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Charge radii of argon isotopes in the $f_{7/2}$ shell and radii systematics in the Ca-region

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Changes in mean square (ms) nuclear charge radii of Ar isotopes across the $1f_{7/2}$ shell are studied by fast beam collinear laser spectroscopy using an ultra-sensitive detection method based on optical pumping and state selective collisional ionisation. The new data set on Ar, in combination with the known charge radii of K, Ca and Ti in the $v1f_{7/2}$ shell, offers an opportunity to obtain a more complete overview of nuclear radii trends around the proton shell closure $Z = 20$ and between the neutron shell closures $N = 20$ and $N = 28$.

Key words: mean square charge radii of $^{38-46}\text{Ar}$ isotopes, nuclear radii trend in the calcium region, collinear fast-beam laser spectroscopy, collisional ionisation, method of direct measurement of the beam kinetic energy.

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1. Introduction

The unusual behaviour of the nuclear charge radii of the Ca isotopes ($Z = 20$) covering the $f_{7/2}$ neutron shell is well known [1]. It is characterized by a symmetric parabolic curve with a maximum in the middle of the shell and by the very surprising fact that the two doubly magic nuclei ^{40}Ca and ^{48}Ca have almost identical ms charge radii [2]. However, this behaviour for the Ca isotopes is only qualitatively reproduced by the data on the neighbouring odd- Z element potassium [3]. Distinct differences include not only the mid-shell maximum compared to shell closures but even more the odd-even staggering. Moreover, earlier results for the argon isotope chain [4] covering the upper sd- and partly the $f_{7/2}$ shell show a trend of generally increasing nuclear charge radii from $N = 20$ to $N = 28$. From the point of view of the gross nuclear radii systematics such large structural differences are unusual for neighbouring isotopic chains. Thus, several questions arise, for example: what is the influence of the proton magic number on the development of the radii around calcium; should one ascribe the difference between Ca and K to an odd-even effect in the proton number or it is due to an exceptional situation in the neighbourhood of the $Z = 20$ proton shell closure, and so on? In this context it is very interesting to extend the measurements of argon radii to the other neutron rich Ar nuclei in the $1f_{7/2}$ shell, in order to get a complete picture of the ms nuclear radii evolution in the calcium region.

The optical investigation of radii and moments in long chains of isotopes with $Z < 20$ is rather difficult because of the atomic properties of light elements and because of the low production yield of isotopes away from stability. For these reasons the experimental situation is very challenging. It requires high sensitivity and selectivity and very high spectroscopic accuracy. The experimental technique, used for the study of the $f_{7/2}$ argon isotopes, has proven to meet these requirements.

2. Experiment

The experiments were performed at the ISOLDE on-line isotope separator at the CERN PS-Booster synchrotron. The isotope shift investigations were carried out by collinear fast-beam laser spectroscopy combined with an ultra-sensitive resonance detection technique. The method is based on neutralizing the ions in a charge exchange cell followed by optical pumping, state-selective collisional ionization and non-optical detection via ion or beta-decay counting [4]. The experimental setup is shown in Figure 1. The long lived argon isotopes between mass numbers $A = 40$ and 46 have been detected by direct ion counting. This technique provides a detection efficiency superior to the fluorescence photon counting and does not suffer from background due to the stray laser light. Although its application is restricted to rather pure beams a mass resolution of about 1500 was sufficient for the suppression of beam contaminants in the investigated argon region.

Figure 1. Experimental setup for collinear laser spectroscopy involving collisional ionization in a gas target and resonance detection of ions.

The atomic transition suitable for probing the nuclear structure of argon using this experimental technique is the transition $3p^5 4s [3/2]_2 \rightarrow 3p^5 4p [3/2]_2$ with $\lambda = 763.7$ nm [4]. Near resonant charge exchange between argon ions and potassium atoms in the charge exchange cell predominantly populates the metastable $3p^5 4s [3/2]_2$ state in atomic argon. As ionization of the metastable state is favoured in collisions with the gas target molecules, optical resonance pumping the atoms to the ground state lowers the ionization efficiency and the detected optical resonances appear as flop-out signals in the ion count rate. The involved efficiencies were typically 50% for the neutralization and 10% for the re-ionization with about 25% drop of the count rate in the single resonance of an even-even isotope.

