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

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PACS-numbers : 21.10.Ft Nuclear Structure / Charge distribution

27.40.+z Properties of nuclei with $39 \leq A \leq 59$

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

(IS 304)

accepted for publication in Journal of Physics G

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 $\text{IS}^{40,39}$ in the transition $4s\ ^2S_{1/2} \rightarrow 4p\ ^2P_{1/2}$ ($\lambda=397.0\text{ nm}$) 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 $2.4\mu\text{s}$ long pulses with $2\text{-}3 \times 10^{13}$ 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 5×10^{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 % ($T_{1/2}(^{39}\text{Ca}) = 860$ ms). The spectrum of the reference isotope ^{40}Ca was recorded before and after each measurement on ^{39}Ca by detecting the fluorescence photons ($\lambda=866$ 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 ($\mu(^{39}\text{Ca})=1.022(4)\mu_N$) deduced from $A_{4s}(^{39}\text{Ca})$ in combination with the A_{4s} factor and the magnetic moment of ^{43}Ca [18] agrees perfectly with the literature value : $\mu(^{39}\text{Ca}) = 1.0216(2)\mu_N$ [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 :

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

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 :

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

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

$$\delta\langle r^2 \rangle^{40,39} = \langle r^2 \rangle^{39} - \langle r^2 \rangle^{40} = -0.127(16) \text{ fm}^2.$$

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 : $\delta\langle r^2 \rangle^{41,39} = -0.115(18) \text{ fm}^2$ and $\delta\langle r^2 \rangle^{43,41} = -0.129(9) \text{ fm}^2$. 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 $N=28$.

This work has been funded by the German BMBF under contract numbers 06 MZ 501 I and 06 MZ 566, and by the Belgian NFWO.

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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 .