Lifetimes of First 2+ and 4+ States of ^{192}Pt and Some Systematics of $E2$ Transitions in Even-Even Nuclei*

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The mean lifetimes of the first 2+ (316-keV) and 4+ (785-keV) states of ^{192}Pt have been measured using the delayed-coincidence method. The results are $\tau_m(2+)=(5.1\pm0.4)\times10^{-11}$ sec and $\tau_m(4+)=(1.7\pm0.3)\times10^{-11}$ sec. The $2\rightarrow0$ transition is enhanced by a factor 69 and the $4\rightarrow2$ by a factor 31 relative to the single-particle estimate. Thus $B(E2;\,4\rightarrow2)/B(E2;\,2\rightarrow0)=0.45\pm0.10$. The systematics of the 2+ states and $B(E2)$ values for nuclei with $170\leq A\leq210$ are presented. In addition, a compilation of measured ratios $B(E2;\,4\rightarrow2)/B(E2;\,2\rightarrow0)$ for all nuclei is given. Comparison with these systematics indicate that in ^{192}Pt the $2\rightarrow0$ transition is unusually fast and $B(E2;\,4\rightarrow2)/B(\mathrm{E2};\,2\rightarrow0)$ is small. Studies of the conversion electron spectrum of ^{192}Pt show that the previous assignment of a $4\rightarrow2'$ transition is incorrect.

I. INTRODUCTION

THE electromagnetic transition probabilities for the first 2+ to ground-state levels of even-even nuclei have been measured for over 150 nuclei. In all cases, the transitions have reduced transition probabilities appreciably greater than the Weisskopf single-particle estimate. Except for the very light nuclei, the enhancements F vary from about 10 in semimagic nuclei to over 200 for the highly deformed nuclei.[1] The theoretical calculations of these enhancements in the deformed region according to the Bohr-Mottelson theory, and in the spherical regions according to the calculations of Kisslinger and Sorensen, give a reasonable agreement with experiment. In the transition regions there is no good quantitative description of the observed enhancements.

In 1962 Grodzins[2] considered the systematics of $E2$ transitions for all nuclei. He pointed out that the product, $E_\gamma\times F$, was approximately constant and equal to about 17 (where E_γ is in MeV) for all nuclei. This suggests that the energy of the 2+ level and the $E2$ transition probability are connected together in an intimate way.

The lifetime of the 2+ state of ^{192}Pt was measured by deBoer, Voorthuis, and Block[3] in 1962. The value obtained by them [$\tau_m=(3.9\pm0.5)\times10^{-11}$ sec] indicated that the product $E_\gamma F$ equals 29. This appeared as a departure from the Grodzins systematics. In addition, several groups have measured the precession of the angular correlation through the 2+ state to determine the magnetic moment of this state. The derivation of the moment from the precession requires, of course, knowledge of the lifetime of the 2+ state. For these reasons, we attempt to remeasure this lifetime.

In contrast with the large number of 2+-state lifetimes known, there are very few measurements of 4+-state lifetimes. For deformed nuclei the ratio $B(E2;\,4\rightarrow2)/B(E2;\,2\rightarrow0)$ should equal 10/7. This prediction of the theory has been shown to be accurate for about 10 nuclei to within experimental error (several percent) in the deformed region of the rare-earth nuclei as well as for some deformed heavy nuclei. The vibrational model of Scharff-Goldhaber and Weneser predicts a ratio $B(E2;\,4\rightarrow2)/B(E2;\,2\rightarrow0)=2$ for the simple vibrational nuclei. Recently, the transition probabilities for the 4+ states of several Cd and Pd nuclei have been determined[4] using multiple Coulomb excitation. These results show quite close agreement with the vibrational model prediction. Although neither model is expected to be applicable to ^{192}Pt, it might have been expected that the 4+ lifetime would be too short ($\sim$5 psec) for electronic measurement. In the course of measuring the 2+ lifetime, however, it became obvious that the 4+ state has a measurable lifetime.

The results we have obtained for the two lifetimes thus suggest that the 2+ state has an appreciably shorter lifetime than might be expected from systematics. Also, the nature of the 4+ state, as evidenced by its long lifetime, is appreciably more complicated than might have been expected.

The lifetimes measured are essentially at the edge of the range accessible to electronic measurement. In addition, the decay scheme of ^{192}Ir $\rightarrow$ ^{192}Pt is reasonably complicated. The possibilities for systematic errors in these measurements are manyfold. For this reason several alternative methods have been used to cross-check our results and these will be presented in some detail.

The last section of this paper contains a comparison of the Pt transition probabilities with those in other nuclei. In recent years measurements have been made by double Coulomb excitation of a number of 4+ states in nuclei throughout the periodic table. We

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[1] An excellent review of the systematics of transition probabilities and the related theories are contained in the article of O. Nathan and S. G. Nilsson, in *Alpha-, Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn, (North-Holland Publishing Company, Amsterdam, 1965), Vol. 1, p. 601.

[2] L. Grodzins, Phys. Letters **2**, 88 (1962).

[3] Th. J. de Boer, H. Voorthuis, and J. Block, Physica **28**, 417 (1962).

[4] F. K. McGowan, R. L. Robinson, P. H. Stelson, and J. L. C. Ford, Jr., Nucl. Phys. **66**, 97 (1965); P. H. Stelson (private communication).

present the systematics of $B(E2; 2 \rightarrow 0)$ for nuclei in the mass region $170 < A < 210$ as well as measured ratios of $B(E2; 4 \rightarrow 2)/B(E2; 2 \rightarrow 0)$ for even-even nuclei of all masses. These systematics show that the transition probabilities in ^{192}Pt are somewhat anomalous.

II. EXPERIMENTS

A. Fast Electronics and Detectors

All lifetime measurements were performed using plastic scintillators mounted on XP1020 (Amperex) photomultipliers. A $\frac{3}{4}$-in.$\times\frac{3}{4}$-in. Naton 136 plastic scintillator covered with MgO powder in an aluminum can was used as the γ-ray detector. A 2-mm-high$\times$1-cm-diam plastic scintillator, covered with a 100 μg/cm^2 Al foil was used for detection of β rays. Anode pulses from the multipliers were processed in fast tunnel diode discriminators. The discriminator outputs were mixed in a transistorized, overlap-type, time-to-amplitude converter. A coincidence was required between the time-to-amplitude converter and the slow, energy selecting signals, in a conventional fast-slow coincidence circuit. In addition, the time signals were mixed with small fractions of the amplitude signals to achieve pulse height compensation of the time signals.[5,6] The pulse height compensated time signals were displayed on an RIDL analyzer with appropriate coincidence requirements.

