Formes nucléaires et physique atomique

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FORMES NUCLEAIRES ET PHYSIQUE ATOMIQUE

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Résumé

Ce cours donne une introduction au déplacement isotopique et aux variations du rayon quadratique moyen de charge pour des noyaux instables, mesurés par des méthodes optiques laser. S'y ajoutent spins et moments statiques mesurés par les memes procédés atomiques. Les résultats présentés servent à démontrer quelques aspects récents, mais aussi à caractériser les régions de formes rigides se pretant à des modèles nucléaires cohérents au contrast des formes instables et dont la bonne compréhension fait à présent défaut.

Abstract

This lecture presents a introduction to the optical isotope shift and the mean squared charge radius of unstable nuclei, observed by laser optical methods which also give access to spins and static moments. Some recent aspects of experimental results are given. A survey on regions of stable shapes well described by nuclear models is shown as contrast to unstable shapes, which are still difficult to understand from isotope shift and static moments.

Introduction

Until now experimental nuclear physics is always performed in presence of atomic electrons in targets, heavy ions and radioactive sources. Generally the large difference in hadronic and electronic binding energies allow to separate nuclear and atomic structure to a reasonable extent. In special cases however the nuclear structure can be observed by laser spectroscopy as minute changes in the atomic system. The interest in such a indirect nuclear study relies on the high sensitivity of laser spectroscopy. Using procedures on-line with the production it is possible to collect informations directly related to nuclear shapein a large region of the valley of β-instability[1]. In principle this on-line laser spectroscopy of radioactive atoms allows to study nuclear groundstates and isomeric states as far as their lifetime and the production process allow to prepare sufficient amounts of atoms in the apropriate electronic states.

Hyperfine Structure and Isotope Shift

The nuclear structure information transferred to the atomic shells is visible in the hyperfine structure (HFS) of atomic levels and the optical transitons between them and the isotope dependent shift (IS) of some spectral lines. Formally the hyperfine energy can be expressed as products of atomic and nuclear factors

$$(1)\quad W_{HFS} = A \cdot K/2 + B \cdot (3K(K+1) - 4I(I+1)J(J+1))/8I(2I-1)(2J-1)$$

with $K = F(F+1) - I(I+1) - J(J+1)$

and $A = \mu_I/I \cdot \langle H(0) \rangle / J \qquad B = eQ_s \cdot \langle \varphi_{zz} \rangle$

where I,J are nuclear and electronic spins, u_I, eQ_s are the static nuclear magnetic dipole and electric quadrupole moments projected on the nuclear spin I axis and finally $\langle H(0) \rangle$, $\langle \varphi_{zz} \rangle$ represent the atomic magnetic field and the electric field gradient projected on the spin J axis.
For a pure electronic state $|nlj\rangle$ the magnetic A factor reads

$$(1a)\quad A_{nlj} = \mu_I/I \cdot \mu_o/4\pi \cdot 2\mu_B\, l(l+1)/j(j+1) \langle r^{-3} \rangle_{nl} \times F_j(Z_i)\,(1-\delta)\,(1-\varepsilon)$$

for orbital momentum $l \neq 0$ and

$$(1a^*)\quad A_{ns} = \mu_I/I \cdot \mu_o/4\pi 2\mu_B\, 8\pi/3 \langle \Psi^2(0) \rangle_{ns} \times F_{1/2}(Z)\,(1-\delta)\,(1-\varepsilon)$$

for orbital momentum $l = 0$

where the factors in the lower line represent the relativity correction for the atomic factor $\langle r^{-3} \rangle_{nl}$ or $\langle \Psi^2(0) \rangle_{ns}$ then the Breit- Crawford- Schawlow correction for the electron density by the finite nuclear size and finally the Bohr- Weiskopf effect for the extended nuclear magnetisation.
The atomic factors may be given by the semiempirical Goutsmit Fermi Segrè relations

$$(1r)\quad \langle r^{-3} \rangle_{nl} = a_o^{-3} Z_i Z_a^{\,2}/n_{eff}^{\,3}$$

$$(1s)\quad \langle \Psi^2(0) \rangle_{ns} = Z_i Z_a^{\,2}/a_o^{\,3}\,(1 - d\sigma/dn)/n_{eff}^{\,3}$$

with $n_{eff} = n - \sigma = (Ry \cdot Z_a^{\,2}/E_n)^{1/2}$

The B factor containing the electric quadrupole moment is expressed by

$$(1b)\quad B_{nlj} = eQ_s \cdot e/4\pi\varepsilon_o\,(2j-1)/(2j+2) \langle r^{-3} \rangle_{nl} R_{lj}(Z_i)$$

$$(1b^*)\quad Q_s^{corr} = Q_s/(1-R)$$

with the relativity correction $R_{lj}(Z_i)$ and the so- called Sternheimer correction R for the quadrupole core polarisation of the inner atomic shells.

