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高工研図書室

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/86-191
18 November 1986

HYPERFINE STRUCTURE AND ISOTOPE SHIFT INVESTIGATIONS IN $^{202-222}$Rn FOR THE STUDY OF NUCLEAR STRUCTURE BEYOND Z = 82

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The hyperfine structure (hfs) and isotope shift (IS) in the isotopic chain of the radioactive element radon have been studied for the first time. The measurements were carried out by collinear fast-beam laser spectroscopy at the mass separator facility ISOLDE at CERN. The IS between 16 isotopes in the mass range $202 \leq A \leq 222$ and the hfs of 7 odd-A isotopes were determined in the transitions $7s[3/2]_2 - 7p[5/2]_3$ (745 nm) of Rn I. The nuclear spins and moments, as well as the observed inversion of the odd-even staggering for $^{218-222}$Rn, can be associated with the effects of octupole instability around N = 134.

1. Introduction

A region of special interest for the study of nuclear moments and charge radii is localized beyond the last known magic numbers Z = 82 and N = 126. The recent discussion on these nuclei has been raised by the theoretical /1,2/ and experimental /3,4/ postulation of a nearly stable octupole deformation of the nuclei around Z = 88 - 90 and N = 134 - 136 (Ra-Th region). In this context the hyperfine structure (hfs) and isotope shift (IS) of long chains of radium (Z = 88) /5,6,7/ and francium (Z = 87) /8/ isotopes have been studied recently, yielding from the nuclear spins, magnetic dipole and electric quadrupole moments and the changes of the mean square charge radii several hints of an intrinsic reflection-asymmetric nuclear shape.

We have carried out hfs and IS studies on the heaviest noble gas radon (Z = 86) in order to localize the borders of this region of unusual nuclear ground state behaviour towards the proton-magic heavy lead isotopes (Z = 82). Up to now we have investigated 16 isotopes in the mass range $202 \leq A \leq 222$ with a gap between A = 212 and 218, due to the short half-lives of these isotopes ($\tau_{1/2} \approx 0.3$ µs - 25 ms).

2. Experiment

The measurements have been carried out by collinear fast-beam laser spectroscopy using the set-up installed on-line with the mass separator facility ISOLDE at CERN. The radon isotopes are produced by proton-induced spallation of thorium in a ThO_2 or ThC_2 target and ionized in a plasma discharge ion source. The production yield of radon and the details of the target-ion source assembly are given in /9/. After acceleration to 60 keV and isotope separation, the

Contribution to the 7th International
Conference on Hyperfine Interactions,
Bangalore, 8-12 September 1986

(To be published in Hyperfine Interactions)

ion beam is transmitted to the experimental set-up.

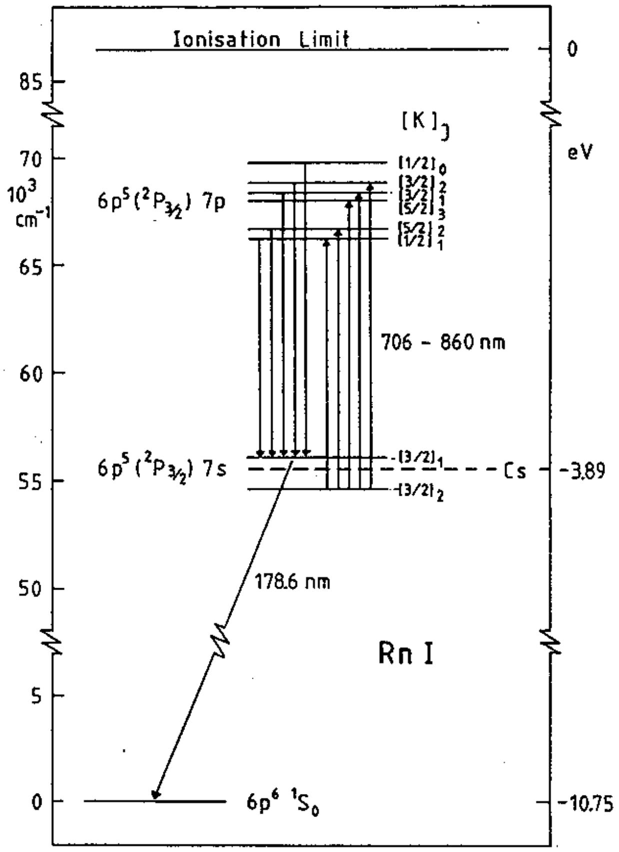

Fig.1. Part of the level scheme of Rn I, showing the population and excitation of the metastable 7s[3/2]$_2$ level.

