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ABSTRACT

Collinear fast-beam laser spectroscopy, with improved sensitivity for ions with hyperfine split transitions, is performed to measure the hyperfine structure and the isotope shift of the well deformed short-lived ^{99}Sr . The new method consists in ground state depopulation by a two-step optical pumping sequence prior to state selective neutralization and fast-atom counting. A definitive nuclear spin value $I=3/2$, the change in mean square charge radius $\delta\langle r^2 \rangle^{98,99}$ and the nuclear moments are derived. These results are compared to nuclear spectroscopy information and are interpreted in the frame of the particle plus deformed core model.

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NUCLEAR GROUND STATE PROPERTIES OF ^{99}Sr BY COLLINEAR LASER SPECTROSCOPY WITH NON-OPTICAL DETECTION

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Abstract

Collinear fast-beam laser spectroscopy, with improved sensitivity for ions with hyperfine split transitions, is performed to measure the hyperfine structure and the isotope shift of the well deformed short-lived ^{99}Sr . The new method consists in ground state depopulation by a two-step optical pumping sequence prior to state selective neutralization and fast-atom counting. A definitive nuclear spin value $I=3/2$, the change in mean square charge radius $\delta\langle r^2 \rangle^{98,99}$ and the nuclear moments are derived. These results are compared to nuclear spectroscopy information and are interpreted in the frame of the particle plus deformed core model.

The neutron rich $A \approx 100$ region has been the subject of extended nuclear and optical spectroscopy studies [1]. A very abrupt transition from near-spherical ($^{96,98}\text{Zr}$ and ^{96}Sr) to strongly deformed nuclei ($\beta \approx 0.4$ for $^{100,102}\text{Zr}$ and $^{98,100}\text{Sr}$) is observed in rubidium, strontium and zirconium isotopes. Reasons for this behaviour are commonly sought in proton-neutron interactions between overlapping high- j orbitals, which cause changes in populations of single-particle states [2,3]. In this perspective, a detailed study of the energy level systematics and electromagnetic properties of low lying states of odd nuclei can give valuable information concerning populations of nucleon orbitals.

Of particular interest are the odd- N nuclei in the vicinity of the sharp deformation transition at $N=60$. ^{97}Sr ($N=59$) has been described as a shape coexistent nucleus with spherical low energy levels and a low lying deformed excited band [4,5]. On the other hand, the nuclear level scheme and recent measurements of $B(E2)$ -values [6] indicate a large ground-state deformation for ^{99}Sr .

In this Letter, we report the extension of the fast ion beam collinear laser spectroscopy work on odd- N strontium isotopes [7] into the strongly deformed region of the neutron rich isotopes. To attain this, we applied a new measuring scheme with increased sensitivity, especially adapted to ions with hyperfine split transitions. The obtained nuclear spin, nuclear moments and mean square charge radius for ^{99}Sr allow, in combination with the available nuclear spectroscopy data, a solid description in the frame of the particle plus deformed core model.

The experiments were performed at the CERN on-line isotope separator ISOLDE 2, equipped with a surface ionization ion source. Neutron rich strontium isotopes were produced by fission of uranium (UC_2) upon impact of 600 MeV protons. Collinear laser spectroscopy with non-optical detection is performed on the 60 keV mass separated ion beam. The beam intensity was about 10^5 ions/s for ^{99}Sr ($T_{1/2} = 290$ ms) on an isobaric rubidium background about 10 times higher.

The detection scheme used is similar to the one applied previously to study the low intensity even- N isotopes $^{98,100}\text{Sr}$ [8]. The method basically consists in efficient ground state depopulation through optical pumping ($5s\ ^2S_{1/2} \rightarrow 5p\ ^2P_{1/2,3/2} \rightarrow 4d\ ^2D_J$) by resonant laser - ion beam interaction, state selective neutralization in a sodium vapour and charge state separated atom counting (fig. 1.). The strong state dependence of the neutralization cross sections ($\sigma(4d)/\sigma(5s) \approx 1.5$ at 60 keV) offers a good signal-to-background ratio, whereas the particle detection guarantees excellent detection efficiency. To overcome the considerable loss in ground state depopulation pumping efficiency due to hyperfine pumping, a new optical pumping scheme was realized by splitting the pumping section of the beam path into two zones. With fixed laser frequency, an appropriate voltage U_B applied on zone B tunes the strong non-hyperfine pumping $F = I + 1/2 \rightarrow F' = I + 3/2$ component (see fig. 1.) into

resonance. A varying voltage U_A provides a velocity scan over the different hyperfine components in zone A. In this way, the ground state depopulation pumping by the $F = I - 1/2 \rightarrow F' = I \pm 1/2$ transitions is intensified. All ions transferred from $F = I - 1/2$ to $F = I + 1/2$ in zone A are pumped to the metastable state in zone B. This results in enhanced positive resonance signals with an amplitude comparable to the signal of the strongest line. Similarly, rate equation calculations show amplified negative signals for the $F = I + 1/2 \rightarrow F' = I \pm 1/2$ transitions, due to strong depletion of the $F = I + 1/2$ level in the first zone [9].