The optical isotope shift IS is the sum of a purely atomic part called mass shift and a nuclear part called volume shift.
The first part is a consequence of the nuclear motion in the center of gravity system. In one lepton systems this (normal) mass shift is expressed by the reduced mass but in many electron atoms the nuclear cinetic energy is influenced additionally by electron correlations giving rise to the specific mass shift, which cannot be calculated with sufficient confidence to isolate the volume part of the IS. Instead a comparison with IS in other transitions, the so-called King plot must be used.
The volume shift is described by

$$(2)\quad dE_{vol} = 2\pi/3\, Ze^2 <\psi_s(0)>^2 d<r^2>_{ch}^{AA'} f(Z)$$

where $<\psi_s(0)>^2$ is the electron density at the nucleus

and $d<r^2>_{ch}^{AA'}$ the variation of the rms charge radius between the isotopes A and A'.

For heavy elements this volume shift is dominating the IS, whereas the mass shift prevail in light elements. The higher moments of the charge radius also entering the IS of heavy elements are discussed in the literature.

Static Moments and Nuclear Shape

The nuclear shape and more precisely the nuclear deformation influences indirectly spin and magnetic moment but the deformation parameter β can be directly measured via the quadrupole moment. The intrinsic quadrupole moment is given by

$$(3)\quad Q_0 = 6/(5(5\pi)^{1/2}) <r_0^2> Z\beta(1+0.36\beta)$$

whereas the spectroscopic moment Q_s measured in the HFS is the projection of the intrinsic quadrupole moment on the spin axis. In strong coupling this reads

$$(3a)\quad Q_s = Q_0 I(2I-1)/(I+1)(2I+3)$$

The mean squared charge radius is also dependent on deformation

$$(4)\quad <r^2> = <r_0^2>((1+5/4\pi\cdot\textstyle\sum_i <\beta_i^2> + 0.3<\beta^3>\cos\gamma(1-4\sin^2\gamma))$$

Here the scalar β^2 includes static and dynamic contributions to be summed over all modes i. In the case of triaxial nuclei a moderate term containing the parameter γ must be respected.

Collinear Laser Spectroscopy

This experimental method has been described in its principle many times. An ion beam from an on-line mass separator is neutralized in an alcali vapour and merged with a laser beam. At resonance the fluorescence light is observed with a photon counting photo-multiplier.

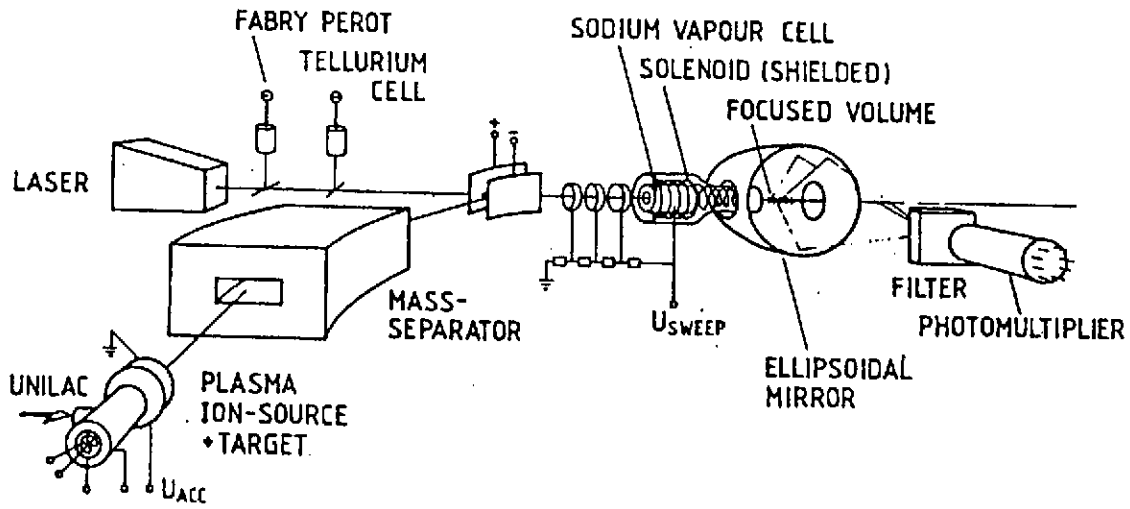

Fig. 1: Scheme of a collinear set-up at the GSI mass separator[2)]
The ISOLDE set-up[3)] differs in details only

