NUCLEAR ISOMER SHIFT IN THE OPTICAL SPECTRUM OF Hg^{195}: INTERPRETATION OF THE ODD-EVEN STAGGERING EFFECT IN ISOTOPE SHIFT*

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High-resolution optical measurements which we have obtained of the spectra of Hg^{194} (~130 days), Hg^{195} (9.5 h), and Hg^{195m} (40.0 h) now provide us, through the isotope shifts, with a detailed picture of the variation of the mean-square nuclear charge radius, $\langle R^2\rangle$, from neutron numbers $N=114$ to $N=124$. In addition to the spins of Hg^{195} and Hg^{195m} which we have determined to be $\frac{1}{2}$ and $\frac{13}{2}$, respectively, the data display: (1) the increasing polarizability of the nucleus by the odd $p_{1/2}$ neutron as one proceeds from the magic number of neutrons, $N=126$, to the collective region; (2) a trend for a greater effectiveness of odd neutrons in higher angular momentum orbits to distort a parent nucleus; and (3) an interpretation of the "odd-even staggering" effect in the isotope shifts. We recall that when optical transitions involve electrons which in the initial or final state penetrate the nucleus, the spectral lines are sensitive to the variations of the nuclear charge distribution which arise from changes in neutron number. This dependence enters through a factor of approximately $\langle R^2\rangle$. (For heavy nuclei the effect of the mass differences among the isotopes can be neglected.) It has long been known that upon successive addition of neutron pairs, the shifts (or changes in $\langle R^2\rangle$) are nearly equal for even-N isotopes. On the other hand, the addition of an odd neutron to an even-N nucleus usually produces less than one half of the shift produced by the neutron pair; the center of gravity of the spectral line for an odd-neutron isotope lies closer to that of the adjacent lighter even-N isotope than to the center of gravity of the heavier even-N isotope. This is known as "odd-even staggering." Up to the present time, there has been no entirely satisfactory account of this effect, although several possibilities have been suggested.[1]

In Table I we show the results for the isotope shifts in the 2537Å line. These include the present work on Hg^{194}, Hg^{195}, and Hg^{195m}, as well as the data on other mercury isotopes which have been summarized by Bitter.[2] Detailed results of the hfs intervals and nuclear moments, which are not essential to the present analysis, will be published subsequently. Since we are interested here in nuclear properties, we divide out the dependence on the electron wave functions by normalizing to the $N=122$-124 shift. These ratios are given in Table I under "Relative shifts." We also list in Table I the relative shifts for thallium.[3] A diagram of these relative shifts is given in Fig. 1. The meas-

Table I. Isotope-shift data. The Doppler linewidths limit the precision of the measurements to approximately $\pm 0.004\ cm^{-1}$ for the radioactive isotopes and approximately one-tenth of this for the stable isotopes.

Neutron number	Hg isotope shifts in 2537Å line ($10^{-3}\ cm^{-1}$)	Relative shifts Thallium	Relative shifts Mercury	Measured spins	γ
124	-510.77	0.00	0.00		
123	···	0.61	···	(5/2)	(0.78)
122	-336.96	1.00	1.00		
121	-213.80	1.76	1.71	3/2	0.60
120	-160.29	2.10	2.01		
119	- 21.73	2.86	2.81	1/2	0.28
118	0.00	3.00	2.94		
117	91		3.46	1/2	0.68
117*	70		3.34	13/2	0.98
116	137		3.72		
115	210		4.15	1/2	1.14
115*	215		4.17	13/2	1.08
114	308		4.71		

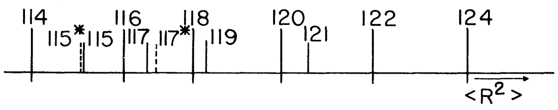

FIG. 1. Variation in $\langle R^2\rangle$ of the nuclear charge distribution as a function of neutron number.

ured spins of the odd mercury isotopes are also included in Table I.

When we build up a nucleus we know that the competition between pairing energy and single-particle energy usually favors the higher angular momentum states for pairs of nucleons. In the case of an odd nucleon there is no pairing energy, so that lower angular momentum states are favored.[4] In the case of mercury the last neutron pairs are believed to go into the $1i_{13/2}$ orbit. From the measured spins of the isomers we know that the odd neutron goes into the $i_{13/2}$ orbit. From Fig. 1 and Table I one is struck immediately by the lack of odd-even staggering for the isomeric states. We can conclude, therefore, that paired or unpaired neutrons in the $i_{13/2}$ orbit produce equal changes in $\langle R^2\rangle$ of the nuclear charge distribution. It can be seen from Fig. 1 that this is usually not the case for neutrons in lower angular momentum states. From the spins given in Table I we can make the following orbit assignments for the odd neutrons: Hg^{195}, Hg^{197}, and Hg^{199}, $3p_{1/2}$; Hg^{201}, $3p_{3/2}$. By extrapolating the other Hg-Tl comparisons, Hg^{203} is expected to produce a shift similar to that of Tl^{204}, and to have a spin of $\frac{5}{2}$.[3] We can characterize these differences between the odd-neutron and pair effects by a staggering parameter γ, where

$$\gamma \equiv \frac{\langle R^2\rangle_{N+1} - \langle R^2\rangle_N}{\frac{1}{2}(\langle R^2\rangle_{N+2} - \langle R^2\rangle_N)}, \quad (N \text{ even}). \tag{1}$$

