OBSERVATION OF CENTRIFUGAL STRETCHING IN Sm^{152}

D. Yeboah-Amankwah and L. Grodzins
Laboratory for Nuclear Science* and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts

and

Richard B. Frankel
National Magnet Laboratory,† Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received 27 March 1967)

An isomer shift has been observed in the Mössbauer study of the 121.8-keV ($2^+ \rightarrow 0^+$) transition in Sm^{152}. A value of $(\Delta\langle R^2\rangle/\langle R^2\rangle)_{2-0} = (10 \pm 3) \times 10^{-4}$ is deduced, based on isotope shift data for Sm^{152} and Sm^{154}. This value disagrees with present theoretical prediction. In particular, the influence of the β band in Sm^{152} can only account for about 20% of the observed stretching.

In a previous Letter[1] we reported the observation that in the deformed nucleus W^{182}, the mean square radius of the first 2^+ state was greater than that of the 0^+ ground state. The observation was based on an unambiguous measurement of the isomer shift (I.S.) in the Mössbauer spectrum between two valence states of W. A meaningful estimate of $\Delta\langle R^2\rangle/\langle R^2\rangle$ for W^{182} was, however, impossible due to the large uncertainties in estimating the electronic contribution $\Delta|\Psi(0)|^2$ to the I.S. Comparison with nuclear models was further complicated by the sparsity of relevant nuclear information for W^{182}.

We report here the observation of the I.S. for the $2^+ \rightarrow 0^+$ transition in Sm^{152}. In this case, $\Delta\langle R^2\rangle/\langle R^2\rangle$ can be reliably estimated from experimental data. Moreover, the rotational and vibrational bands of this pivotal nucleus have been studied in sufficient detail so that a value of $\Delta\langle R^2\rangle/\langle R^2\rangle$ provides a meaningful test of nuclear models. We find that the value of $\Delta\langle R^2\rangle/$

$\langle R^2\rangle$ supports the conclusion that centrifugal stretching is smaller than expected on the basis of the deviations of the energy levels from that of a pure rotor. Only about 20% of the radial change in Sm^{152} is accounted for by β-band mixing.

The experiments were carried out at liquid-helium temperatures with a standard electromechanical Mössbauer drive system, using a time-mode drive for the multichannel analyzer. Special care was taken to build a highly stable system in which the velocity calibration did not vary for weeks at a time. Most of the various source and absorber matrices that were investigated yielded an impractically small effect. A 2^+ valence source of Eu^{152} in CaF_2 and a 3^+ valence absorber $^{152}Sm_2O_3$ gave a single line and a relatively large effect. The 5-mC source was prepared by neutron irradiation, in the MIT reactor, of 0.1 mole% Eu^{151} in the 2^+ valence state in CaF_2 (as determined by spectroscopic analysis).[2] The Mössbauer spectra obtained with this source and a $^{152}Sm_2O_3$ absorber are shown for two velocity ranges in Figs. 1(a) and 1(b). The linewidth is approximately four times broader than natural. The isomer shift is 1.65 ± 0.15 mm/sec and is so large as to be unambiguous. The results for other source and absorber matrices, as well as for Gd^{154} and Gd^{156}, will be presented in a more comprehensive paper.[3]

The I.S. is related to the change in mean square charge radii by

$$\Delta E = \frac{2\pi}{5} Ze^2R^2 \frac{[\langle R^2\rangle_{2^+} - \langle R^2\rangle_{0^+}]}{\langle R^2\rangle}\{L_A - L_S\}, \qquad (1)$$

where we have used the symbol $L \equiv \sum|\Psi(0)|^2$, and S and A stand for source and absorber, respectively.

One can estimate $L_A - L_S$ within an uncertainty of about 30%. The following two approaches have been used:

(1) The I.S. between the 0^+ and 2^+ states of Sm^{152} can be compared with the isotope shift between the 0^+ ground states of Sm^{152} and Sm^{154}. Striganov, Katulin, and Eliseev[4] have measured the latter shift for a number of atomic transitions. The average of the six largest energy shifts between the $4f^65d6s^2$ and $4f^66s^2$ configurations was found to be 41.5×10^{-3} cm^{-1}. The ratio of the I.S. to the isotope shift is, therefore,

$$\frac{\Delta E\,(\text{Isomer})}{\Delta E\,(\text{Isotope})} = 0.13 = \frac{[\langle R^2\rangle_{2^+} - \langle R^2\rangle_{0^+}]_{152}}{[\langle R^2\rangle_{154} - \langle R^2\rangle_{152}]_{0^+}} \frac{L(4f^5) - L(4f^6)}{L(4f^56d6s^2) - (4f^66s^2)}. \qquad (2)$$

