nal momentum distribution of nucleons and light clusters.

Whether either of these distributions is relevant to our fragment-momentum distributions remains to be established. It is possible that the apparent regularities in Figs. 1 and 2 are accidental. Measurements of individual nuclides over a wider range of masses and momenta and for additional reactions would enable us to evaluate the significance of the apparent universal distribution.

We have had useful conversations with R. Blankenbecler, G. E. Brown, G. F. Chew, S. Frankel, A. S. Goldhaber, and A. M. Poskanzer.

[a]Research supported in part by U. S. Energy Research and Development Administration.

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Nuclear Shape Staggering in Very Neutron-Deficient Hg Isotopes Detected by Laser Spectroscopy[a]

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(Received 1 April 1977)

The isotope shifts of ^{188}Hg, ^{186}Hg, and ^{184}Hg in the 2537-Å line have been measured by use of a tunable dye laser at the on-line mass separator ISOLDE at CERN. The results are $\delta\nu(^{188}\text{Hg}-^{204}\text{Hg}) = 35.8(2)$ GHz; $\delta\nu(^{186}\text{Hg}-^{204}\text{Hg}) = 39.4(2)$ GHz; and $\delta\nu(^{184}\text{Hg}-^{204}\text{Hg}) = 43.1(2)$ GHz. These data combined with those obtained by β-radiation–detected optical pumping (β-RADOP) on the odd Hg isotopes yield a huge odd-even staggering for ^{185}Hg of $\gamma = (2\delta\nu^{185/184})/\delta\nu^{186/184} = 13(1)$ which has to be interpreted as nuclear shape staggering.

A sharp onset of nuclear deformation of $\delta\langle\beta^2\rangle^{185/187} = 0.054(5)$ has been discovered between ^{187}Hg and ^{185}Hg by measurements of the isotope shift (IS) $\delta\nu$ with the β-RADOP (β-radiation–detected optical pumping) technique.[1-3] Hartree-Fock[4] and Strutinski calculations[5-7] have interpreted this finding as transition from a slightly deformed oblate shape ($A \geq 187$) to a strongly deformed prolate shape ($A \leq 186$). γ spectroscopy of ^{188}Hg,[8,9] ^{186}Hg,[10-12] and ^{184}Hg[13,14] has yielded evidence for a coexistence and crossing of two bands in these nuclei, one built on an almost spherical shape and one on a strongly deformed shape. The ground states have been found to belong to the vibrational band. Thus a strong odd-even staggering of the nuclear shape occurs in the light Hg isotopes. Recently, this staggering could be explained theoretically.[15-16] However, a quantitative interpretation of the shape transition and of the shape staggering calls for a model-independent measurement of these effects by one and the same observable, e.g., by the change of the nuclear charge radius $\delta\langle r^2\rangle$ as determined by IS experiments. Since RADOP fails in the case of $I = 0$ isotopes, purely optical techniques have to be used. Recently, an experiment on ^{190}Hg was reported which made use of a tunable dye laser in order to measure $\delta\nu$ in the $6s^2\,{}^1S_0$-$6s6p\,{}^3P_1$, $\lambda = 2537$ Å transition.[17] The same technique has now been extended to the lighter even-even isotopes ^{188}Hg, ^{186}Hg, and ^{184}Hg.

The experimental setup will be recalled very briefly (for details see Ref. 17). The dye laser is pumped by a 400-kW pulsed nitrogen laser. Laser light in the ultraviolet is generated by frequency doubling in an ammonium dihydrogen phosphate crystal. The laser beam passes a resonance cell, which is periodically filled with the isotope under investigation. Isotopically pure samples are obtained by the ISOLDE II facility,[18] an isotope separator on line with the 600-MeV synchrocyclotron at CERN. The intensities of the mass-separated ion beam, as obtained in the actual experiment, are given in Table I.

TABLE I. Data of neutron-deficient even-even Hg isotopes obtained by laser spectroscopy and $B(E2)$ measurements, and comparison with theory.