In order to extract ms charge radii changes from isotope shifts in the argon system, the small nuclear field shift must be accurately determined. The two main experimental limitations, affecting the absolute accuracy, were found to be the laser frequency stabilization and the absolute determination of the total acceleration voltage. Special care was taken to keep the laser frequency stabilized, to prevent mode-hops and to eliminate long-term instabilities. The problem with the accuracy of the acceleration voltage was tackled by the development of a method for high accuracy determination of the beam kinetic energy [5]. It is based on the excitation of two optical transitions, separated by twice the Doppler shift, at the same laser frequency in collinear and anti-collinear laser beam geometry, without changing the static part of the acceleration voltage. As both transitions are serving as secondary wavelength standard, their frequencies are very precisely known, and the kinetic energy can be calculated to 0.3 eV from the resonances recorded within a narrow range of the Doppler-tuning voltage. This accuracy corresponds to systematic uncertainties of the isotope shift not exceeding 1 MHz for two neighbouring argon isotopes.

Examples of the recorded spectra are shown in Figure 2 for two odd- A argon isotopes. As can be seen, most hyperfine structure components are well resolved. The resonances were modelled by a convolution of a Lorentzian profile with an exponential function which was found to describe most adequately the line shape [6].

Figure 2. Hyperfine structure of the odd- A isotopes ^{41}Ar and ^{43}Ar

3. Experimental results

Isotope shifts measurements, $\delta\nu^{38,4}$, were performed on the argon isotopes $^{38,40-44,46}\text{Ar}$ and used to evaluate the mean square nuclear charge radii for the majority of the $f_{7/2}$ shell nuclei with $Z = 18$. Some special problems of extracting information about nuclear charge radii from isotope shifts of light elements are pointed in the previous paper on argon [4]. Because of these problems a deliberate treatment of the experimental data is necessary. The procedure of data analysis and evaluation will be described in detail in our forthcoming paper [7].

The results of the isotope shift measurements for the long sequence of Ar isotopes covering the upper vsd and nearly the whole $\nu f_{7/2}$ shell have been expressed in the corresponding nuclear radii and

presented in Figure 3. The data on $^{41-44}\text{Ar}$ have been obtained for the first time and should be regarded as preliminary. As can be seen, the charge radii evolution in the $f_{7/2}$ shell is characterised by (i) a non symmetric parabola-like trend; (ii) a “normal” well pronounced odd-even staggering effect and (iii) a slope of the curve steeper at the beginning of the interval between both neutron magic numbers and saturating at the end. These features are insensitive to the systematic uncertainties affecting only the overall scale of the radii changes [4,7].

Figure 3. Mean square nuclear charge radii of argon, calcium, potassium, titanium and chromium nuclei versus neutron number.

The experimental data are in a good qualitative agreement with the predictions of Klein et al. [4] based on the spherical HF approach with the Skyrme interaction. It describes explicitly the role of the configuration mixing within the proton sd shell, predicts qualitatively a steady increase of nuclear radii between both neutron shell closure $N = 20$ and $N = 28$, but fails to explain the parabolic shape and the odd-even staggering of the radii variation. In a more complete discussion the role of the collective effects has to be taken into account.

4. Nuclear charge radii in the calcium region - overview

The present data on Ar together with earlier data for K, Ca and the recent laser spectroscopy results on $^{44-50}\text{Ti}$ [8] may serve as a cornerstone for a more global systematics of the nuclear radii in the calcium region. According to Figure 3 the well pronounced symmetric parabolic shape observed for the Ca case is not reproduced either in the lower- Z or in the higher- Z neighbouring isotope chains. Now it becomes more evident that the shape asymmetry for elements below and above Ca is in the opposite direction. As mentioned in the introduction, such behaviour is in contrast to what is expected from the nuclear radii systematics at N greater than 28 [9]. In general, as more experimental data become available, it is the behaviour of the Ca chain radii that should be considered as anomalous in this region. The strongly-magic proton number, $Z = 20$, of Ca seems to reinforce the $N = 20$ and 28 closures, leading to reductions, particularly in the neutron, but also proton radii.