The radial change deduced from the isotope shift[5] is

$$\frac{[\langle R^2\rangle_{154} - \langle R^2\rangle_{152}]}{\langle R^2\rangle_{152}} = 1.2\left(\frac{2}{3}\frac{\delta A}{A}\right) = 1.05 \times 10^{-2}.$$

Shielding effects are not very different for similar configurations,[6] so that

$$L(4f^56d6s^2) - L(4f^66s^2)$$
$$\simeq L(4f^56d) - L(4f^6) \simeq L(4f^5) - L(4f^6).$$

Thus,

$$(\Delta\langle R^2\rangle/\langle R^2\rangle)_{2^+-0^+} = (+14 \pm 4) \times 10^{-4}.$$

The uncertainty arises mainly from the assumption about equivalent configurations.

(2) Brix <u>et al.</u>[6] evaluated $L(4f^6) - L(4f^7)$ for Eu by noting that if one combines isotope shift data in Sm together with hyperfine data on Eu and the assumptions about equivalent orbitals indicated above, then

$$L(4f^6) - L(4f^7) = (1.9 \pm 0.4) \times 10^{26} \text{ cm}^2.$$

This relation should represent,[6] to first approximation, the difference $\Delta L(4f^5 - 4f^6)$ for the neighboring Sm. Using this value, we obtain

$$(\Delta\langle R^2\rangle/\langle R^2\rangle)_{2^+-0^+} = (+7.3 \pm 2) \times 10^{-4}.$$

The error is taken from Brix <u>et al.</u> as 30%. The two determinations agree reasonably well and are sufficiently independent to warrant combining them. Therefore, we take as the most reliable estimate for Sm^{152}

$$(\Delta\langle R^2\rangle/\langle R^2\rangle)_{2^+\to 0^+} = (+10 \pm 3) \times 10^{-4}.$$

The stretching may also be deduced from muonic-isomer-shift data[7] in which the energy of the $2^+ \to 0^+$ state, excited by the muon, is compared with the transition energy using a radioactive source. If the observed muonic energy shift is ascribed solely to centrifugal stretching, then $\Delta\langle R^2\rangle/\langle R^2\rangle = (5.8 \pm 0.7) \times 10^{-4}$, in good agreement with the present result.