The two-step optical pumping spectrum of the D2-transition $5s\ ^2S_{1/2} \rightarrow 5p\ ^2P_{3/2}$ in $^{99}\text{SrII}$ is presented in fig. 2.a. In order to have a consistency check on the hyperfine parameters and the isotope shift, we also studied the D1-transition $5s\ ^2S_{1/2} \rightarrow 5p\ ^2P_{1/2}$ (fig. 2.b.). The resonances of two reference isotopes ($^{88,98}\text{Sr}$) were recorded simultaneously providing a relative frequency calibration. Some oscillations, stemming from ion beam transport instabilities, showed up over the whole spectral range. These did not hamper the extraction of the nuclear ground state spin I , the isotope shift (IS) and the hyperfine parameters by a least squares fitting procedure for which only seven out of the ten recorded hyperfine components are required. In the derived errors, the effect of the oscillations is included.

The analysis gives the nuclear spin $I = 3/2$ unambiguously. It agrees with earlier spin assignments from nuclear spectroscopy experiments [5,10]. The extracted isotope shift ($\text{IS}^{98,99}$) and the hyperfine parameters $A(^2S_{1/2})$, $A(^2P_{1/2})$, $A(^2P_{3/2})$ and $B(^2P_{3/2})$ for ^{99}Sr are given in table 1. The ratio $A(^2S_{1/2})/A(^2P_{3/2})$ is consistent with the mean value of 27.74(8) obtained from the odd strontium isotopes between $A = 79$ and $A = 95$ [4]. In the final analysis, the A-factor ratio was kept fixed at this mean value, resulting in slightly smaller errors for the hyperfine constants and the isotope shift.

The change in mean square charge radius $\delta\langle r^2 \rangle^{98,99}$ and the nuclear moments for ^{99}Sr are deduced from the isotope shift and hyperfine parameters following the procedure described in refs [7,8]: $\delta\langle r^2 \rangle^{98,99} = 0.093(5)\text{ fm}^2$, $\mu = -0.261(5)\ \mu_N$ and $Q_s = 0.84(8)\text{ barn}$. The magnetic moment includes an additional error of $0.003\ \mu_N$ accounting for the hyperfine anomaly which is estimated using the semi-empirical calculation of Moskowitz and Lombardi [11] in combination with the Bohr and Weisskopf estimate [12]. Using the previously measured value for the change in mean square nuclear charge radius between ^{88}Sr and ^{98}Sr [8], a $\delta\langle r^2 \rangle^{88,99} = 1.718(8)[63]\text{ fm}^2$ is obtained. The systematic error from the calibration procedure of $\delta\langle r^2 \rangle$ (in square brackets) is calculated as in ref. [8].

The quadrupole moment can be interpreted in the strong coupling limit, yielding the intrinsic quadrupole moment $Q_0 = \frac{2 I^2 + 5 I + 3}{2 I^2 - I} Q_s = 4.2(4) \text{ eb}$ for ^{99}Sr .

Assuming pure quadrupole deformation we deduce $\beta_{\text{strong coupling}} = 0.48(5)$. A similar value for β ($\langle \beta^2 \rangle^{1/2} = 0.42(2)$) is obtained when the change in mean square charge radius is interpreted in the frame of the macroscopic droplet model [13]. Furthermore, $\langle \beta^2 \rangle^{1/2} = 0.43(4)$ derived from B(E2) measurements [6] is also in agreement with these values. For consistency reasons, droplet model expressions are used to calculate the deformations [7,8], explaining the small difference with the β -value quoted in ref. 6. The different way of taking into account higher order contributions in the different models, indeed becomes relatively important for these large deformations.

The value of $\delta \langle r^2 \rangle^{88,99}$ follows the behaviour of charge radii beyond the jump in charge radius and the corresponding increase in nuclear deformation at $N = 58$ [8,14–16], showing no odd–even staggering effect with respect to the rather pure rotors $^{98,100}\text{Sr}$. This supports the indications for ^{99}Sr to be as deformed as its even neighbours.

