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STUDIED BY COLLINEAR FAST-BEAM LASER SPECTROSCOPY

R. Neugart and K. Wendt
Institut für Physik, Universität Mainz, Mainz, Fed. Rep. of Germany

S.A. Ahmad¹⁾ and W. Klemp²⁾
EP Division, CERN, Geneva, Switzerland

C. Ekström
Department of Physics, Chalmers University of Technology,
Gothenburg, Sweden

and

The ISOLDE Collaboration
CERN, Geneva, Switzerland

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1) On leave from the Bhabha Atomic Research Centre, Bombay, India.
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The collinear fast-beam laser technique is being used to measure systematically hyperfine structures and isotope shifts of unstable nuclides in the rare-earth region. This brief report gives a general survey of the results obtained for the even-Z elements ^{64}Gd , ^{66}Dy , ^{68}Er and ^{70}Yb , with emphasis on the nuclear spins and moments. They allow a rather complete mapping of the single-particle structure and the development of nuclear deformation in the $N > 82$ region. The spins, magnetic moments and spectroscopic quadrupole moments of $^{159-169}\text{Yb}$ are presented in detail.

1. Introduction

The nuclides in the $N = 82$ region exhibit a change from spherical to deformed nuclear shapes on either side of the $N = 82$ neutron-shell closure. Their behaviour around $Z = 64$ is particularly interesting in view of the suggestion of a proton-subshell closure.

We present here some results of our continuing programme at the ISOLDE facility [1] at CERN to measure systematically hyperfine structures and isotope shifts of elements in the range $^{56}\text{Ba} - ^{70}\text{Yb}$ using collinear fast-beam laser spectroscopy. This technique is distinguished by its high sensitivity and resolution, combined with a high degree of versatility. Our work on the even-Z elements in this region includes the previous experiment on $^{122-146}\text{Ba}$ [2,3], the experiments on the neutron-deficient isotopes of the heavier rare-earths $^{156-176}\text{Yb}$, $^{150-170}\text{Er}$, $^{146-164}\text{Dy}$ and a recent extension to $^{142-160}\text{Gd}$ which is expected to have a semi-magic proton number. These experiments are complemented by an odd-Z case, $^{140-153}\text{Eu}$, which will be presented at a later stage of the data analysis.

The neutron-deficient isotopes of the rare-earth elements were produced in spallation reactions induced by 600 MeV protons in a target of Ta foils. The 60 keV ion beams from the ISOLDE mass separator were directed through the collinear-beam apparatus and neutralized in a charge-exchange cell to form a fast atomic beam. The resonances were recorded by tuning the Doppler shift with an additional voltage and counting the emitted fluorescence photons.

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The nuclear information on mean square charge radii, spins and moments, evaluated from the experimental data, will be discussed separately below.

2. Mean square charge radii

The changes in mean square charge radii, as obtained from the isotope shifts, are displayed in Fig. 1. This differential plot shows the influence of adding neutron pairs within the sequences of the doubly-even isotopes of Ba, Dy, Er and Yb. The droplet-model prediction for spherical nuclei is indicated by the dashed line. Apart from the influence of the neutron-shell closure at $N = 82$, indicating an increase in deformation on both sides of $N = 82$, the influence of the proton-subshell closure at $Z = 64$ manifests itself by the large value of $\delta\langle r^2 \rangle_{88,90}$ in Dy. This irregularity in the isotope shifts was observed earlier in the stable isotopes of Gd, Sm and Nd [4], and is associated with the strong increase in nuclear deformation between $N = 88$ and 90 . The effect becomes less pronounced in the lighter as well as the heavier elements. In Ba and Yb, the step vanishes completely, and there is a smooth transition from spherical to strongly deformed nuclear shapes above $N = 82$. Within this general picture, it is evident that the $Z = 64$ proton-subshell closure, with its stabilizing effect for spherical shapes, plays an important rôle.

Fig. 1 Differential change of the mean square charge radii of even-A barium, dysprosium, erbium and ytterbium isotopes under the addition of neutron pairs, plotted versus the neutron number.

3. Nuclear spins and moments

The nuclear spins and moments, derived from the measured hyperfine structures, add important information on the single-particle structure of the investigated nuclides. The completeness of the present data allows one to follow trends and to map a considerable portion of the nuclear chart in the neutron-deficient heavy rare-earth region. Here, we consider mainly the odd-neutron nuclides of the elements ^{64}Gd , ^{66}Dy , ^{68}Er and ^{70}Yb .

The results for the ytterbium isotopes are given in Table I. The technical aspects of this experiment, including the evaluation of isotope shifts and A-and B-factors of the hyperfine structures, have been described earlier [5]. The spin assignments have been made on the basis of the intensity ratios of the hyperfine components. In the evaluation of the nuclear moments, the known data for ^{173}Yb have been used. The uncertainty in the evaluation of the dipole moments due to the hyperfine anomaly has been taken into account by adding an error of 0.007 n.m. (cf. [3]).