After the accelleration by the mass separator (54kV) the longitudinal velocity spread is reduced to

$$(5) \quad dv_{beam} = 1/2\, dv_{source} \cdot (dE/E)^{1/2}$$

since the energy spread is conserved during accelleration

$$(6) \quad dE = 1/2\, M\, (dv_{source})^2 = M\, (dv_{beam} \cdot v_{accell})$$

By this the residual Doppler width in collinear exitation of the resonance fluorescence is close to the natural width. These narrow resonances with the single mode dye laser are Doppler shifted by $f_{optical} \cdot v_{accell}/c$ and can be tuned easily via a sweep voltage at the charge exchange cell. Many variations of this experimental method have been adopted in special cases and are described in the literature[1)]. A combination of collinear spectroscopy with a pulsed laser ion source has been proposed as well[4)].

Experimental results

As an illustration of the behaviour of the charge radii one may discuss the rubidium[5)] and strontium[6)] isotope chain, both crossing the N = 50 neutron shell at almost spherical shape and extending to strongly deformed neutron deficient and neutron rich nuclei.
The agreement between experimental charge radii analyzed via relation (4) and microscopic calculations is restricted to nuclei with stable spherical or strongly deformed shape. In the transitional region the experiments show larger rms charge radii than can be reproduced by calculation, even when surface vibrations are added to the static deformation.

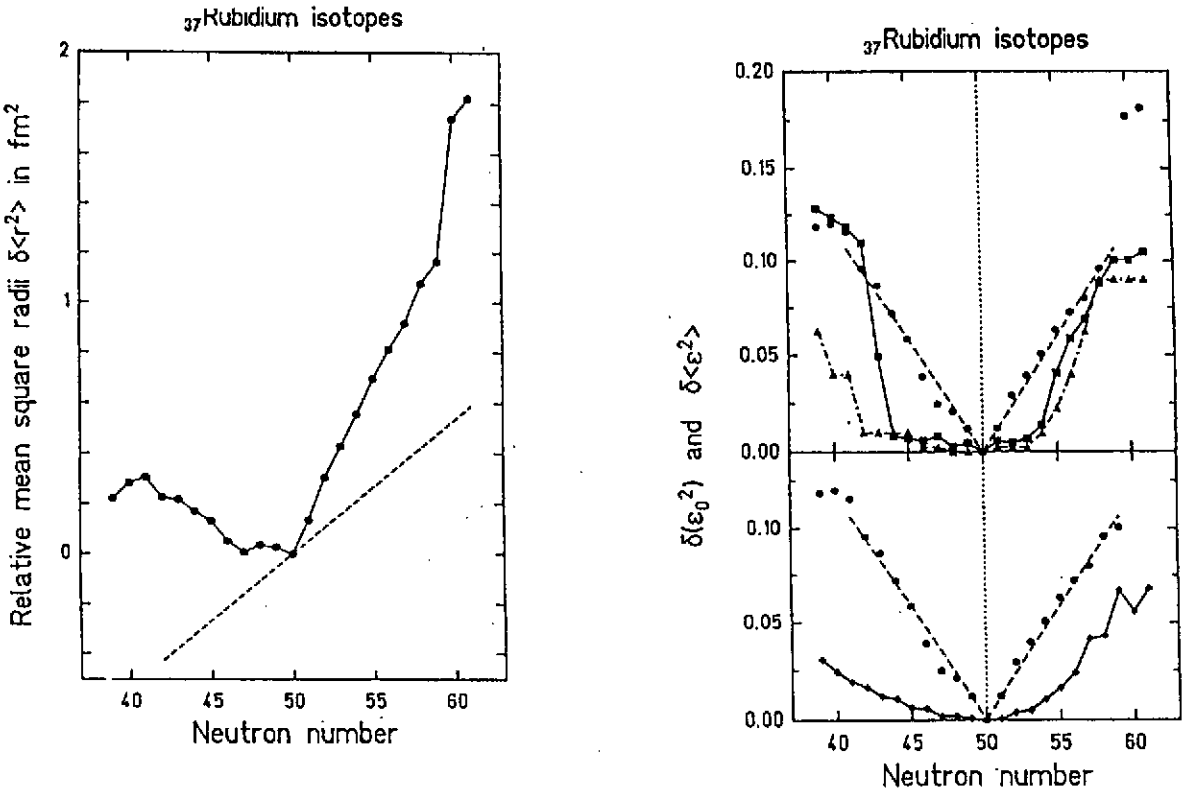

Fig. 2: Isotope shift data on Rb shown with the spherical droplet model (dotted line) on the left part. The deformation contribution according to (4) is compared with various model calculations. Agreement is found for N = 50 and N > 58 only.