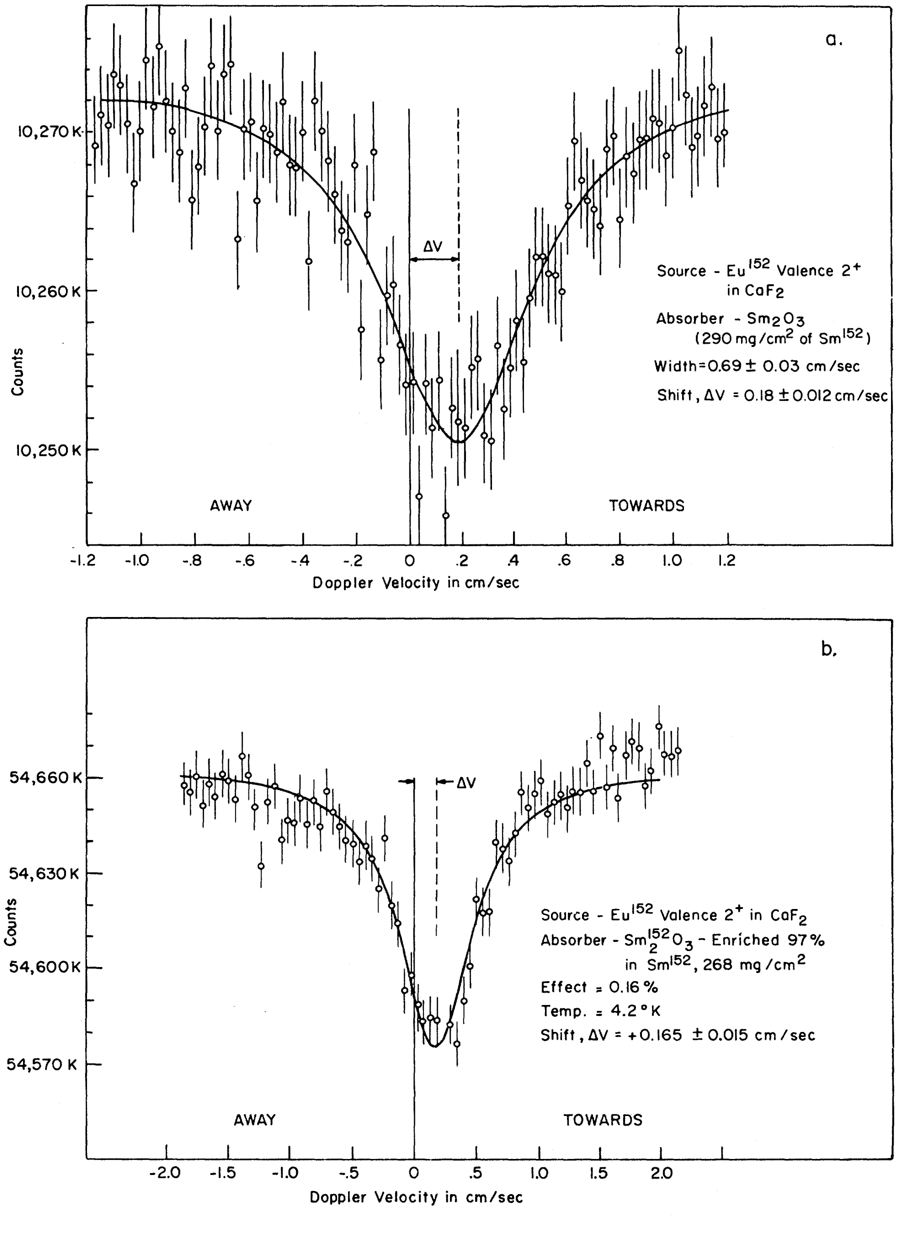

FIG. 1. (a) Mössbauer absorption resonance in the 122 keV, $2^+ \rightarrow 0^+$ transition in Sm^{152}, for a ^{152}Eu^{2+} source in CaF$_2$ and a ^{152}Sm$_2$O$_3$ absorber. (b) Same as (a), except covering a wider velocity range.

The radius change can be related to the change in deformation by assuming that the nucleus is axially symmetric and incompressible. In that case, $\Delta\langle R^2\rangle/\langle R^2\rangle = 5/(2\pi)\beta\Delta\beta$. For Sm^{152}, $\beta = 0.304$,[8] so that $\Delta\beta_{2-0} = 4.2\times10^{-3}$ and $(\Delta\beta/\beta)_{2-0} = 1.4\times10^{-2}$.

The measured value is not in accord with theoretical predictions. Thus we have the following:

(1) Udagawa and Sheline[9] have calculated $\Delta\beta_{2-0}$ for Sm^{152} on the basis of a microscopic model involving Coriolis antipairing forces. They predict $\Delta\beta_{2-0} = 1.3\times10^{-2}$, approximately three times the observed value.

(2) One can estimate $\Delta\beta/\beta$ from the deviations of the ground-state rotational band from that of a pure rotor. The derivation of the relationship between E and $\Delta\beta/\beta$ assumes that the mo-

ment of inertia $\mathscr{I}$ is proportional to β^2. From Ref. 1,

$$E_I = \frac{\hbar^2}{2}\frac{I(I+1)}{\mathscr{I}}\left[1-\frac{\Delta\beta}{\beta}\right]. \tag{3}$$

Using the accurately measured values[10] of the 2^+ and 4^+ excited states of Sm^{152}, 121.78 and 366.44 keV, respectively, $(\Delta\beta/\beta)_{2-0} \approx 4.2\times10^{-2}$, again considerably larger than the observed value.

(3) The rotational-vibrational interaction will cause centrifugal stretching. The largest contribution might be expected to come from the β-band $(K=0)$ mixing, which has been well studied in Sm^{152}. One can estimate the contribution of the β-band mixing to the change in mean radius in a model-independent way in terms of the mixing parameter[11] ϵ, obtaining

$$\Delta\langle R^2\rangle/\langle R^2\rangle = 2\epsilon I(I+1)\rho/Z, \tag{4}$$

where $\rho = \langle I_{\mathrm{gr}}|(\sum_p)(r_p{}^2/R^2)|I_\beta\rangle$, defined by Church and Weneser.[12] From the measurements of the $(0_\beta{}^+ \to 0_{\mathrm{gr}}{}^+)$ transition[13] and the $B(E2)$ values,[11,14] one obtains $\rho \simeq 0.16$ and $\epsilon = (6\pm1)\times10^{-3}$. Thus, $\Delta\langle R^2\rangle/\langle R^2\rangle \simeq 2\times10^{-4}$, only one fifth of the measured value.[15]

We conclude that present theoretical predictions do not explain the observed change in nuclear radius.

