ISOTOPE SHIFTS, SPINS AND HYPERFINE STRUCTURES OF $^{118,146}\text{Cs}$
AND OF SOME FRANCIUM ISOTOPES

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july 1986

submitted to Nuclear Physics A

ABSTRACT

High-resolution laser spectroscopy using thermal atomic beams has been performed on-line with the ISOLDE facility at CERN. It allowed the measurement of the spins, isotope shifts and hyperfine structures of the D_2 line of $^{118,146}\text{Cs}$, and that of the hyperfine factors of the first $P_{1/2}$ level of $^{133,135,137,139,141,143}\text{Cs}$ and $^{210,212,213,221}\text{Fr}$. Previous data concerning $^{207-213,220-228}\text{Fr}$ have also been reanalysed. All results are discussed in terms of deformations with a special attention to the possible occurrence of octupole deformations.

KEYWORDS

NUCLEAR STRUCTURE : $^{118,133,135,137,139,141,143,146}\text{Cs}$, $^{207-213,220-228}\text{Fr}$; measured isotope shifts, spins, hyperfine constants; deduced μ , quadrupole moments, rms charge radii, deformation parameters β ; on-line high-resolution laser-spectroscopy using thermal atomic beams.

PACS

21.10 Ft, Hw, Jx, Ky

27.60 +j

27.90 +b

32.30 Jc

1 - INTRODUCTION

Hyperfine spectroscopy of long chains of radioactive atoms has proved to be a very efficient tool to provide a wealth of data concerning both the atomic and the nuclear structures of elements.

We present here new results on cesium nuclei extending this isotopic chain on both neutron-deficient and neutron-rich sides.

We also give new hyperfine factors of the first D_1 line for some cesium and francium isotopes. In addition, we take the opportunity to give here the results of a new analysis of our already published data concerning francium isotopes ¹⁾.

2 - EXPERIMENTAL METHOD

The experimental set-up has been extensively described in previous papers ²⁾. We shall just recall briefly its main points.

The radioactive alkaline isotopes of interest are produced either by fission or by spallation induced by the 600 MeV protons from the SC at CERN. They are first ionized and accelerated by the on-line isotope separator ISOLDE to form a monoisotopic 60 keV ionic beam which is then converted into a thermal atomic beam. This beam is illuminated at a right angle by the light of a cw tunable single mode dye laser which may induce an optical pumping in the hyperfine levels of the ground state of the atom. This pumping is detected using the strongly inhomogeneous field of a sixpole magnet which focuses the atoms with $m_J=+1/2$ and defocuses those with $m_J=-1/2$. The focused atoms are counted after ionization and mass selection through a magnetic spectrometer.

The laser interacts with the atomic beam in the presence of a weak homogeneous magnetic field defining a quantization axis. Polarized light can then be used, giving therefore the possibility of Zeeman optical pumping. Furthermore, a radio-frequency wave-guide located between the

interaction zone and the sixpole magnet enables the induction of rf transitions between adjacent Zeeman sublevels, so that nuclear spins can be determined.

3 - RESULTS ON CESIUM ISOTOPES

For $^{119-145}\text{Cs}$, the spins (I), the hyperfine structures (HFS), and the isotope shifts (IS) had already been measured and published ³⁾, together with an attempt of study of ^{118}Cs for which only some of the hyperfine components of the resonance line had been observed.

3.1 - ^{118}Cs

In the present work, several measurements of the spin, isotope shift and complete HFS of ^{118}Cs have been performed (Table 1). The previous results have been found to be incorrect due to mode hopping of the laser-frequency. The deduced nuclear moments and the change $\delta\langle r^2 \rangle$ of the mean square charge radius are reported in Table 2 together with previous results obtained for neighbouring isotopes ³⁾. As already noticed ³⁾, figure 1 shows that two isomeric states with different mean square charge radii coexist in light cesium isotopes. Their intrinsic quadrupole moments differ significantly too. While the spin of the less deformed odd-Z=55, even-N isotopes $^{119m,121}\text{Cs}$ is 3/2, the spin of the more deformed ones $^{119,121m}\text{Cs}$ is 9/2. The 9/2 spin can be explained by the presence of a proton hole in an intruder level ^{4,5)} labeled by the oscillator quantum numbers [404]9/2. This hole polarizes the core so as to come closer to the Fermi level, resulting in an increase of the axial deformation. This difference in deformation can be qualitatively reproduced by using Hartree-Fock + BCS calculations ⁶⁾ with blocking of the 55th proton in the relevant levels ⁷⁾. The m.s. radius of ^{118}Cs (Fig. 1) clearly

