# Isotope shift in erbium I by laser-atomic-beam spectroscopy

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High-resolution laser spectroscopy has been performed on an atomic beam of natural erbium isotopes. The isotope shift in the 582.7 nm transitions $[4f^{12}6s^2(^3H_6)\rightarrow 4f^{12}(^3H_6)6s\,6p(^3P_1^0)J=7]$ for the pairs of $^{162,164,166,167,168,170}$Er I was obtained with an accuracy of about 4 MHz. Relative changes of mean-square nuclear charge radii $\delta\langle r^2\rangle$ for these isotopes were thus deduced. The isotope shift in $^{167}$Er, obtained from the well-resolved hyperfine components, shows similar even-odd staggering effect in $\delta\langle r^2\rangle$ found in the nearby elements.

The optical isotope shift (IS) in atomic spectra has been studied for many years.[1] In the region of medium-heavy and heavy elements, it has provided important information on the changes of the size and the shape of the nuclear charge distribution. Recent development of tunable high-resolution dye lasers has enabled us to resolve well the hyperfine structure of less abundant isotopes including radioactive nuclei far from stability, thus giving accurate data on the changes in mean-square nuclear charge radii $\delta\langle r^2\rangle$ for the long chain of odd as well as even isotopes.[2]

The isotope shift between even isotopes in natural erbium I has been studied by a number of investigators with the method of interferometry.[3–6] Also, $^{167}$Er I has been studied by Haynes and Ross with the interferometric method.[7] However, they did not resolve the hyperfine components and deduced the isotope shift only from the two complexes due to the unresolved hyperfine structure components.

Recently the hyperfine structure ($^{167}$Er) and the optical isotope shift of natural Er I isotopes have been measured by a number of authors;[8–13] the laser-atomic-beam spectroscopy on the transitions $4f^{12}6s^2$-$4f^{12}6s\,6p$ and $4f^{11}5d\,6s^2$ has been performed by Pfeufer *et al.*,[10] and on the transitions $4f^{12}6s^2$-$4f^{11}5d\,6s^2$ and $4f^{11}5d\,6s^2$-$4f^{11}5d\,6s\,6p$, by Bernard *et al.*[12] Relative values of the changes in mean-square nuclear charge radii $\delta\langle r^2\rangle$ in some transitions have been thus evaluated by Bernard *et al.*[12] In addition to natural Er I isotopes, Neugart *et al.*[13] also measured the isotope shift in radioactive Er ($150\leq A\leq 160$) isotopes with the collinear fast-beam laser spectroscopy.

In the present study, hyperfine components of $^{167}$Er in the 582.7 nm transition

$$[4f^{12}6s^2(^3H_6)\text{-}4f^{12}(^3H_6)6s\,6p(^3P_1^0)J=7]$$

were resolved with high-resolution atomic-beam laser spectroscopy, and isotope shift between the pairs of $^{162,164,166,167,168,170}$Er I was measured with an accuracy of about 4 MHz. The isotope shift in $^{167}$Er was obtained from the well-resolved hyperfine components. These results provide new accurate data on the changes of the values of $\delta\langle r^2\rangle$ from the 582.7 nm line which has not been investigated by Bernard *et al.*[12] The isotope shift in the 582.7 nm transition has been measured by Neugart *et al.*[13] However, no numerical data have yet been published. In this Brief Report the experimental results on the isotope shift and the hyperfine structure of $^{167}$Er are presented and the relative $\delta\langle r^2\rangle$ values evaluated are compared with those for the other transitions by Bernard *et al.*[12]

The atomic beam of natural erbium was produced by resistance heating of an erbium-loaded Ta oven with a 1 mm diameter orifice, and was intersected orthogonally by the light from a tunable single-mode ring dye laser, pumped by a continuous-wave (cw) Ar laser (Spectra Physics Model 380 A and 164, respectively). The laser light of 582.7 nm wavelength was tuned to the transition from the ground state $[4f^{12}6s^2(^3H_6)]$ to the excited $[4f^{12}(^3H_6)6s\,6p(^3P_1^0)J=7]$ state.[14] The output power of 10—50 mW was obtained in the present experiment with a dye of Rhodamine 6G. The Ta oven was heated to about 1500 °C to get the atomic beam with enough signal-to-noise ratio. The atomic beam was collimated by a slit at 8 cm above the oven to reduce the Doppler broadening in the direction of the incident laser light. The fluorescence due to the deexcitation of the $6s\,6p(^3P_1^0)J=7$ state was detected with a photomultiplier (Hamamatsu R712) in front of which an interference filter and a focusing lens were placed to reduce background lights. The laser frequency was monitored by a Fabry-Perot interferometer (Spectra Physics Model 470) with the free spectral range (FSR) of 2 GHz. Another interferometer of 300 GHz FSR was also used for checking stable laser operation. The signals from these devices were fed to analog-to-digital converters and then read by a microcomputer system which also controlled the laser scan. The scanning rate was about 8 GHz/sec.