We would like to thank J. Weneser for numerous discussions and C. S. Wu for communicating her results to us prior to publication.

---

*Work supported in part through funds provided by the U. S. Atomic Energy Commission under Contract No. At(30-1)-2098.

†Work supported by the U. S. Air Force Office of Scientific Research.

[1] S. G. Cohen, N. A. Blum, Y. W. Chow, R. B. Frankel, and L. Grodzins, Phys. Rev. Letters 16, 322 (1966).

[2] The preparation and analysis of the Eu^{151} grown in the CaF_2 crystal was carried out by W. A. Hargreaves, Optovak, Inc., Brookfield, Massachusetts.

[3] A report of some of the measurements in Sm^{152}, Gd^{154}, and Gd^{156} are contained in D. Yeboah-Amankwah, L. Grodzins, and R. B. Frankel, Bull. Am. Phys. Soc. 12, 580 (1967).

[4] A. R. Striganov, V. A. Katulin, and V. V. Eliseev, Opt. i Spektroskopiya 12, 91 (1962) [translation: Opt. Spectry. (USSR) 12, 171 (1962)].

[5] H. Kopfermann, Nuclear Moments (Academic Press, Inc., New York, 1958), pp. 181, 182.

[6] P. Brix, S. Hüfner, P. Kienle, and D. Quitmann, Phys. Letters 13, 140 (1964).

[7] S. Bernow, S. Devons, I. Duerdoth, D. Hitlin, J. W. Kast, E. R. Macagno, J. Rainwater, K. Runge, and C. S. Wu, preceding Letter [Phys. Rev. Letters 18, 787 (1967)].

[8] B. Elbek, M. C. Olesen, and O. Skilbreid, Nucl. Phys. 19, 523 (1960).

[9] T. Udagawa and R. K. Sheline, Phys. Rev. Letters 16, 325 (1966), and private communication.

[10] Nuclear Data Sheets, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences-National Research Council, Washington, D.C.).

[11] Y. Yoshizawa, B. Elbek, B. Herskind, and M. C. Olesen, Nucl. Phys. 73, 273 (1965); G. G. Seaman, J. G. Greenberg, D. A. Bromley, and F. K. McGowan, Phys. Rev. 149, 925 (1966).

[12] E. L. Church and J. Weneser, Phys. Rev. 103, 1035 (1956).

[13] The ratio of K electrons depopulating the $0_\beta{}^+$ state has been taken from I. Marlund, O. Nathan, and O. B. Nielsen, Nucl. Phys. 15, 199 (1960), who report $N_K(0_\beta{}^+ - 0_{\mathrm{gr}}{}^+)/N_K(0_\beta{}^+ - 2_{\mathrm{gr}}{}^+) = 1.4 \pm 0.15$. G. Ewan and coworkers have recently remeasured this ratio and report (private communication) a preliminary value of 1.8.

[14] According to G. D. Symons and A. C. Douglas, Phys. Letters 24B, 11 (1967), who quote private communications, the measured value of $B(E2)(0_{\mathrm{gr}}{}^+ - 2_\beta{}^+)$ from Yoshizawa, Elbek, Herskind, and Olesen (Ref. 11), should be reduced by nearly a factor of 3, which would reduce the contribution of the β-band-mixing value to $\Delta\langle R^2\rangle/\langle R^2\rangle$ by about a factor of 3.

[15] One can, of course, invoke the weak coupling model to eliminate ρ/Z and obtain

$$\frac{\Delta\langle R^2\rangle}{\langle R^2\rangle} = \frac{3}{\pi}\epsilon I(I+1)\beta_0{}^2 \times\left(\frac{B(E2, 0_{\mathrm{gr}}{}^+ - 2_\beta{}^+)}{B(E2, 0_{\mathrm{gr}}{}^+ - 2_{\mathrm{gr}}{}^+)}\right)^{1/2}_{\mathrm{Intrinsic}} = 5.9\times10^{-4},$$

where we have again used the data of Ref. 11. The near agreement of this value with experiment is probably not too meaningful, but rather points up the fact that the weak coupling model does not yet account for the experimental ρ value in Sm^{152}.