The time calibration was performed utilizing General Radio 20 cm air dielectric lines. Usually, time dispersions of the order of 30 channels per nanosecond were used. Over the range of several nanoseconds, the time converter output was a linear function of delay within several percent.

All the measurements to be described determine lifetimes by centroid shift relative to a prompt coincidence source. For some of the measurements, the prompt and delayed source were separately placed between the counters. They were alternated frequently in order to minimize the effects of drift. In addition, the counting rates of both sources were adjusted to be approximately equal. For some of the measurements, both the prompt and delayed sources were placed between the fast plastic counters simultaneously. A third NaI(Tl) counter then viewed the combination of activities. The time pulses were sorted by a selective storage technique on the basis of the energy of the third coincident radiation as observed in the NaI detector. This method, which reduces systematic errors in the time spectra due to rate shift and secular shifts, is described in detail in Ref. 5.

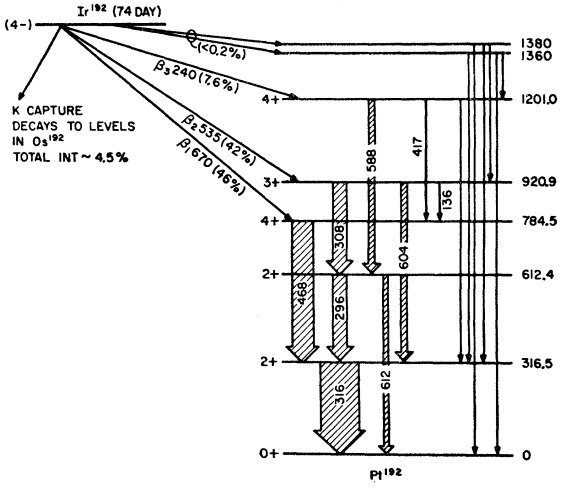

FIG. 1. Decay scheme of 74-day ^{192}Ir. The decay scheme is taken from the Nuclear Data Sheets (Ref. 7). Intensities of the stronger γ rays are indicated by widths of lines. The γ transitions shown on the right side of the decay scheme (and not labeled with their energies) have a total intensity of less than 0.2% of all decays. The transition between the 784.5- and 612.4-keV states shown in the Nuclear Data Sheets does not belong there, as indicated in the Appendix to this paper. The precise energies of the states are taken from the precision measurements of R. L. Graham, J. S. Geiger, and G. Kaye, Progress Report Atomic Energy of Canada Ltd. AECL-2044, Chalk River, Ontario, 1964 (unpublished).

In addition to the use of the selective storage feature of the analyzer to record simultaneous prompt and delayed time spectra, another mode of operation was sometimes used. By using two separate single-channel analyzers to detect the pulse amplitude signal from one plastic detector, and two separate slow-coincidence channels, the time spectra associated with different energies in a single detector were selectively stored simultaneously. By using this technique, it was possible to measure the time shift associated with "background" radiations (from other cascades) simultaneously with the desired radiation. This is essentially a time-saving feature and does not particularly reduce systematic errors.

B. Sources and Decay Scheme

The ^{192}Ir activity was prepared by neutron irradiation of a fine metal iridium powder of natural isotopic abundances. After irradiation and aging for about two weeks, the powder was spread on scotch tape and covered with 0.001-in.-thick Mylar. This source could then be viewed through the Mylar to detect β rays.

A decay scheme[7] of ^{192}Ir is shown in Fig. 1. Transitions in ^{192}Os fed from the decay of the ^{192}Ir are not

[5] A. Schwarzschild, Nucl. Instr. Methods **21**, 1 (1963). The scheme for pulse-height compensation is given in this reference. Block diagrams of the other circuitry used are contained in this reference and in Ref. 6. The fast electronics (discriminator and time-to-amplitude converter) circuits are described in detail in R. Sugarman, F. C. Merritt, and W. A. Higinbotham, Brookhaven National Laboratory Report BNL 711 (T248), 1962 (unpublished). A description of the conventional fast-slow multiple coincidence circuit appears in R. L. Chase, Rev. Sci. Instr. **31**, 945 (1960).

[6] G. Present, A. Schwarzschild, I. Spirn, and N. Wotherspoon, Nucl. Instr. Methods **31**, 71 (1964).

[7] Nuclear Data Sheets, compiled by Nuclear Data Group (National Academy of Sciences—National Research Council, Washington, D. C.)

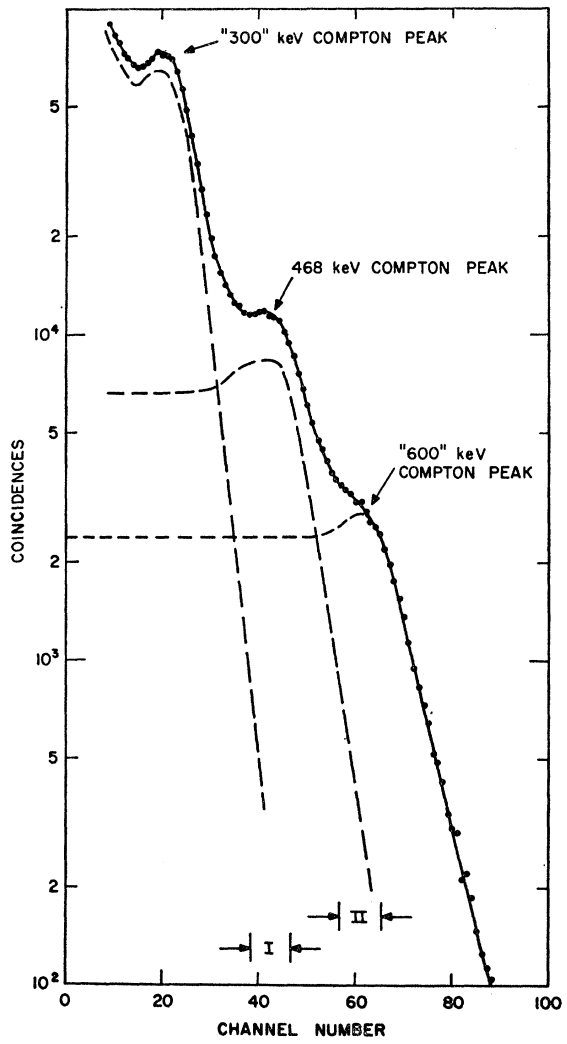

FIG. 2. Coincidence pulse-height spectrum of Compton events in plastic scintillator in coincidence with another plastic scintillator with channel set on "300"-keV Compton peak. The dashed lines show schematic resolution of the total spectrum into three components.

shown, but they are weak, and they have essentially no effect upon our measurements.