places it in the most deformed family, thus leading to assign $\Omega=9/2$ for the 55th proton. Furthermore, it appears to be very similar to ^{120}Cs since for both the spin is $I=2$, the magnetic moment is $\mu \sim 3.9 \mu_N$ and the spectroscopic quadrupole moment is $Q_S \sim 1.4$ b. The deformation parameter $\langle \beta^2 \rangle^{1/2} \sim 0.3$ has been deduced from the comparison between the experimental m.s. radius and its theoretical value at zero deformation obtained from the spherical droplet model ⁸⁾. Assuming that $K=I=2$, the intrinsic quadrupole moment may be deduced from Q_S using the well known projection formula :

$$Q_0 = Q_S \frac{(I+1)(2I+3)}{3K^2 - I(I+1)}$$

leading to $Q_0 \sim 5$ and $\langle \beta \rangle \sim 0.33$ in agreement with the value of $\langle \beta^2 \rangle^{1/2}$.

The spin $I=2$ of $^{118,120}\text{Cs}$ may be accounted for if the unpaired neutron belongs to an orbital with $\Omega=5/2$. It can be either the $[413]5/2$ or the $[532]5/2$ one which are naturally filled by the last neutron when $\beta \sim 0.3$ ⁹⁾.

3.2 - ^{146}Cs

On the neutron-rich side, ^{146}Cs has been studied for the first time. The results are reported in Tables 1 and 2, and the variation of the m.s. radius is shown in Fig. 1. The behaviour of ^{146}Cs exhibits no drastic effect when compared to the lighter isotopes. In particular, it is in many points similar to that of ^{144}Cs : for both $I=1$, $\mu \sim 0.52 \mu_N$, $\langle \beta^2 \rangle^{1/2} \sim 0.27$, but Q_0 is larger for ^{144}Cs (3.0 b) than for ^{146}Cs (2.2 b). However, no evidence of the existence of a theoretically expected static octupole deformation around ^{144}Cs ¹⁰⁾ can be found.

4 - MEASUREMENTS IN THE D_1 LINE

As a by-product of a study on the relativistic effects in the isotope shifts ¹¹⁾, we have measured the hyperfine structure of the $6p^2P_{1/2}$ excited state of some cesium isotopes. The values of the $A(6p^2P_{1/2})$ hyperfine factors are given in Table 3.

In the same way, the $A(7p^2P_{1/2})$ hyperfine factors of some francium isotopes have been determined. Results are gathered in Table 4.

5 - RESULTS ON FRANCIUM

New measurements on $^{207-213,220-228}\text{Fr}$ have been recently published ¹⁾. We present here an up-dated evaluation of these data and a more detailed discussion ⁷⁾.

a) A new code has been used for the deconvolution of the resonance peaks belonging to very narrow HFS, i.e. for $^{220,221,225}\text{Fr}$. Therefore, the positions of their resonances and the error bar evaluations have been improved (Table 5).

b) A non-relativistic value of the electronic wave function at the center of the nucleus $|\psi_s(0)|^2$ had been used to deduce the variation of the m.s. radii $\delta\langle r^2 \rangle$ from the measured isotope shifts ¹⁾. The introduction of the relativistic correction leads to values of $\delta\langle r^2 \rangle$ about twice smaller. Furthermore, a new evaluation of C_{uniform} which also enters into this calculation, is now available ¹²⁾. Table 6 and Fig. 2 thus give the up-dated values of $\delta\langle r^2 \rangle$ which supersede the previous ones.

c) For the more neutron-rich isotopes $^{220-228}\text{Fr}$, we have tried to estimate the intrinsic quadrupole moments ⁷⁾. At first, $K=I$ was assumed which leads to Q_0 values consistent with the deformations inferred from the m.s. radii, except for $^{221,222,226}\text{Fr}$. In the case of ^{226}Fr , the consistency is restored if $K=0 \neq I=1$ is assumed. For $^{221,222}\text{Fr}$, this can only be obtained by mixing of orbitals with different K values. The

results are reported in Table 7. We also give the deformation parameters deduced either from the quadrupole moment (leading to $\langle\beta\rangle$) or from $\delta\langle r^2\rangle$ (leading to $\langle\beta^2\rangle^{1/2}$). Using the single particle level spectra from ref.13, the spin of the odd-even Fr isotopes can easily be accounted for with or without octupole deformation.