The nuclear moments, combined with the available spectroscopic data, allow a description of the ^{99}Sr nucleus in the frame of the particle plus deformed core model. A full description of the model and details of the LUND calculation method are given in ref. [17]. In the literature, different sets of the Nilsson parameters κ_n, μ_n for neutron levels (1s and 1l coupling) are existing. Galeriu et al. [18] obtained a set by fitting experimental single particle energy levels. Rekstad and Løvnhøiden [19] suggested that a strong dependence of κ_n and μ_n on the number of valence nucleons available in a major nuclear shell could take into account the fact that single particle states shift considerably with mass throughout the shell. By comparing experimental one–particle and one–hole levels with calculated single particle levels, they find very small μ_n -values in the beginning of a shell and very large values at the end. For the neutron rich strontium nuclei (filling of the $N > 50$ shell), interpolation of their quoted parameters yields $\kappa_n = 0.06$ and $\mu_n = 0.20$. Calculations of the nuclear energy levels and nuclear moments are carried out with these parameters.

The pairing strength is taken as $GA = 22 - 8 \frac{N - Z}{A} \text{ (MeV)}$ and $\sqrt{5N}$ orbitals above and below the Fermi level are included in the calculation. The moment of inertia is assumed to vary according to the formula [20] :

$$J_i = 4 B \epsilon^2 \sin(\gamma - \frac{2\pi i}{3}) \quad \text{with} \quad \hbar^2/B = 150/A^2 \text{ (MeV)}$$

The gyromagnetic ratios $g_R = Z/A$ and $g_s = 0.7 g_s^{\text{free}}$ are used to calculate the magnetic moment.

The energy levels are calculated at an assumed deformation of $\epsilon = 0.38$ (or $\beta = 0.40$, see the discussion on the deformation). This results in a fair reproduction of the experimentally observed bands, although not all at the correct energies. Fig. 3. shows a comparison of the experimental level scheme [10] with the calculation. A $[404^9/2]$ band and a strongly decoupled $[411^1/2]$ band, both not seen experimentally, show up at low excitation energies in the calculation. The experimental ground state band is well reproduced as a Nilsson $[411^3/2]$ configuration, as are the two other bands ($[413^5/2]$ and $[422^3/2]$).

The calculated spectroscopic quadrupole moment is in excellent agreement with the experiment (see table 2.). Although the theoretical result for the magnetic moment is strongly dependent on the relative contribution of the $1g^7/2$ and $2d^5/2$ orbitals in the ground state configuration, which is of course influenced by the choice of κ_n and μ_n , the calculation allows an unambiguous characterization of the ^{99}Sr ground state as a Nilsson $[411^3/2]$ configuration.

The calculation shows that the band based on this $[411^3/2]$ configuration is very pure. Therefore, a pure Nilsson model calculation (i.e. no mixing of different Nilsson orbitals) of the electromagnetic moments was performed alternatively. The results included in table 2 show no major differences with the full particle-rotor calculation. This strengthens the idea that ^{99}Sr is, at least in the ground state, a nearly rigid rotor which can be well described in the strong coupling scheme.

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Table 1 : Isotope shifts and hyperfine parameters of ^{99}Sr ($I = 3/2$) given in MHz.

	$A(^2S_{1/2})$	$A(^2P_{1/2})$	$A(^2P_{3/2})$	$B(^2P_{3/2})$	$IS^{98,99}$
$5s\ ^2S_{1/2} \rightarrow 5p\ ^2P_{1/2}$	-723(8)	-131(6)	—	—	-142(15)
$5s\ ^2S_{1/2} \rightarrow 5p\ ^2P_{3/2}$	-716(6)	—	-25.8(2)	222(11)	-111(7)

Table 2 : Experimental and calculated magnetic moments and spectroscopic quadrupole moments.

	experimental	calculated	
		particle-rotor model	Nilsson model
$\mu[\mu_N]$	-0.261(5)	-0.278	-0.262
$Q_s[b]$	0.84(8)	0.909	0.909

Fig. 1. Experimental setup. The inset shows the partial level scheme of $^{99}\text{SrII}$.

Fig. 2. Spectra of $^{99}\text{SrII}$: the D2 transition with two-step optical pumping (a) and the D1 transition (b). The full lines are fits to hyperfine parameters.

Fig. 3. Comparison between experimental and calculated nuclear level schemes ($2I$ is indicated). The Nilsson parameters $\kappa_n = 0.06$ and $\mu_n = 0.20$ [19] were used.

Fig. 1.

Fig. 2.

Fig. 3.