The lifetimes to be measured are those of the 316- and 785-keV states. Four separate measurements were performed. They are all centroid shift measurements and will be described as follows: (1) A double coincidence measurement between the 468- and 316-keV γ rays yielding $\tau(316)$. (2) A double coincidence measurement between β rays above $\sim$500-keV (i.e., β_1) and 468-keV γ rays yielding the lifetime $\tau(785)$. (3) A triple coincidence measurement between β rays >200 keV (i.e., β_1 and β_2) and the 468-keV γ ray in the timing counters, and the 316-keV γ ray detected in a NaI crystal for identification, which also yields $\tau(785)$. (4) A triple coincidence measurement of β rays >200 keV and the 316-keV γ ray in the timing channel and the 468-keV γ ray in NaI for identification, yielding a value for $[\tau(316)+\tau(785)]$. Each of these measurements and the relevant corrections are described in detail below.

C. 468- and 316-keV γ-γ Coincidences

On the basis of the decay scheme of Fig. 1, one concludes that in coincidence with the composite "300-keV" Compton edge observed in a plastic scintillator[8] one expects to find coincidences with "300"-, 468-, and "600"-keV radiation. Figure 2 shows the pulse-height spectra in the second plastic detector in coincidence with the "300"-keV Compton edge in the first detector. This spectrum may be resolved into essentially three Compton distributions due to the composite "300"-keV line, the 468-keV transition and the composite 600-keV group. If a channel is set as indicated in the figure (for channel I), then approximately 70% of the resulting coincidence are due to the 316–468-keV cascades and $\sim$30% to the composite "300"- and "600"-keV cascades. Approximately 3% of the coincidences come from "300"–"300" coincidences as well as 468–"300" in which the 300-keV γ ray enters the "468" channel and therefore the time ordering is reversed. The time delay between the 468- and 316-keV radiations is a direct measure of the 316-keV level lifetime. The delay between the composite 300–600-keV radiations is a rather complicated function of the lifetime of the first and second 2+ states and must be separately measured. The 3% contaminant of "300"–"300"-keV and 468–316-keV (i.e., reverse order) time delay would show approximately $\frac{1}{3}[\tau(2+)]$ in the reverse direction. (This value comes from consideration of the possible γ rays entering the windows and the properties of the decay scheme. The "300"–"300" coincidences should show no centroid shift since there is no identification of the early and late radiations. It should be noted that this correction affects our results only slightly as evidenced by the very small coefficient appearing in the equation for $\tau(2+)$ below.)

With the pulse-height channels set as indicated above (i.e., "300"-keV Compton peak and 468-keV Compton peak) a prompt ^{60}Co time spectrum was run. The resulting time spectrum showed a full width at half-maximum of 3.8×10^{-10} sec and approximately exponentially decaying wings with apparent $\tau_{1/2}=6\times10^{-11}$ sec.

Utilizing the selective storage method described above, time spectra were recorded simultaneously for pulses lying within both the pulse-height regions marked I and II in Fig. 2. In addition, prompt time spectra were recorded with identical energy selection with a ^{60}Co source. Seven runs were made of the centroid shifts and the results averaged. Internal and external

[8] Throughout this discussion the notation "300"-keV radiation is used to denote the unresolved γ rays of 296, 308, and 316 keV, and "600"-keV radiation to denote the unresolved 588-, 604-, and 612-keV γ rays.

errors were consistent with the assumption that the data show proper statistical behavior.

The results were as follows: (1) The centroid shift for pulse-height channel I was (46±3) psec. (2) The centroid shift for pulse-height channel II was (41±5) psec.

A decomposition of the coincidences in channel I as given above results in the following expression for deriving $\tau(2+)$ (in psec units) from the observed centroid shifts,

$$0.7[\tau_m(2+)]+0.3[\tau(\text{“600”})]-0.03[\tfrac{1}{3}\tau(2+)] = 1.03(46\pm3).$$

The quantity $\tau(\text{“600”})$ is the centroid shift associated with the background of pulses due to the composite “600”-keV radiation in channel I. This is obtained in a similar way from decomposing the intensities in channel II into the part due to the 468-keV radiation and the “600”-keV radiations according to Fig. 2. This results in the relation

$$0.8\tau(\text{“600”})+0.2\tau(2+)=(41\pm5).$$

Solution of these equations results in the following value for the mean life of the 2+ state[9]:

$$\tau_m(2+)=(52\pm6)\text{ psec}.$$

D. β-Ray—“468”-keV γ-Ray Coincidences

Inspection of the decay scheme of Fig. 1 shows that the delay between β rays above ~200 keV and the 468-keV γ ray is essentially entirely due to the lifetime of the 4+ level at 785 keV. Selection of the β rays at the upper end of the composite β spectrum tends to enhance the coincidences with the 468-keV γ ray relative to the composite “600”-keV gammas which form a background for the time measurement. Figure 3 shows the spectra obtained in the plastic γ detector. The enhancement of the 468-keV line relative to the 600-keV line in coincidence with β rays is obvious. Centroid shift measurements were performed with an energy selection channel set as indicated in Fig. 3.