The method of collinear fast-beam laser spectroscopy is well known and has been described in detail, e.g. in /10/. Owing to the fast-beam properties, it combines the features of high sensitivity and high resolution which are important for systematic measurements on radioactive isotopes. A further advantage is essential for the optical spectroscopy on the noble gas elements: The population of metastable states in a near-resonant charge-exchange process avoids the necessity of an excitation from the atomic or ionic ground state, which in all cases requires far UV photons. This situation is illustrated in Fig. 1. The charge exchange with cesium atomic vapour predominantly populates the $6p^5 7s$ states of Rn I, of which 7s[3/2]$_2$ is metastable. The optical excitation is then carried out in the transition 7s[3/2]$_2$ - 7p[3/2]$_3$ at λ = 745 nm. The optical resonances are detected by the standard procedure of counting the re-emitted fluorescence photons. The hfs spectra are taken by Doppler tuning of the effective laser frequency in the rest frame of the fast atoms. A typical example for the isotope ^{207}Rn (I = 5/2) is given in Fig. 2. Twelve of the expected 14 hfs

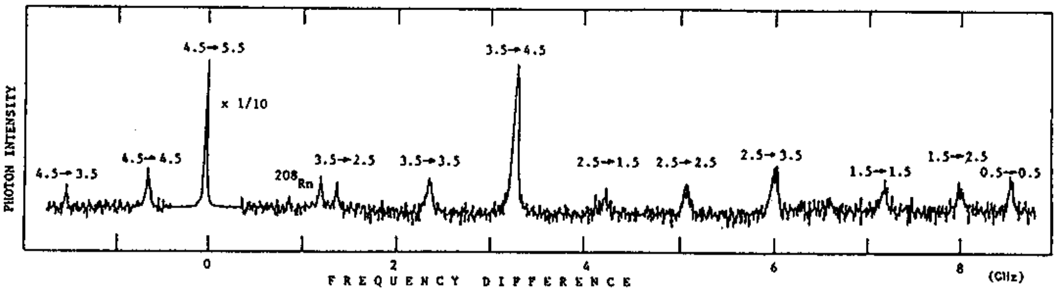

Fig.2. Fluorescence spectrum of ^{207}Rn ($T_{1/2}$ = 9.3 m, I = 5/2) in the transition $7s[3/2]_2$ - $7p[5/2]_3$. The values of the total angular momenta $F_g \rightarrow F_e$ are indicated.

components are clearly resolved, and in addition the contamination from the neighbouring isotope ^{208}Rn in the beam gives rise to a strong signal. The nuclear spin I, the hfs factors A and B of both states involved in the transition and the centers of gravity for the odd isotopes are determined by fitting the peak positions with the hfs formula.

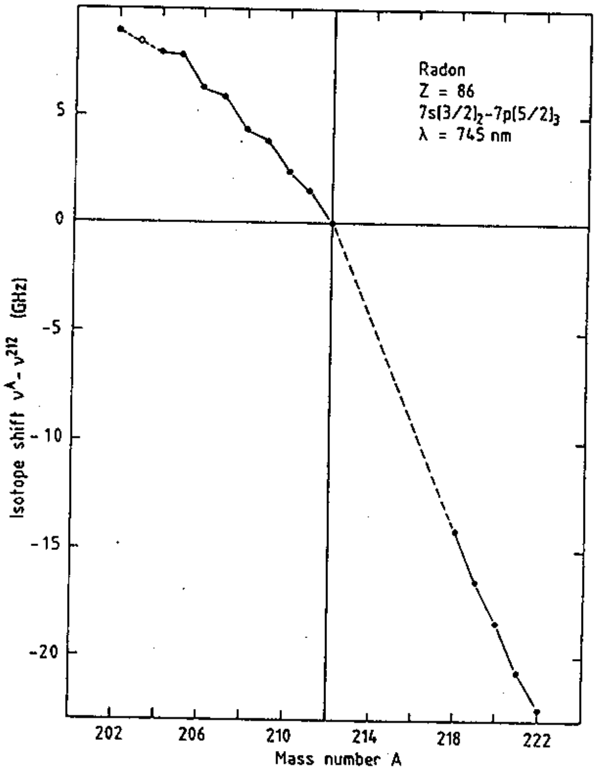

Fig.3. IS in the 745 nm line, relative to the reference isotope ^{212}Rn. For A = 203 only the isomer ^{203m}Rn (I = 13/2) is indicated.