1 X_{Hg}	2 $T_{1/2}$ (min)	3 Yield (ions/sec)	4 $\delta\nu^{204/X}$ (GHz)	5 $\lambda^{204/X}$ (fm^2)[a]	6 $\langle\beta^2\rangle_{X_{Hg}}-\langle\beta^1\rangle_{X-1Hg}$ from IS[b]	7 $\langle\beta^2\rangle_{B(E2,2^+\to0^+)}$ $-\langle\beta^2\rangle_{B(E2,6^+\to4^+)}$	8 $\langle\beta^2\rangle_{X_{Hg}}-\langle\beta^2\rangle_{X-1Hg}$ Theory[c]
^{184}Hg	31/60	4×10^7	43.1(2)	−0.962(4) {106}	−0.060(6)	−0.055(30)	−0.051
^{186}Hg	1.4	2×10^8	39.4(2)	−0.881(4) {97}	−0.053(5)	−0.056(31)	−0.040
^{188}Hg	3.3	2×10^9	35.8(2)	−0.800(4) {88}	−0.002(1)		−0.001
^{190}Hg[d]	20	1×10^9	31.8(2)	−0.711(4) {79}	0.000(1)		

[a] Two different uncertainties are given. The first one includes only the error of the IS measurement (preceding column) and the uncertainty in the mass shift. The second one (quoted in wavy brackets) includes, in addition, the uncertainty of c_1.

[b] Obtained by use of the relation of $\delta\langle r^2\rangle=(3/4\pi)R_0^2\,\delta\langle\beta^2\rangle$.

[c] Frauendorf and Pashkevich, Ref. 15.

[d] Duke *et al.*, Ref. 17; by recent measurements the error could be reduced.

The IS of the spectral line $\lambda=2537$ Å of the radioactive atoms in the resonance cell is measured by tuning the frequency of the laser over the Doppler-broadened absorption profile, and by observing the intensity of the fluorescence light by means of a photomultiplier. A typical scanning pattern for ^{186}Hg is shown in the upper part of Fig. 1. The measurement took roughly 10 min, and about ten sweeps of the frequency of the laser over the absorption line of the isotope under investigation were summed up. To obtain a calibration of the channel numbers in frequency units, the laser beam is sent through a second resonance cell containing stable even-even Hg isotopes and placed in the pole gaps of a magnet. Thus it is possible to shift the Zeeman components into the region of the signal of the unstable isotopes (lower part of Fig. 1), and the IS is determined from the magnetic field values with the help of the known Landé factor.

The results are tabulated in column 4 of Table I, which also includes the data on ^{190}Hg.[17] After correction for the mass shift $\delta\nu_M^{AA'}$, the remaining field shift between the isotopes with mass numbers A and A' can be expressed by a power series in the change of radial moments[3]:

$$\delta\nu^{AA'}-\delta\nu_M^{AA'}=\sum_k c_k^{AA'}\delta\langle r^{2k}\rangle^{AA'}$$
$$=c_1^{AA'}\left\{\delta\langle r^2\rangle+\sum_{k=2}^{\infty}\frac{c_k^{AA'}}{c_1^{AA'}}\delta\langle r^{2k}\rangle\right\}$$
$$=c_1^{AA'}\lambda^{AA'}, \qquad (1)$$

where the radial moments higher than $\delta\langle r^2\rangle$ contribute about −7% of $\delta\langle r^2\rangle$ for the case of Hg (assuming spherical shape). The parameters c_k/c_1 have been computed by Seltzer.[19] The parameter c_1 can be deduced from optical data, and for the pair ^{204}Hg-^{202}Hg it is given by $c_1^{204/202}=-44.9(5.0)$ GHz/fm^2 (Ref. 3), where the slight dependence of c_1 on the mass number involved can be calculat-

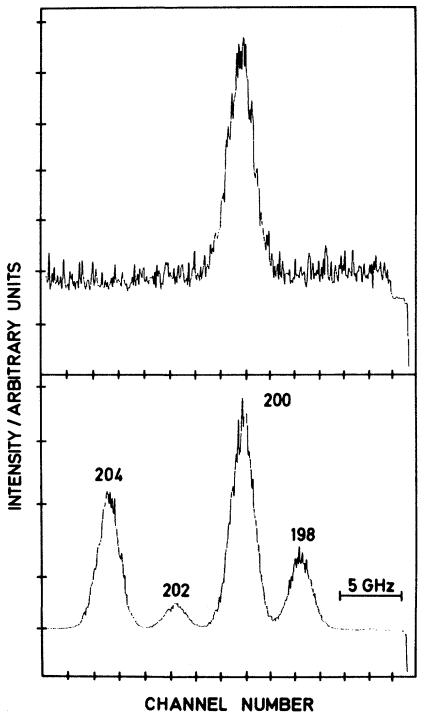

FIG. 1. Intensity of the fluorescent light in the $6s^2\,{}^1S_0$-$6s6p\,{}^2P_1$, $\lambda=2537$ Å line of ^{186}Hg (upper part) and of the σ^+ Zeeman components of the even stable Hg isotopes in a magnetic field of 13.9 kG (lower part) vs the frequency of exciting laser light.