For a prompt comparison source, the radiations of ^{60}Co are not suitable since the β-decay energy is lower than the β window used for the Ir source. Two comparison sources were used. They were ^{198}Au and ^{24}Na. For ^{198}Au the β-γ coincidences are not prompt. The 2+ level of ^{198}Hg at 412 keV has a lifetime of the order of 33 psec. For ^{24}Na the β-γ-γ cascade is known

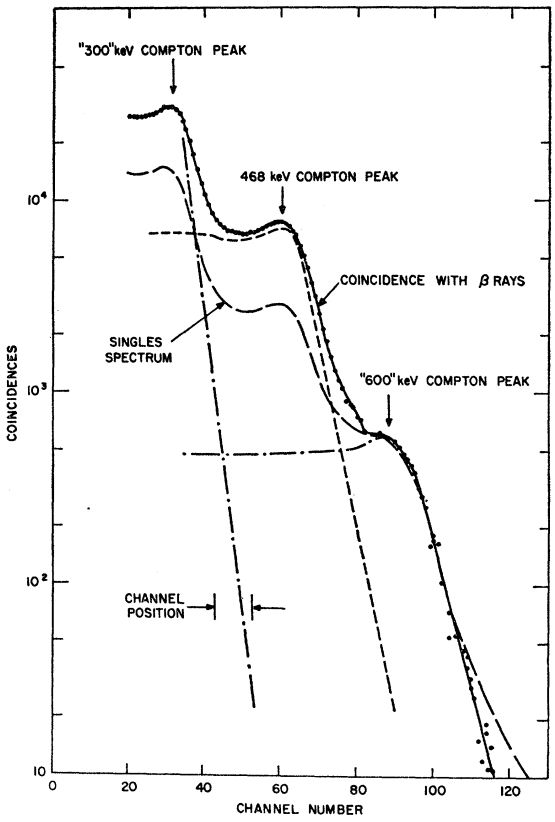

FIG. 3. Pulse-height spectra of Compton events in plastic scintillator. A singles spectrum (normalized to the coincidence spectrum in the 600-keV region) is shown as well as coincidence spectrum gated by β particles of $E_\beta>200$ keV in the β detector. Resolution of the coincidence spectrum into three components is shown. The channel position for the time measurement is indicated.

to be prompt, however, the γ-ray energies (2.7 and 1.4 MeV) are so high that special care must be taken to insure that the back-scattered photons do not count in the β crystal, resulting in a time shift due to their time of flight. To insure that such effects were not of significance, we measured the ^{198}Au time spectrum as a check. The three sources (^{192}Ir,^{198}Au,^{24}Na) were alternated frequently in the coincidence spectrometer. Several measurements of the centroid shifts at different rates and a slightly different energy-selection channels resulted in consistent centroid shifts. The results of these measurements were that the centroid shifts relative to ^{24}Na were (34±2) psec for ^{198}Au, and (19±2) psec for the ^{192}Ir source. The average of several measurements of the ^{198}Au mean life given in the literature is (32.4±1.5) psec.[7]

The centroid shift of (19±2) psec observed for the Ir source must be corrected for the effects of background of pulses due to “300”-keV and “600”-keV radiations accepted in the 468-keV pulse height window. (Note that this window was set as shown in Fig. 3, at a somewhat lower energy than the peak of the 468-

[9] The value derived for $\tau(\text{“600”})$ from these results is (38±8) psec. This number can be calculated from the decay scheme assuming only that the second 2+ state has a lifetime which is very short. The value is a composite mixture of the various possible “300”–“600” coincidences that can be observed. Such a calculation results in $\tau(\text{“600”})=(30\pm4)$ psec. The agreement is reasonable especially in view of the uncertainties in the relative γ-ray intensities in the decay scheme and the somewhat crude assumption that 308-, 296- and 316-keV radiations are detected with equal efficiencies in the selecting channel of the “300” counter.

keV Compton edge, in order to accommodate the 412-keV radiation of the comparison ^{198}Au source.) Within the window indicated in Fig. 3, approximately 7% of the counts are due to the composite "600"-keV radiation and ~4% due to "300"-keV radiation. A measurement of the delay associated with the "600"-keV peak yielded a shift of (18±12) nsec. From the decay scheme and the measured τ of the 2+ state, a shift of ~(45±6) nsec is ascribed to the composite "300"-keV radiation. Thus the 4+ lifetime is derived from the measured shift by the following relation:

$$0.89\tau(4+)+0.07(18\pm12)+0.04(45\pm6)=(19\pm2).$$

This results in $\tau(4+)=(18\pm3)$ psec.

E. Triple Coincidence Measurement of $\tau(4+)$

Sources of both ^{192}Ir and ^{60}Co in contact with each other were placed between the two detectors. The channel of the β detector was set in the region between about 200- and 260-keV β energy. The gamma counter window was set near the Compton peak of the 468-keV γ ray. In addition the two sources were viewed by a 3 in.×3 in. NaI or a 5 in.×5 in. NaI detector. Pulses from the NaI detector were selected for pulse amplitude in two separate single-channel analyzers to select the photopeaks of either a "300"-keV γ ray which follows the 468-keV γ in the ^{192}Ir decay or either the 1.17- or 1.33-MeV γ rays of the ^{60}Co decay. A triple coincidence requirement together with the selective storage feature of the RIDL analyzer then permitted simultaneous storage of two time spectra from either the Ir or Co decays sorted on the basis of the NaI pulse amplitude. The time spectrum associated with the 1.17- or 1.33-MeV photopeaks in the NaI results essentially in a clean prompt peak. The pulses corresponding to the "300"-keV photopeak in the NaI reflects mainly the lifetime of the 4+ state in ^{192}Ir. Several corrections to the observed centroid displacement must be made to obtain the 4+ lifetime. There are pulses in the NaI spectrum in the region of 300 keV due to the ^{60}Co source (Compton events in the NaI). Both the intensity of such pulses and the centroid shift associated with them were determined by running only the ^{60}Co source under identical conditions. Several runs were made with different relative ^{60}Co-^{192}Ir source intensities. The results of these measurements were as follows: The combination source centroid shift was of the order of 13 psec. Counts due to ^{60}Co radiations in the time spectrum associated with Ir accounted for approximately $\frac{1}{4}$ of the counts and evidenced a centroid shift of ~(4±5) psec.[10]

[10] The centroid shift associated with counts in which one ^{60}Co γ ray enters the NaI detector and deposits only 300 keV therein may seem somewhat strange at first sight. The plastic γ counter, in principle, is seeing a prompt coincidence from the second ^{60}Co γ ray. However, the following event may take place: The β ray counts in the β detector, one γ ray counts in the NaI (by a Compton event), and the backscattered γ ray counts in the plastic detector. Such counts have a centroid shift associated with them due to the γ-ray flight time. Although some shielding is used between the detectors, the effect may still be present to some small extent.