3. Optical isotope shift

The IS, i.e. the differences of the centers of gravity to the reference isotope ^{212}Rn with the magic neutron number N = 126 are shown in Fig. 3. For the sake of clearness the individual hfs components of the odd-A isotopes are omitted. In the spectrum of ^{203}Rn only the components from the I = 13/2 isomer could be analysed so far because of the poor statistics. The influence of the neutron-shell closure at N = 126 gives rise to the kink observed in the trend of the IS which are small below and large above the shell closure. For the light odd-A isotopes ^{205,207,209,211}Rn the usual strong odd-even staggering, corresponding to staggering parameters of $\gamma \leq 0.4$, is observed. This behaviour is explained by smaller quadrupole correlations in the odd-neutron nuclei compared to their even neighbours. This "normal" trend is inverted for the heavy odd-A isotopes ^{219}Rn and ^{221}Rn, similarly to the corresponding isotopes of Ra and Fr /6,7,8/. This phenomenon has been connected with the occurence of strong octupole correlations, which may develop to a nearly static deformation of odd-A isotopes by polarization effects from the unpaired neutron.

4. Hfs, nuclear spins and moments

The A and B factors and the nuclear spins, determined unambigously in the fitting procedure, are listed in Table 1.

Table 1
Nuclear spins and hfs interaction constants of radon isotopes evaluated from the measurements in the transition $7s[3/2]_2$ - $7p[5/2]_3$ (λ = 745 nm) of Rn I. Preliminary magnetic moments are included.

A	I	$7s[3/2]_2$		$7p[5/2]_3$		μ_I
		A (MHz)	B (MHz)	A (MHz)	B (MHz)	(n.m.)
203m	13/2	-471.9(6)	-5904.1(6.1)	-94.9(3)	-5655.5(5.9)	-0.94
205	5/2	1024.6(8)	-287.(12.)	205.5(4)	-276.(10.)	0.79
207	5/2	1042.3(6)	-1014.7(3.1)	208.5(3)	-968.9(4.3)	0.80
209	5/2	1071.9(5)	-1433.6(2.7)	214.6(3)	-1370.7(3.3)	0.82
211	1/2	3841.9(2.5)	-	773.8(1.3)	-	0.59
219	5/2	-564.9(1.2)	-5316.(10.)	-112.2(7)	-5079.(12.)	-0.43
221	7/2	-18.4(6)	2184.4(4.4)	-3.75(40)	2082.5(6.0)	-0.02

4.1. Neutron-deficient isotopes

^{211}Rn has the spin I = 1/2, arising from a $p_{1/2}$ neutron as in the isotones ^{205}Hg /11/, ^{207}Pb /12/ and ^{213}Ra /5/. The magnetic moments μ_I of these isotopes are constant within 3 % and very close to the Schmidt value of 0.64 n.m., according to the general rule that the $p_{1/2}$ moments are not affected by first-order core polarization. Therefore we can use their average value for a preliminary calibration of the magnetic hyperfine fields in the radon atom and determine all other magnetic moments from the ratios of the A factors. These magnetic moments are included in Table 1, assuming an accuracy of 5 %. Hfs anomaly effects are expected to be considerably smaller /5/ and can be neglected. The spin values I = 5/2 for ^{205,207,209}Rn, together with the magnetic moments, confirm the assignment of a $f_{5/2}$ shell model state of which successive filling is also observed in the isotones of Ra, Po and Pb. The isomer in ^{203}Rn arises from $i_{13/2}$.

4.2. Neutron-rich isotopes

The spins and magnetic moments of the two heavier isotopes ^{219,221}Rn can be explained only by the inclusion of nuclear deformation. ^{219}Rn shows I = 5/2 equal to the isotone ^{221}Ra, but a considerable larger magnetic moment. Assuming the main Nilsson component [633 5/2] the value of $\mu_I = -0.43$ can be reproduced in a particle-plus-rotor model for deformations of about $\beta_2 \simeq 0.1$ without inclusion of contributions from odd multipole deformations /5/. However, the value of I = 7/2 for ^{221}Rn, different from ^{223}Ra (I = 3/2), is difficult to interpret. Corresponding Nilsson orbitals with $\Omega = 7/2$, arising from the $g_{9/2}$ or $i_{11/2}$ shell are much higher than the Fermi level for reasonable quadrupole deformations of $\beta_2 \simeq 0.1 - 0.15$ /1,2/. A sufficient reduction in energy may occur by the coupling with the $\Omega = 7/2$ orbital from the opposite-parity $j_{15/2}$ shell via the octupole mode /2/. Thus the spin I = 7/2 for ^{221}Rn, which is not observed in the ground states of the radium isotopes, may be due to a reduced quadrupole in combination with an octupole deformation.

A solution to this problem may be found in the understanding of the nearly vanishing magnetic moment $\mu_I = -0.02$ of ^{221}Rn. In addition, the quadrupole moments from the B-factors will allow more detailed comparisons with the pertinent nuclear models.

This work was supported by the Bundesministerium für Forschung und Technologie and the Deutsche Forschungsgemeinschaft.

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