A new analysis of the odd-even staggering of any function $f(N)$ has also been performed using as an indicator the parameter

$$D(N;f) = (-1)^N \left[f(N) - \frac{f(N-1) + f(N+1)}{2} \right]$$

which is easy to manipulate since its sign does not depend on N .

The variations of $D(N;IS)$ calculated for the isotope shifts of Cs, Fr, and Ra ^{14,15)} are shown in Fig. 3. It clearly appears that D is always negative for Cs which may serve as a reference for normal cases : its only positive value at $N=82$ is due to the change of slope at the shell closure. On the contrary, for Fr and Ra, positive "abnormal" values are observed from $N=135$ to 138 , and from $N=133$ to 138 respectively. These inversions of the odd-even staggering have already been discussed and thought to be possible signatures of a stable octupole deformation ^{1,14,15)}.

However, one more argument can be brought. In the case of Fr, $D(N;\beta)$ may be derived for both $\langle\beta\rangle$ and $\langle\beta^2\rangle^{1/2}$ (Fig. 4), while this is not possible for Ra since Q_S cannot be measured for the even-even isotopes. It thus appears that $D(N;\langle\beta^2\rangle^{1/2})$ is indeed abnormal (negative in this case) for $N=135-138$ as $D(N;IS)$ to which it is proportional. For $D(N;\langle\beta\rangle)$ only two values are defined at $N=137$ and 138 since there are no available values of Q_0 for ^{221,222,227}Fr (see Table 7). Contrary to $D(N;\langle\beta^2\rangle^{1/2})$, they are positive, i.e. normal. Such different behaviours of $\langle\beta\rangle$ and $\langle\beta^2\rangle^{1/2}$ can only be explained by putting forward deformations which cancel when averaging β , but not β^2 , such as static octupole deformations

which have been theoretically predicted in this region ^{10,13,16)}. However one should mention that, unlike the abnormal effect on $D(N; \langle \beta^2 \rangle^{1/2})$, $D(N; \langle \beta \rangle)$ is not model independent since Q_0 is extracted by the projection formula assuming no level-mixings. The observed inverted odd-even staggering could be due to a polarization of the nuclear core by the unpaired neutron of even-A isotopes towards a larger octupole deformation ¹⁷⁾. In principle, it would be possible to test such an assumption with codes including octupole deformations and the treatment of odd nuclei. Calculations producing values of the magnetic moments with and without octupole deformations would also be very useful. Our final conclusion is that new theoretical calculations are still strongly wished to better interpret these results.

ACKNOWLEDGMENTS

We are pleased to acknowledge the able technical assistance of J. Biderman, R. Ferger, M. Jacotin, J.F. Képinski and G. Le Scornet for the preparation of the apparatus and data acquisition systems, and for running assistance.

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TABLE 1

Spin, isotope shift and hyperfine structure constants of $^{118,146}\text{Cs}$.

A	I	I.S. ^{133}A MHz	$A(6s^2S_{1/2})$ MHz	$A(6p^2P_{3/2})$ MHz	$B(6p^2P_{3/2})$ MHz
118	2	272 (10)	6034.7(7.5)	126.7(4.1)	202 (24)
146	1	-2611.3(4.4)	-1602.8(6.4)	-35.1(2.8)	31.8(49)

TABLE 2

Nuclear moments, changes $\delta \langle r^2 \rangle$ of the ms charge radius and deduced deformation parameters for the very neutron-rich and very neutron-deficient Cs isotopes.

A	I	$\mu [\mu_N]$	$Q_S [b]$	$Q_0 [b]$	$\langle \beta \rangle$	$\delta \langle r^2 \rangle [\text{fm}^2]$	$\langle \beta^2 \rangle^{1/2}$
a) 118	2	3.876(5)	1.4(2)	4.9(4)	0.32	-0.197(2)	0.32
b) 119	9/2	5.46(3)	2.8(1)	5.1(2)	0.33	-0.136(3)	0.32
b) 119m	3/2	0.838(5)	0.9(1)	4.5(5)	0.30	-0.334(4)	0.28
b) 120	2	3.87(2)	1.45(2)	5.08(7)	0.33	-0.1185(14)	0.31
b) 121	3/2	0.770(4)	0.838(9)	4.19(5)	0.27	-0.2555(9)	0.27
b) 121m	9/2	5.41(3)	2.69(5)	4.93(9)	0.32	-0.0702(8)	0.31
b) 144	1	-0.546(3)	0.30(1)	3.0(1)	0.18	0.9669(7)	0.26
b) 145	3/2	0.784(4)	0.62(6)	3.1(3)	0.18	1.0953(10)	0.27
a) 146	1	-0.515(2)	0.22(3)	2.2(3)	0.13	1.185(2)	0.28