TABLE I. Summary of measurements.

$\tau_m(4+)$	Double coincidence measurement	18±3 psec
	Triple coincidence measurement	16±5 psec
	Average	17±3 psec
$[\tau_m(4+)+\tau_m(2+)]$	Triple coincidence measurement	67±4 psec
$\tau_m(2+)$	Double coincidence measurement	52±6 psec
	From $[\tau_m(4+)+\tau_m(2+)]-\tau_m(4+)$	50±5 psec
	Average	51±4 psec

The result of combining the several runs with varying Ir-Co intensity ratios, corrected for contamination of the Ir time spectrum by counts from ^{60}Co, was a centroid shift of (16.7±3.4) psec. This then is the centroid shift arising from all pulses in the window selecting the 468-keV Compton peak in the plastic γ counter. This centroid shift must be corrected for pulses due to the Compton distribution of the "600"-keV γ rays and "300"-keV γ rays within the 468-keV window. (These pulses have an intensity of ~13% of the total in the window.) The corrections were performed in a manner similar to that described in the doubles measurement of the 4+ lifetime. The centroid shift to be associated with the "600"-keV pulses was measured in the triple coincidence arrangement (by raising the 468 counter channel position) and found to be (18±13) psec. After performing this correction we find

$$\tau_m(4+)=(16\pm5)\text{ psec}.$$

F. Triple Coincidence Measurement of $[\tau(2+)+\tau(4+)]$

This measurement was performed with essentially the same arrangement as the triple coincidence determination of the 4+ lifetime described in the last section. The NaI window for the ^{192}Ir activity was moved to the photopeak of the 468-keV γ ray and the plastic γ-counter window set on the Compton peak of the "300"-keV radiation. The decay scheme of ^{192}Ir is such that in a triple coincidence between β rays and the 468-keV γ ray, one finds only the 316-keV transition. This cascade is completely clean of contamination from the other "300"-keV γ rays or the "600"-keV composite line. Pulse-height spectra in the plastic γ counter taken in triple coincidence with the β and 468-keV NaI pulses show only the Compton distribution due to the 316-keV radiation. Pulses in the region of the 316-keV Compton peak have less than a 2% contamination due to higher energy radiations.

The time spectra taken with ^{60}Co and Ir sources in contact show a centroid shift of (55±3) psec. As described in the previous section, the counts in the Ir time spectrum contain about a 20% contamination of counts from the ^{60}Co activity. Correction of the measured centroid shift for the ^{60}Co contamination of the