A typical fluorescence spectrum measured is shown in Fig. 1. In addition to the strong peaks resulting from the even isotopes, hyperfine components of $^{167}$Er (nuclear spin $I=\frac{7}{2}$) are seen to be well resolved. The observed peak width was about 20 MHz full width at half maximum (FWHM). Final results of the frequency shift were obtained by averaging out many scans. The error of the frequency shift finally obtained was estimated to be about 4 MHz. The isotope shift thus deduced is shown in Table I.

 

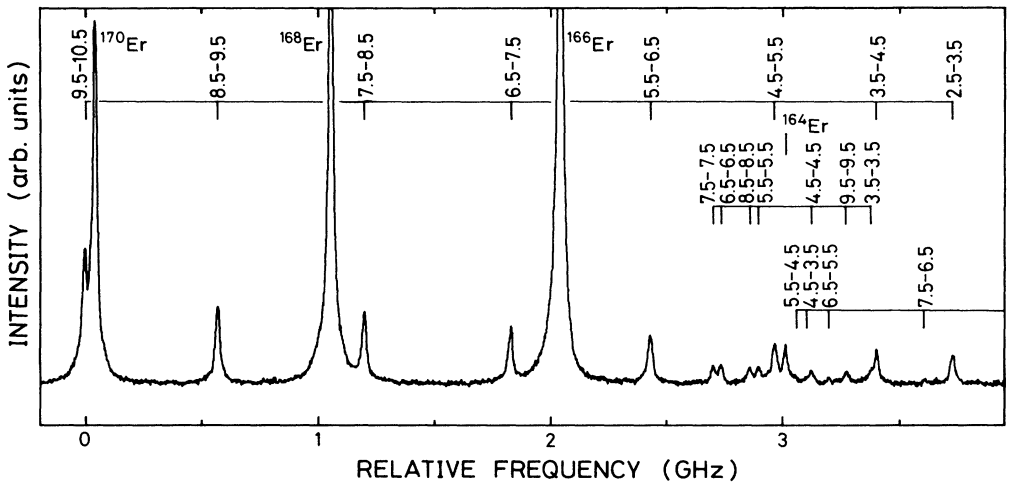


FIG. 1. Typical fluorescence observed as a function of frequency around $\lambda = 582.68$ nm. The hyperfine components of the isotope $^{167}$Er are labeled by the values of the total angular momenta $F$ of the hyperfine levels (lower level − upper level).

The hyperfine constants $A$ and $B$ of the ground and 17 157.307 $cm^{-1}$ excited states, derived with a least-squares fitting method, are shown in Table II and agree well within the errors with the recent high-precision result from the laser-rf double-resonance spectroscopy.[9]

The changes in field shift (FS) between isotopes with mass number $A$ and $A'$ in a transition $i$ with transition frequency $\nu_i$ can be obtained[1] from the observed isotope shift $\delta\nu_i^{AA'}$ by subtracting the contributions of the normal mass shift $\delta\nu_{i,\mathrm{NMS}}^{AA'}$(NMS) and the specific mass shift $\delta\nu_{i,\mathrm{SMS}}^{AA'}$(SMS),

$$\delta\nu_{i,\mathrm{FS}}^{AA'}=\delta\nu_i^{AA'}-\delta\nu_{i,\mathrm{NMS}}^{AA'}-\delta\nu_{i,\mathrm{SMS}}^{AA'} .$$