Very unusual is the behaviour of charge radii around the neutron shell closure $N = 20$ [4,9]. The sequential addition of neutrons going from the sd- to the $f_{7/2}$ -shell gives a smooth change of the successive charge radii, indicating the disappearance of any shell effect. This most striking feature has been explained by different authors [4,10,11] as arising from a cancellation of the monopole polarisation and the quadrupole polarisation of the proton core when valence neutrons are added.

The data in Figure 3 confirms the features of the odd-even staggering (OES) that were already discussed in Sect. 1. Away from Ca the OES decreases. The smallest OES is observed for the odd- Z isotopes of K. Whether this is a result of the pairing effect in the even- Z chains is a question that deserves closer attention than we are able to give now. For the even- Z neighbours of Ca the OES is smaller than in the calcium case. This may be due to the stabilising role of the closed proton shell of Ca.

The mean field calculations, which usually aim to describe nuclear parameters and radii over a large region of nuclear masses and charges, cannot account for the details of the isotope shifts in the calcium region. The predicted isotopic evolutions of the charge radii are usually featureless. However, there are approaches which are able to explain some of the observed features. To this category belong for example: (i) the calculations based on the HF method with Skyrme interactions [4] predicting the general trend of the Ar charge radii in the sp and fp shell; (ii) the shell model calculations of Caurier et al. [11] using cross-shell proton-neutron correlation being the best description of charge radii trend of Ca isotope; (iii) the self-consistent RMF approach [12,13] predicting in the case of Ti a continual increase in the charge radius going from $N = 28$ to the $N = 20$ shell closure. The same RMF calculations do not predict a noticeable kink in the charge radii systematics at $N = 20$ for any isotope chain.

5. Conclusion

In conclusion we will briefly resume the main results of the present work. Isotopes far from stability have become accessible due to the application of the ultra-high-sensitive collinear fast beam laser spectroscopy technique at the ISOLDE facility [4,7]. The isotope shift measurements of $^{38,40-44,46}\text{Ar}$, performed in the present work, together with the data of [4], give insight on the development of the ms charge radii in a long sequence of argon isotopes. Thus, new information on the behaviour of the nuclear charge radius in a scarcely investigated region around the calcium ($Z = 20$) chain is obtained. The data may serve as a guide to incorporate essential new features into the theoretical approaches.

A fuller picture of the nuclear properties in the calcium region implies extending the experimental information. Here we note the importance of some further investigations:

A continuation of the optical investigation of Ti isotopes to the lighter ^{43}Ti and, especially, ^{42}Ti at the $N = 20$ shell is necessary to provide a stringent test of available theoretical models. Information on nuclear radii changes in the isotopic chain of Sc, the second neighbouring odd- Z element of Ca, will enforce a clearer picture of the role of the pairing effect of even- Z isotopes. These are upcoming experiments, planned to be carried out with the laser spectroscopy setup at the IGISOL facility.

In addition the following have to be emphasised.

Based on the data presented in Figure 3, isotonic nuclear radii systematics in the Ca-region could be evaluated [7]. However, it would be of great importance to extend the region of investigated elements to higher Z up to the proton magic number $Z = 28$ in order to obtain more detailed information about the isotonic behaviour of nuclear charge radii in the $1f_{7/2}$ proton shell. For these nuclei the proton drip line is accessible just in the $1f_{7/2}$ shell. Due to the small binding energies of nuclei close to the drip lines, one expects a lowering of the nuclear density, novel type of shell structures, or presently unknown unusual collective modes.

On the contrary, investigations of the isotope chains covering $v1f_{7/2}$ -shell for elements with $Z < 18$ will move us close to the neutron drip line of these elements. In particular, the role of the $N = 28$ gap in the exotic neutron rich isotopes with $Z = 14, 16$ and 18 is widely discussed in the theory [14]. In general, one predicts that the $N = 28$ shell closure persists, even if eroded by the large neutron excess.

Finally, a continuation of charge radii measurements to the neutron rich side of the isotopic sequences with $N > 28$ is also necessary to give a link to the charge radii development toward the next magic numbers $N = 50$.

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