Table I Experimental data on nuclear spins, hyperfine constants in the $6s6p\ ^3P_1$ state from the hfs in the YbI line at 5556 Å, and evaluated nuclear moments.

Mass number	Neutron number	Nuclear spin	Hyperfine constants A (MHz)	B (MHz)	Nuclear moments μ_I (n.m.)	Q_S (b)
159	89	5/2	-589.3(10)	66(4)	-0.366(8)	-0.22(2)
161	91	3/2	-877.7(15)	-303(3)	-0.327(8)	1.03(2)
163	93	3/2	-1003.2(15)	-367(3)	-0.374(8)	1.24(2)
165	95	5/2	769.1(10)	-732(4)	0.478(8)	2.48(4)
167	97	5/2	1002.9(10)	-795(4)	0.623(8)	2.70(4)
169	99	$7/2^6$	$-728(10)^6$ $-730.2(7)$	$-1038(15)^6$ $-1045(5)$	$-0.633(16)$ $-0.635(8)$	$3.52(7)$ $3.54(6)$
169m	99	1/2	4080(4)		0.507(8)	
173	103	$5/2^7$	$-1094.318(35)^8$	$-825.904(85)^8$	$-0.67989(3)^9$	$2.80(4)^{10}$

Fig. 2 Nilsson diagram for odd neutrons close to $N = 82$, calculated with the parameter set $\kappa = 0.05$ and $\nu = 0.20$. The Fermi levels for $N = 83$, 85 and 87 indicate a successive filling of the $f_{7/2}$ neutron shell. In the right part of the figure, experimental data on magnetic dipole moments and spectroscopic quadrupole moments of $I = 7/2$ ground states in $N = 83$, 85 and 87 nuclei (Ba [3]; Ce, Nd and Sm [11]; Gd, Dy and Er [this work]) are compared with the results from the particle-rotor calculations, assuming deformations of $\epsilon = 0.10$ and 0.15 .

The $N = 81$ isotones ^{145}Gd and ^{147}Dy have spin $I = 1/2$ ground states and $I = 11/2$ isomeric states, with nuclear moments well accounted for by the $s_{1/2}$ and $h_{11/2}$ shell-model neutron states. It is interesting to note the change here from the $d_{3/2}$ ground states in the lighter $N = 81$ isotones.

The $N = 83, 85$ and 87 isotones above the neutron-shell closure at $N = 82$ are described essentially by the $f_{7/2}$ shell-model state. Calculations within the particle-rotor model of Larsson et al. [12], assuming small nuclear deformations of the core, account qualitatively for the measured nuclear moments (cf. Fig. 2). The use of the Nilsson model potential parameters derived for the spherical limit [13] is essential for the reproduction particularly of the data on the quadrupole moments.

The nuclear moments of the $I = 3/2$ ground states of the $N = 89$ isotones ^{153}Gd , ^{155}Dy and ^{157}Er indicate permanently deformed nuclear shapes and a description by a mixture of the Nilsson orbitals $[521\ 3/2]$ and $[532\ 3/2]$. For the $I = 5/2$ nuclides ^{145}Ba and ^{159}Yb , on the other hand, there seems to be no straightforward explanation of the measured nuclear moments.

The nuclear spins and moments of the strongly deformed rare-earth nuclides have been discussed in detail previously within the Nilsson model [14]. The

Fig. 3 Comparison between experimental ([11] except for ^{159}Dy , ^{159}Er and $^{161}, ^{163}, ^{165}, ^{167}\text{Yb}$ [this work]) and calculated moments of odd-neutron nuclei in the range $N = 91 - 97$. The experimental data are given at the theoretical equilibrium deformation positions [14]. The dominant Nilsson orbitals are indicated; in the case of the $N = 95$ isotones the orbital $[521\ 3/2]$ is associated with ^{159}Gd , $[642\ 5/2]$ with ^{161}Dy and $[523\ 5/2]$ with ^{163}Er and ^{165}Yb .

addition of the present experimental data, and the refined calculations within the particle-rotor model, including a number of orbitals close to the Fermi surface, have however resulted in a more complete picture and a better understanding of the nuclear single-particle structure in this region.

The nuclear moments of the odd-neutron nuclei in the range $N = 91 - 97$ are compared in Fig. 3 with the results from the particle-rotor calculations using the $A = 161$ potential parameters $\kappa = 0.0637$ and $\mu = 0.425$, and the g-factors $g_R = Z/A$, $g_S = 0.6 \cdot g_S^{\text{free}}$ and $g_J = 0$. The agreement between experiment and theory is shown to be quite good.

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