figure 1 : The $4s^2S_{1/2}$ - $4p^2P_{1/2}$ transition in ^{39}Ca shown as the β-count rate vs. the frequency relative to the resonance frequency of ^{40}Ca : a) the low frequency components; b) the highest frequency component

Figure 2 : Experimental values for the mean square nuclear charge radii of the calcium isotopes relative to ^{40}Ca [6,13], including the new result for ^{39}Ca.