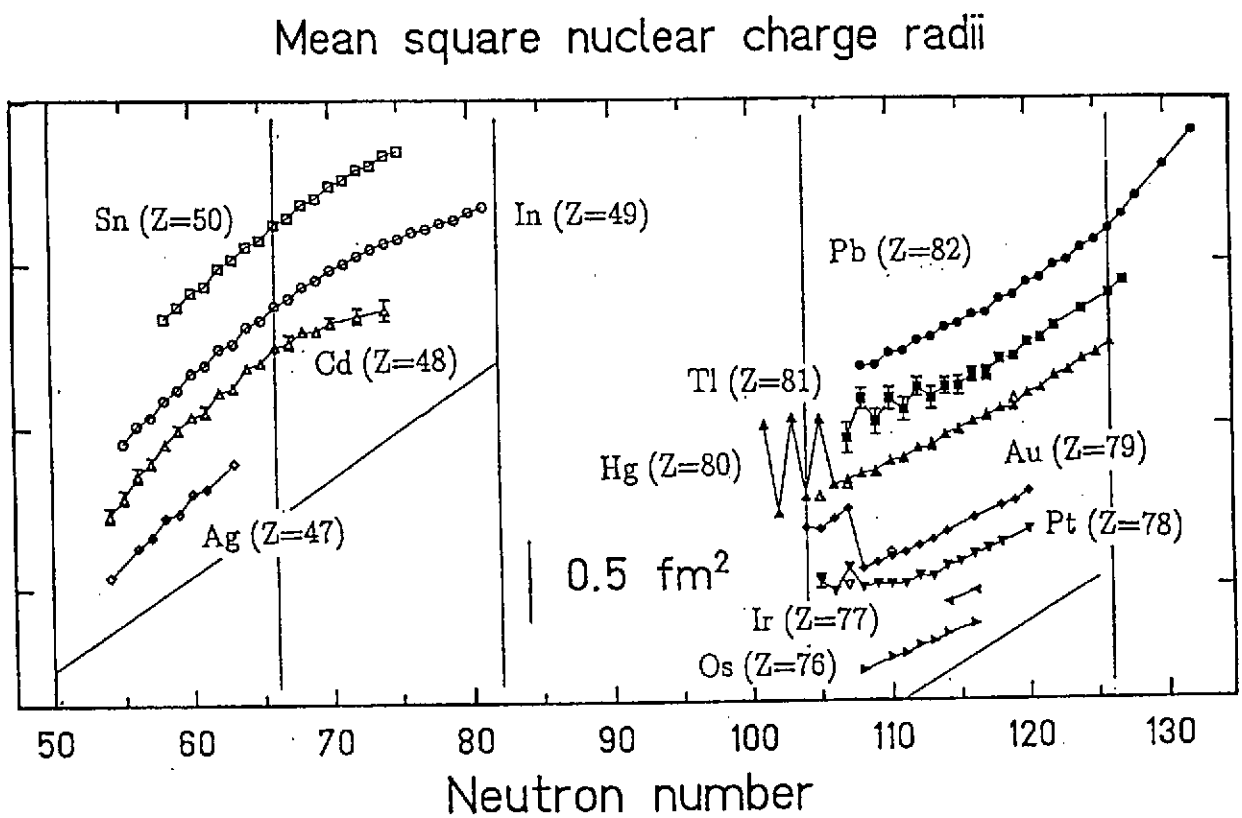

Fig. 3: Rms Charge radii close to the magic proton numbers Z = 50,82 The parabolic slope between N = 50 - 82 is missing for the heavy elements. Shape isomerism and instability is seen instead.

The enhancement of the rms charge radius away from magic numbers gives rise to the parabolic slope of the isotope shift at magic proton numbers and is well studied for tin, indium and partly cadmium and silver[7]. For heavy elements at Z = 82 however shape softness and instability and the well kown shape isomerism for light mercury isotopes is observed[8]. At the same time any regular "parabolic" trend in the rms radii is missing in contrast to all lighter magic proton shells.

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