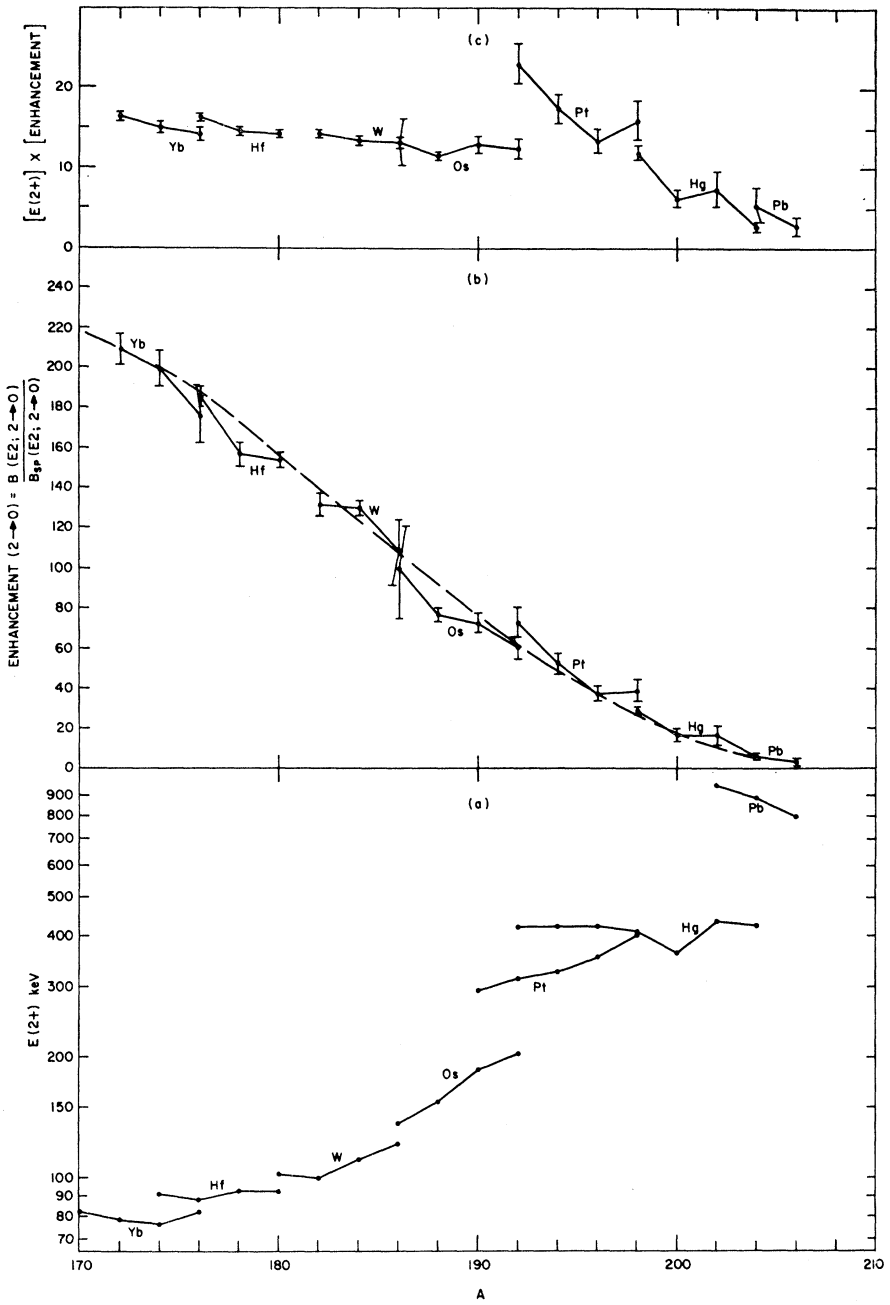

FIG. 4. Systematics of the energy of the first 2+ state and the reduced transition rates for the $2 \rightarrow 0$ transitions for nuclei with $170 < A < 206$. The sources of the data are given in Ref. 11. (a) Energies of the first 2+ state. (b) The enhancement of the $2 \rightarrow 0$ transition. (c) The product of the energy and the enhancement of the $2 \rightarrow 0$ transitions.

spectrum associated with Ir counts results in a centroid shift of (67±4) psec between β rays and the 316-keV γ ray populated by the 468-keV γ ray. It is clear that this *centroid shift* corresponds to the sum of the lifetimes of the 4+ state at 785- and the 316-keV state. Thus we have

$$\tau(4+)+\tau(2+)=(67\pm4)\text{ psec}.$$

III. SUMMARY OF EXPERIMENTAL RESULTS

Table I contains a summary of the results described above. The agreement between the several measurements is quite reasonable. Corrections to the experimental results involved in deriving the lifetimes are relatively large, but quite different for the several measurements. The agreement of the results thus confirms the correction procedures. The errors quoted in Table I are standard deviation mainly due to statistics—errors in corrections have been compounded in the usual way. Estimates of possible systematic errors suggest that they are small compared with quoted errors in Table I. However, it is probably not possible to reduce the uncertainties significantly by increased counting time.

The value for $\tau_m(2+)$ of (51 ± 4) psec is to be compared with the value 39 ± 5 psec obtained by the J. de Boer *et al.*[3] for the same state. These authors performed a measurement essentially identical to our double coincidence measurement (Sec. II.C above). However, they do not consider any corrections due to background radiations except to state that they are expected to be small. In fact, these corrections are not insignificant and probably account for the disagreement.

IV. TRANSITION PROBABILITIES IN ^{192}Pt

The reduced transition probabilities for the $2\rightarrow0$ and $4\rightarrow2$ transitions can be derived as follows. Conversion coefficients are obtained from the tables of Sliv and Band along with the assumption that the conversion in the M and higher shells is equal to $\frac{1}{3}$ the L shell conversion. They are $\alpha_T(316)=0.086$ and $\alpha_T(468)=0.030$. Using the average mean lives given in Table I, one finds that $\tau_\gamma(2\rightarrow0)=(55\pm4)$ psec and $\tau_\gamma(4\rightarrow2)=(17.5\pm3)$ psec. [This value for $\tau_\gamma(4\rightarrow2)$ is based on the assumption that there is no competing radiation from the 785-keV state to the second 2+ state at 612 keV. This point is discussed in detail in the Appendix.]

These lifetimes can be compared to the Weisskopf single-particle estimates. For the single-particle mean life τ_{sp} we use the formula

$$\tau_{sp}=1.35A^{-4/3}E_\gamma^{-5}\times10^{-8}\text{ sec},$$

where E_γ is the γ-ray energy in MeV. The nuclear radius constant is 1.2 F in this formula.

The resulting single-particle estimates are: $\tau_{sp}(2\rightarrow0)=3800$ psec and $\tau_{sp}(4\rightarrow2)=540$ psec. The enhancements of these transitions defined as $F=\tau_{sp}/\tau_m$, are $F(2\rightarrow0)=(69\pm5)$ and $F(4\rightarrow2)=(31\pm6)$. The ratio $B(E2;4\rightarrow2)/B(E2;2\rightarrow0)$ is equal to 0.45 ± 0.10.

As stated in the Introduction, there is no adequate theory with which to compare these results. The most reasonable approach seems to be to compare the transition rates in ^{192}Pt with those in other nuclei.

V. SYSTEMATICS OF $E2$ TRANSITIONS IN EVEN-EVEN NUCLEI

A. 2+ → 0+ Transitions

Figure 4 presents the available data[11] on the $2\rightarrow0$ transitions in nuclei between $A=170$ and $A=206$. This mass region covers the transition from the strongly deformed rare-earth nuclei to the spherical Pb nuclei. Most of the features of these curves are well known. It has perhaps not been appreciated that in spite of the very sharp discontinuities in the energies of the 2+ state, the $B(E2;2\rightarrow0)$ is a rather smooth function of A. Several authors[2,12,1] have commented on the constancy of the product of $E_\gamma\times F$ for all nuclei and possible connections between this fact and some $E2$ sum rules. Figure 4(c) shows that in fact the product $E_\gamma\times F$ changes by a factor of almost 9 from the lightest Pt nucleus to the Pb nuclei. The transition probability $B(E2)$ is decreasing at a much more rapid rate than the increase in the 2+-state energy in this mass region.

B. 4+ → 2+ Transitions

For rotational nuclei the ratio $B(E2;4\rightarrow2)/B(E2;2\rightarrow0)$ should equal 10/7. For simple vibrational nuclei this ratio should equal 2. In Figs. 5 and 6 the available data on these transition rates are presented.[13] Both figures present the same data plotted against different abscissas. The abscissas were chosen so that all nuclei could be compared relative to their qualities as rotational or vibrational nuclei as revealed by their energy level positions or their $B(E2;2\rightarrow0)$. It is clear that the identification by these quantities

[11] The data on the energies of the 2+ states are derived from Ref. 7. The values for transition rates are obtained from Ref. 7 and from J. Lindskog, T. Sundström, and P. Sparrman, p. 411 in *Perturbed Angular Correlations*, edited by K. Karlsson, E. Matthias, and K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1964) and reprinted on p. 1599 in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1965). When several experimental values are available for a single lifetime, we have weighted these in a somewhat arbitrary manner based on our estimates of the reliability of the technique used for measurement and have assigned what may be considered a conservative estimate of the errors based qualitatively on the agreement between the several experiments.