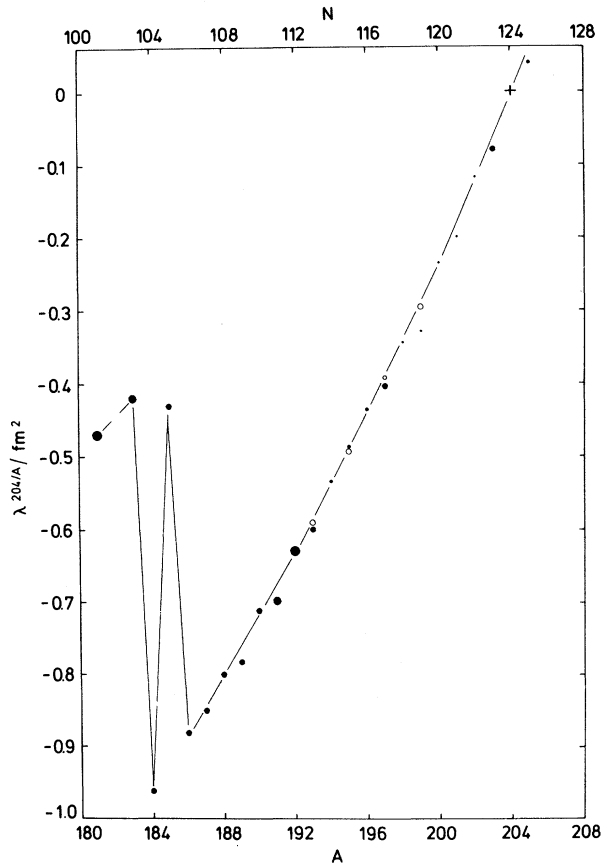

FIG. 2. Changes of charge radii of Hg isotopes relative to ^{204}Hg. $\lambda = \delta\langle r^2\rangle - 1.1\times 10^{-3}\,\delta\langle r^4\rangle + \ldots$. Full dots represent charge radii of ground states, and open circles indicate those of isomers. The statistical errors of λ caused by the experimental uncertainty is given by the diameter of the symbols. An additional (scaling) error of 10% arises from the uncertainty of the electron density at the nucleus.

ed by

$$c_1^{AA'} = [(A + A')/(A'' + A''')]^{-0.125} c_1^{A''A'''}. \qquad (2)$$

The resulting values of $\lambda^{AA'}$ are given in column 5 of Table I, and are plotted (see Fig. 2) versus mass number together with the data obtained earlier by classical optical spectroscopy and RADOP.[20] Apart from small irregularities, the even-even Hg isotopes and the odd ones with $A \geq 187$ follow an almost straight line from the nearly double magic nucleus ^{205}Hg down to ^{184}He, whereas the odd isotopes ^{185}Hg-^{181}Hg show an increase of $\langle r^2\rangle$ of about 0.5 fm^2 in comparison with the neighboring even isotopes. This is a very peculiar behavior, unknown in other mass regions. It can be described by a staggering parameter γ introduced by Tomlinson and Stroke in order to characterize the odd-even effect of the IS in the heavier Hg isotopes.[21] The calculation yields

$$\gamma^{185} = (2\delta\nu^{185/184})/\delta\nu^{186/184} = 13(1), \qquad (3)$$

which is an order of magnitude larger than normally observed, as, for example, in the case of the heavier Hg nuclei. There, the effect is explained as being associated with the zero-point motion of quadrupole vibrations, which produce a mean-square deformation $\langle\beta^2\rangle$ greater for even than for odd isotopes.[22] An alternative explanation is that in even-even isotopes the addition of two neutrons causes a $\delta\langle r^2\rangle$ larger than twice the $\delta\langle r^2\rangle$ of a single low-spin neutron because the pairing of high-spin neutrons is energetically favored.[21] In the case of the Hg nuclei around ^{185}Hg, the large odd-even staggering is caused by the coexistence of two different nuclear shapes which are energetically almost degenerate. Thus, small changes of the potential energy surface, by some few hundred keV, force the nucleus to stagger between the two minima. Energies of this magnitude are easily available because of the strong polarizing power of the $|521\tfrac{1}{2}\rangle$ neutron. Indeed, the odd neutron in ^{181}Hg, ^{183}Hg, and ^{185}Hg belongs most probably to this state,[7] as proved by the determination of the spin and the magnetic moment of these nuclei.[3]