The NMS is given by

$$\delta\nu_{i,\mathrm{NMS}}^{AA'}=M_i(A'-A)/AA' ,$$

where $M_i=\nu_i/1836.1$. The SMS, which originates from the influence of correlations in the motion of the electrons on the recoil energy of the nucleus, is only qualitatively understood now, and the comparison of the optical shifts with other experimental data such as electronic and muonic x-ray shifts and nuclear binding energies, shows that $s$-$p$ and $s^2$-$sp$ transitions always appear to have small SMS.[1] Especially in transition $s^2$-$sp$, the SMS is usually neglected;[1]

$$\delta\nu_{i,\mathrm{SMS}}^{AA'}=(0\pm0.5)\delta\nu_{i,\mathrm{NMS}}^{AA'} .$$

TABLE I. Isotope shift evaluated from the measurements in the 582.68 nm line of Er I. The common reference isotope is $^{167}$Er (center of gravity of the hyperfine components taken as origin).

| $A$ | $\delta\nu^{167,A}$ (MHz) |
|---|---|
| 162 | 2494.4 (4.6) |
| 164 | 1307.9 (4.4) |
| 166 | 334.5 (3.9) |
| 167 | 0.0 |
| 168 | −644.8 (4.3) |
| 170 | −1626.8 (2.8) |

The field shift between two isotopes thus obtained is related to the changes in mean-square charge radii $\delta\langle r^2\rangle$ in the form

$$\delta\nu_{i,\mathrm{FS}}^{AA'}=E_i f(z)\left[\delta\langle r^2\rangle+\frac{c_2}{c_1}\delta\langle r^4\rangle+\frac{c_3}{c_1}\delta\langle r^6\rangle+\cdots\right],$$

where $E_i$ is the electronic factor given by

$$E_i=\pi a_0^3\Delta\,|\,\psi(0)\,|^2/z .$$

Here $a_0$ is the Bohr radius and $\Delta\,|\,\psi(0)\,|^2$ is the change in the electron charge density at the nucleus for the particular transition. The factor $f(z)$ accounts for the relativistic correction to $E_i$ and for the finite nuclear charge dis-

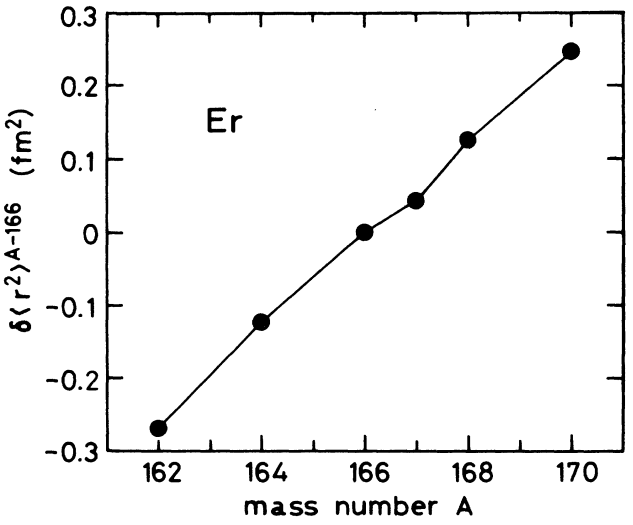


FIG. 2. Change of the mean-square charge radii $\delta\langle r^2\rangle^{A-166}$ in the isotopic chain $^{162-170}$Er as a function of mass number $A$, with $^{166}$Er taken as reference point. The error brackets are well within the solid circles which represent the data points.

TABLE II. Hyperfine structure constants $A$ and $B$ measured by atomic-beam laser fluorescence for the 582.68 nm $^{167}$Er I line.

| State excitation energy ($cm^{-1}$) | hfs constants Present $A$ (MHz) | $B$ (MHz) | Previous[a] $A$ (MHz) | $B$ (MHz) |
|---|---|---|---|---|
| 0 | −120.8 (0.3) | −4546 (11) | −120.487 (1) | −4552.984 (10) |
| 17 157.31 | −172.9 (0.2) | −4457 (14) | −172.5 (0.4) | −4440 (6) |

[a]Reference 9.

tribution. It is given as[1]

$$f(z)=\frac{5}{2}\left[\frac{A+A'}{2}\right]^{1/3} c_{\text{unif}}^{AA'}/[r_0^2(A'-A)] ,$$

where $r_0=1.2$ fm and $c_{\text{unif}}^{AA'}$ is the theoretical isotope shift constant for a uniformly charged nuclear sphere of radius $R=r_0A^{1/3}$, and can be evaluated by using the relation given by Babushkin[15] [corrected for the missing $(n/N)^3$ factor as suggested by Zimmermann[16]].