[12] Y. Yoshizawa (private communication).

[13] Recently there have been many double Coulomb excitation experiments reported which excite the first 4+ states. In view of the uncertainties in the theory of double Coulomb excitation, we have included in these graphs only those cases in which authors derive $B(E2;4\rightarrow2)$ from their own data. For this reason the early results of D. Eccleshall, B. M. Hinds, M. J. L. Yates, and N. Macdonald, Nucl. Phys. **37**, 377 (1962); D. Eccleshall, B. M. Hinds, and M. J. L. Yates, Nucl. Phys. **32**, 190 (1962); and J. de Boer, G. Goldring, and H. Winkler, Phys. Rev. **134**, B1032 (1964) have not been included in the figures. The work of Eccleshall *et al.* on Pd, Ru, and Cd has been largely repeated and newer values (mostly in agreement with these authors) are included in the figures. The work of de Boer *et al.* on 22 even-even nuclei in the range $150<A<192$ shows excellent agreement for the double excitation of the 4+ state with the predictions of the second-order excitation theory using the rotational model. The following references refer to the points included in Figs. 5 and 6: M. A. Eswaran and C. Broude, Can. J. Phys. **42**, 1311 (1964); ^{22}Ne. P. Stelson (private communication) and Proceedings of Brookhaven Summer Study Group on Physics of the Emperor Tandem Van de Graaff Region, 1965 (unpublished); ^{100,102,104}Ru, ^{106,108}Pd. F. K. McGowan, R. L. Robinson, P. H. Stelson, and J. L. C. Ford, Nucl. Phys. **66**, 97 (1965); ^{110,112,114,116}Cd. W. M. Currie, Nucl. Phys. **32**, 574 (1962); ^{140}Ce. D. G. Alkhazov, V. D. Vasilev, Yu. P. Gangreskii, and I. Kh. Lemberg, Isv. Akad. Nauk. SSSR Ser. Fiz. **28**, 229 (1964) [English transl.: Bull. Acad. Sci. USSR Phys. Ser. **28**, 146 (1964)]; ^{152,154}Sm, ^{182,184,186}W. A. C. Li and A. Schwarzchild, Phys. Rev. **129**, 2664 (1963); ^{160,162}Dy, ^{166,168}Er, ^{180}Hf. A Sunyar (private communication) ^{190}Os. Yu. P. Gangriskii, I. Kh. Lemberg, and V. A. Nabichvrishvili, Program for Fifteenth Annual National Meeting on Nuclear Spectroscopy, Minsk, 1965 (unpublished), p. 100; ^{194,196}Pt. W. R. Neal and H. W. Kraner, Phys. Rev. **137**, B1164 (1965); ^{224}Ra, ^{228,230}Th. H. Gove, Nucl. Instr. Methods **28**, 180 (1964); ^{20}Ne. A. C. Douglas, W. Bygrave, D. Eccleshall, and M. J. L. Yates, p. 274 in *Proceedings of the Third Conference on Reactions Between Complex Nuclei*, edited by A. Ghiorso, R. Diamond, and H. Conzett (Univ. California Press, Berkeley, California, 1963); ^{76}Se. A. W. Sunyar, D. Alburger, G. Friedlander, M. Goldhaber, and G. Scharff-Goldhaber, Phys. Rev. **79**, 181 (1950); ^{204}Pb, also see Ref. 7 for more recent confirming results.

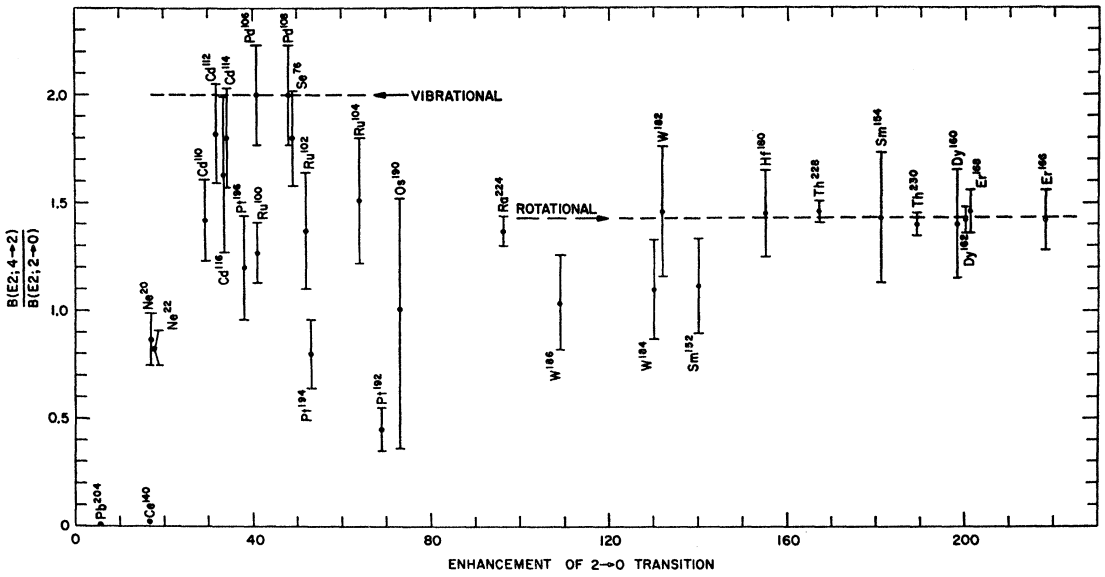

FIG. 5. Systematics of measured transition probabilities of the $4+ \rightarrow 2+$ states in all even-even nuclei. The ratio $B(E2; 4 \rightarrow 2)/B(E2; 2 \rightarrow 0)$ is plotted against the enhancement (τ_{sp}/τ) of the $2 \rightarrow 0$ transition in the same nucleus. The limiting theoretical values for deformed rotational nuclei and vibrational nuclei are indicated. The sources of the data are given in Ref. 13.

is not unique since there is quite some rearrangement of the nuclei between the two graphs.