Figure 2 is a plot of γ as a function of N. We note that for the $p_{1/2}$ neutron the effectiveness in changing $\langle R^2\rangle$ of its parent nucleus increases as we go away from the closed neutron shell, $N=126$. The

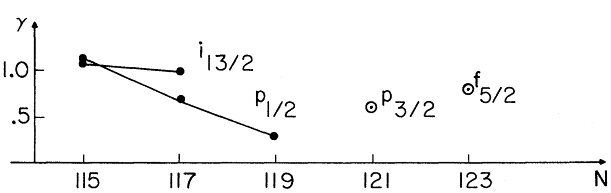

FIG. 2. Variation of the staggering parameter with neutron number.

variations of $\langle R^2\rangle$ are believed to reflect both the change in volume and distortion of the nucleus upon addition of neutrons.[5] Since for an incompressible nucleus we do not expect the volume effect to vary over the range of these isotopes, the increase in γ for decreasing N may reflect a greater polarizability for the nuclei farther away from the closed shell. In shell-model language we can think of this as a decrease in the purity of a single-particle description. It is difficult, however, to reconcile this observation with the facts: The even-N shifts ($i_{13/2}$ pairs) are substantially equal, except for the $N=116$-118 shift, which bridges the middle of the $i_{13/2}$ shell; and $\gamma(i_{13/2}) \approx 1$ for $N=115$ and 117.

If we extrapolate γ for a $p_{1/2}$ neutron to $N=123$ and 125, we would expect that γ would be very small. The observed value for the $p_{3/2}$ neutron is, in fact, larger than the extrapolated $\gamma(p_{1/2})$; the γ for Hg^{203}, with expected spin $\frac{5}{2}$, may be even larger. It therefore appears that the higher angular momentum neutrons are more effective in producing distortions.

A dependence on the orbital angular momentum, l, has already been suggested by Breit.[5] The dependence on the total angular momentum, j, can possibly be understood on the basis of the shell model. If we consider the $3p_{1/2}$ and $3p_{3/2}$ neutron wave functions, which we have calculated using a Saxon-Woods potential,[6] we find that the $j=l+\frac{1}{2}$ state has a greater probability of being inside the nuclear core than the $j=l-\frac{1}{2}$ state, as a result of spin-orbit energy. If it is assumed that the short-range force coupling with the core is similar for the two states, the larger j would therefore interact more strongly. It is likely that an approach to the isotope-shift problem in which we consider details of the overlap of the nucleon and core wave functions should be fruitful. We conclude, therefore, that a possible basis for odd-even staggering is that usually the odd neutron goes into a lower angular momentum orbit than the neutron pair, and that in this lower angular momentum orbit it is less effective in producing distrotions. If the odd neutron goes into the same orbit as the neutron pair, no staggering should be expected on this basis. In the collective region, where the deformations and particle orbits may change radically upon addition of one or two neutrons, one must consider in detail the effects of such variations.

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SUPERCONDUCTING NUCLEAR PARTICLE DETECTOR

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Recently the cryotron was proposed as a detector of nuclear particles.[1] An even simpler detector should be possible, capable of discriminating between particles of different ionizing power. It would consist of a narrow, thin film of current-carrying superconductor cooled well below its transition temperature, in series with a small resistance. Should an ionizing particle pass through the film, the current will be reduced and a voltage pulse will appear across the resistor.

The previous discussion was in terms relating to the superconducting energy gap. The detector response can also be examined in terms of heat transfer from a decaying microplasma (the particle track) imbedded in a superconducting medium at temperature T_0. If the radial temperature profile in a cylindrical track has the form suggested by Seitz and Koehler[2] and Brooks,[3] the radius of a region attaining the maximum temperature T_m for Q units of heat injected per unit length is[4]

$$r = [Q/e\pi c\rho(T_m - T_a)]^{1/2}, \qquad (1)$$

where c is the specific heat, ρ the density, and T_a the ambient temperature of the medium. For fission-fragment tracks in mica, where T_d is the decomposition temperature (~1200°K), the radius is $r_d \sim 200$ Å.[5,6] At such temperatures, heat loss by radiation is negligible compared to loss by conduction, so that further radial growth is due to adiabatic slumping of the thermal spike.

If we choose tin as the superconductor and use the same Q as for mica (since the range is nearly the same), the radius of the region switched to normal is

$$r_n = [c_d\rho_d(T_d - T_a)/c_n\rho_n(T_n - T_0)]^{1/2} r_d, \qquad (2)$$

where $T_n = T_c = 3.75$°K is the boundary temperature of the normal region. For $T_0 = 3$°K, $r_n \simeq 0.8$ micron. This is conservative since $Q \ll Q_0 = E/JR$, where E is the energy and R the range of the fragment. Indeed, if the initial lattice temperature at the axis of the spike is about 1/200 of the electron temperature T_e,[7] it may exceed 10^5 °K, suggesting an r_n of about 4 microns.

For an alpha particle,

$$Q_\alpha \simeq (E_\alpha/E)(R/R_\alpha)Q. \qquad (3)$$

Comparing a 5-MeV alpha with a 60-MeV fission fragment, $Q_\alpha \sim Q/30$. Hence $r_n(\alpha) \simeq 0.15$ micron.

Traversal of a film 1000 Å thick and 10 microns wide by the fission fragment or alpha particle should cause a change in resistance from zero to about 1 ohm and 0.2 ohm, respectively, by inserting a transverse strip of normal material in the path of the current. The film should not be thinner, so as to avoid permanent damage due to overheating which has been observed in thin met-