The absolute values of the $\delta\langle r^2\rangle$ which can be obtained from the above prescription are not reliable unless the related atomic states have pure configurations. Toward the end of the $4f$ shell, the spin-orbit interaction becomes very strong and multiplets become widely spread and interspersed, the levels thus becoming considerably configuration mixed. Unfortunately the spectroscopy of Er I isotopes is very incomplete and it is not yet possible to obtain exact wave functions of the mixed excited states even for the low levels. Because of these circumstances, we evaluated only the relative values of $\delta\langle r^2\rangle$ from the above prescriptions. The isotope dependence of the values of the $\delta\langle r^2\rangle$ relative to $^{166}$Er is shown in Fig. 2 and the relative values of $\delta\langle r^2\rangle$ for the Er isotopes normalized to the $\delta\langle r^2\rangle$ between $^{168}$Er and $^{170}$Er are listed in Table III. Also in Table III are the previous data[1,12] for transitions other than the one for 582.7 nm. The main contribution to the errors in the present data is from the uncertainties in the SMS values.

As seen in Table III, the present data of the relative $\delta\langle r^2\rangle$ values are in good agreement with the recent results obtained from the $4f^{11}5d\,6s^2$-$4f^{11}5d\,6s\,6p$ and $4f^{12}6s^2$-$4f^{12}6s\,6p$ transitions by Bernard *et al.*,[12] thus showing consistent deduction of the relative $\delta\langle r^2\rangle$ values independent of the relevant transition frequencies. The errors of their results are almost the same as ours.

Bernard *et al.*[12] compared their experimental results of the changes in $\delta\langle r^2\rangle$ for stable Er isotopes with the predictions of the liquid drop[17–19] and the droplet models[20–22] and found a strong discrepancy for the odd $^{167}$Er isotope. In many isotopes, the increase in mean-square nuclear charge radius due to the addition of one neutron to an even-$A$ nucleus is considerably less than half the corresponding increase due to the addition of two neutrons.[23] This even-odd staggering is characterized by the parameter

$$\gamma=\frac{2\delta\langle r^2\rangle^{A,A+1}}{\delta\langle r^2\rangle^{A,A+2}} .$$

The ratio $\gamma$ obtained in the present experiment for the Er isotopes ($A=166$) is 0.676(20). The even-odd staggering thus observed in the present measurement shows a similar tendency to those in the neighboring nuclei.[2,13,23]

Even-odd staggering has been attributed in some cases to a staggering in nuclear deformation between the odd and even isotopes,[24–26] to the blocking of ground-state quadrupole vibrations of the nucleus by the odd neutrons,[27,28] and to the blocking of pairing correlations together with core polarization by valence neutrons.[29–31] Since the Er nuclei with neutron numbers larger than 90 are strongly deformed, the even-odd staggering effect observed in $^{167}$Er might be related to the staggering in nuclear deformations.[24–26] It seems not the case, however, for Er; the quadrupole deformation parameters $\beta_2$ for the $^{166}$Er and $^{168}$Er (0.323 and 0.325, respectively) obtained from the Coulomb excitations[32] are almost the same as that for the $^{167}$Er (0.323) from the muonic atom;[33] thus no appreciable even-odd staggering is expected from the difference in nuclear deformations in the present case.

TABLE III. Relative differences in mean-square charge radii $\delta\langle r^2\rangle$ of the Er isotopes normalized to the value between $^{168}$Er and $^{170}$Er.

| Er $A$ $A'$ | Rel.$\delta\langle r^2\rangle^{AA'}$ Present | HS74[a] | BBP[b] |
|---|---|---|---|
| 170–168 | 1 | 1 | 1 |
| 168–166 | 0.997 (17) | 0.98 (3) | 0.984 (15) |
| 166–164 | 0.990 (17) | 1.01 (4) | 0.984 (15) |
| 164–162 | 1.199 (19) | 1.18 (8) | 1.198 (18) |
| 167–166 | 0.337 (8) | 0.50 (3) | 0.3357 (50) |

[a]Reference 1.
[b]Reference 12.

More detailed investigations are thus required for further understanding the behavior of the $\delta\langle r^2\rangle$ in this region.

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