Changes in mean-square deformation from $B(E2)$ measurements in the $6^+ \rightarrow 4^+$ and the $2^+ \rightarrow 0^+$ transition are listed in column 7 of Table I.[11,13] To compare these numbers with those of IS measurements, the dependence of $\langle r^2\rangle$ on the deformation parameter has to be known. Using a simple two-parameter model as a first approximation,[3] the change in deformation between the ground state of the even and that of the neighboring, lighter, odd isotope can be calculated (column 6). Theoretical numbers are available only from the paper of Frauendorf and Pashkevich.[15] However, they did not calculate the experimental quantity $\delta\langle r^2\rangle$, but the less direct deformation parameter $\langle\beta^2\rangle$ (column 8). All numbers are in good agreement.

Very recently, the band head of the deformed band of ^{184}Hg has been found.[14] It decays by an electric monopole transition to the 0^+ ground state with a decay energy $E_\gamma = 375$ keV and a lifetime of $\tau = 0.9(3)$ nsec. Since the $E0$ matrix element is (to a good approximation) an off-diagonal element of the r^2 operator, it represents the dynamic analog to the field shift in atomic spectra.

It is remarkable that just in this exotic corner of the chart of nuclei, experimental data from both sources are available and can hence be related for the first time as shown below.

The transition probability is given by[23]

$$W(E0)_{i\to f} = \Omega\rho^2 \simeq \Omega(Z, E_\gamma)(Z/R_0^2)|\langle\varphi_f|r^2|\varphi_i\rangle|^2, \quad (4)$$

with $R_0 = 1.2A^{1/3}$ fm and $\Omega(Z, E_\gamma)$ tabulated by Hager and Seltzer.[24] As in Ref. 16 and the work of Dickmann and Dietrich,[25] we may write the two physical 0^+ wave functions as mixtures of the pure oblate and prolate solutions:

$$\varphi_i = a\psi_{\text{prol}} + b\psi_{\text{obl}} \text{ and } \varphi_f = b\psi_{\text{prol}} - a\psi_{\text{obl}}. \quad (5)$$

From Eq. (5) it follows immediately that

$$\langle r^2\rangle_{fi} = (a^2 - b^2)\langle r^2\rangle_{\text{obl,prol}} + ab(\langle r^2\rangle - \langle r^2\rangle_{\text{obl}}). \quad (6)$$

With neglect of terms in b^2, the difference $\langle r^2\rangle_{\text{prol}} - \langle r^2\rangle_{\text{obl}}$ can be read from Fig. 2 as $0.5(\lambda^{204/183} + \lambda^{204/185}) - \lambda^{204/184}$. The nondiagonal matrix element $\langle r^2\rangle_{\text{obl,prol}}$ is expected to be small because of the large difference in shape. This is just the usual argument for shape isomerism. With $\langle r^2\rangle_{\text{obl,prol}} = 0$ we obtain

$$\rho = 0.9(1)b. \quad (7)$$

The experimental value for ρ is $0.07^{+0.02}_{-0.01}$ (Ref. 14). Inserted into Eq. (7) it yields

$$b = 0.085(15), \quad (8)$$

which is a quite accurate determination of such a small mixing parameter, provided that the assumption of a negligible contribution of $\langle r^2\rangle_{\text{obl,prol}}$ to the $E0$ transition is justified.

The extension of these measurements down to ^{180}Hg might be made feasible by improving experimental details. It could thus be determined whether the shape staggering extends further, and where the nuclear shape becomes stabilized finally.

The authors are indebted to the members of the ISOLDE Group at CERN for their continuous support and hospitality. One of us (C.D.) was supported by a research grant from the North Atlantic Treaty Organization. This work was sponsored by the Bundesministerium für Forschung und Technologie and the Deutsche Forschungsgemeinschaft.

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[a]This publication comprises part of the thesis of T. Kühl.

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