a) this work b) ref. 3

TABLE 3
Hyperfine constants of the $6p^2P_{1/2}$ level of some cesium isotopes

A	133	135	137	139	141	143
$A(6p^2P_{1/2})$ [MHz]	291.3(7)	308.8(8)	320.4(3)	305.4(2)	273.1(7)	232.1(8)

TABLE 4
Hyperfine constants of the $7p^2P_{1/2}$ level of some francium isotopes.

A	210	212	213	221
$A(7p^2P_{1/2})$ [MHz]	945.6(5.8)	1189.1(4.6)	1150.5(7.5)	808.(12.)

TABLE 5
Isotope shift and hyperfine structure constants of some francium isotopes.

A	I.S. ^{212}A MHz	$A(7s^2S_{1/2})$ MHz	$A(7p^2P_{3/2})$ MHz	$B(7p^2P_{3/2})$ MHz
220	-20808 (11)	-6539 (11)	-68.5(6.2)	123 (9)
221	-23569.4(8.0)	6205.6(1.7)	65.4(2.9)	-259 (16)
225	-32297.1(5.5)	6980.1(7.5)	77.2(3.0)	346 (13)

TABLE 6

Changes in the ms charge radius of francium isotopes. The error bars are only the statistical ones. The systematic error due to the uncertainty of the determination of $|\Psi_S(0)|^2$ using the HFS and magnetic moment of ^{211}Fr is evaluated to be 2%.

A	$\delta\langle r^2 \rangle^{212,A} [\text{fm}^2]$
207	-0.21794(16)
208	-0.20804(12)
209	-0.13043(8)
210	-0.10831(4)
211	-0.03757(4)
212	0
213	0.06829(8)
220	0.86725(45)
221	0.98269(33)
222	1.09534(12)
223	1.16507(8)
224	1.28937(4)
225	1.34862(22)
226	1.43700(4)
227	1.60249(8)
228	1.67522(20)

TABLE 7

Intrinsic quadrupole moments and deformation parameters from the quadrupole moment ($\langle\beta\rangle$), and from the change in the m.s. radius ($\langle\beta^2\rangle^{1/2}$). For $\langle\beta\rangle$, the projection formula has been applied with $K=I$ except in the case of ^{226}Fr (see note b)

A	I	Q_0 [b]	$\langle\beta\rangle$	$\langle\beta^2\rangle^{1/2}$
220	1	4.7(3)	0.137	0.189
221	5/2	a)	-	0.201
222	2	a)	-	0.213
223	3/2	5.85(5)	0.164	0.216
224	1	5.17(4)	0.145	0.228
225	3/2	6.6(3)	0.183	0.229
226	1	6.7(1) ^{b)}	0.185	0.235
227	1/2	c)	-	0.253
228	2	8.3(2)	0.227	0.256

a) $K \neq I$ with mixing : Q_0 cannot be deduced by using the simple projection formula

b) $K=0 \neq I=1$ has been used

c) Q_0 cannot be measured since $I=1/2$ (no B factor)

FIGURE CAPTIONS

Figure 1 Variation of the mean square charge radius of Cs isotopes as a function of the mass number, and comparison with the prediction from the spherical droplet model.

Figure 2 Variation of the mean square charge radius of Fr isotopes as a function of the mass number, and comparison with the prediction from the spherical droplet model.

Figure 3 Odd-even staggering of the isotope shift IS in cesium (Fig.3a), and in francium and radium (Fig.3b) isotopes. The $D(N;f)$ function is defined by : $D(N;f) = (-1)^N (f(N) - (f(N-1)+f(N+1))/2)$. Negative values of $D(N;IS)$ indicate a "normal" odd-even staggering.

Figure 4 Odd-even staggering of $\langle \beta \rangle$ and $\langle \beta^2 \rangle^{1/2}$ for francium isotopes. The function D is defined as in Fig.3, but the "normal" odd-even staggering corresponds to positive values.

Figure 1

Figure 2

Figure 3a

Figure 3b

Figure 4