The figures show that for the strongly deformed nuclei both the experimental-energy ratio and the ratio of transition probabilities agree very well with the predictions of the simple theory. For the spherical nuclei the situation is more complicated. Generally the energy ratio $E(4+)/E(2+)$ is appreciably larger than 2 and the $B(E2)$ ratio is somewhat lower than 2. On these figures ^{192}Pt is shown to have one of the lowest known ratio $B(E2; 4 \rightarrow 2)/B(E2; 2 \rightarrow 0)$. Also, the Ne nuclei which are often considered to be quite highly deformed show a rather anomalous value of the $B(E2)$ ratio. The extremely low value for ^{140}Ce of $B(E2; 4 \rightarrow 2)/B(E2; 2 \rightarrow 0) = (0.012 \pm 0.002)$ has been discussed recently by Rho[14] in terms of quasiparticle interactions in even semimagic nuclei. A similar analysis may also be pertinent in the explanation of the

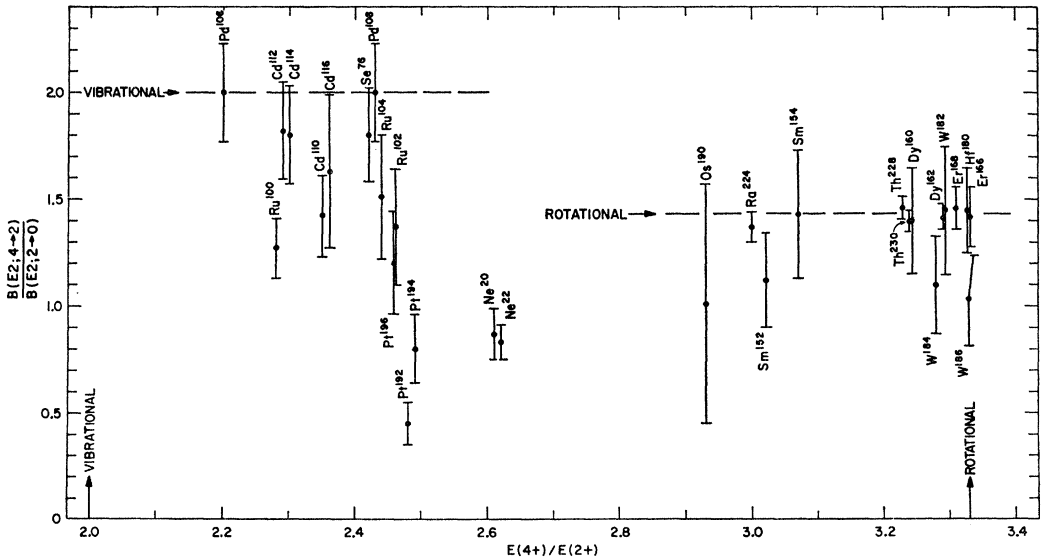

FIG. 6. The measured ratios $B(E2; 4 \rightarrow 2)/B(E2; 2 \rightarrow 0)$ plotted against the energy ratios of the $4+$ and $2+$ states. (The points for ^{140}Ce and ^{204}Pb are not shown. In both cases $B(E2; 4 \rightarrow 2)/B(E2; 2 \rightarrow 0)$ is less than 10^{-2} and the energy ratios $E(4+)/E(2+)$ are 1.3 for ^{140}Ce and 1.4 for ^{204}Pb.)

[14] M. Rho, Nucl. Phys. **65**, 497 (1965).

very low value for ^{204}Pb. It also should be noted that the behavior of the ratios for a given Z as shown for Ru and Pt nuclei is opposite to the expectation that the $B(E2)$ ratio will approach 1.43 as the $2 \rightarrow 0$ enhancement increases.

Data on $4 \rightarrow 2$ transition probabilities are increasing at a rapid rate due to the availability of heavy-ion beams. It will be most interesting to investigate the high lying 4+ states in nuclei where the energy ratio $E(4+)/E(2+)$ is close to 2.

ACKNOWLEDGMENTS

The author would like to thank Dr. L. Grodzins for calling to his attention the apparent anomaly in the old ^{192}Pt lifetime measurement. Dr. M. Perlman has frequently made his double focusing β-ray spectrometer available for conversion studies. We appreciate greatly his aid and hospitality.

APPENDIX

The Decay Scheme of ^{192}Ir-^{192}Pt

The decay of ^{192}Ir has been investigated by many authors. Most of the properties of the level scheme of ^{192}Pt are established on the basis of very precise γ ray and internal-conversion energy measurements and conversion-coefficient data. Most of the previous work (to May 1963) has been enumerated in the Nuclear Data Sheets.[7]

One point in the decay scheme of particular relevance to this work has been investigated. In the early work of Cork *et al.*[15] and of Johns and Nablo,[16] a γ ray of $\sim$174 keV was observed. This transition was assumed to be between the 4+ level and the second 2+ state and to have an intensity of about 2% of the 468-keV transition between the 4+ and the first 2+ state. If this assignment were correct, then the reduced transition probability for the $4 \rightarrow 2'$ transition would be greater by a factor of about 3 than that of the $4 \rightarrow 2$ transition.

The transition energy between the 4+ and the second 2+ state should be (172.105±0.020) keV (based on energies of Graham *et al.*, see Fig. 1). The line reported by Johns and Nablo had an energy of (174.0±0.4) keV. (Almost all of the γ-ray energies reported by Johns and Nablo in 1954 agree extremely well with the more recent high-precision measurements.) We therefore suspected that this γ ray does not belong in the decay scheme as previously placed.

A careful search was made with a high-resolution β spectrometer for the internal conversion line of the "174"-keV transition observed by Johns and Nablo. In the region of K internal conversion of γ rays between 170 and 177.5 keV we have found no line with intensity greater than 1/40 of the K conversion line of the 468-keV $(4 \rightarrow 2)$ transition [Combining this result with theoretical conversion coefficients one finds that $I_\gamma(170\text{–}177.5)/I_\gamma(468) < 7 \times 10^{-3}$ even if the transition were an $E1$.] A more careful search in the immediate region of 172.1 keV yielded a limit for the intensity of conversion line of a transition of 172.1 keV. The limit is $I_K(172.1)/I_K(468) < 1.5 \times 10^{-2}$. Combining this result with theoretical $E2$ conversion coefficients we find $I_\gamma(4 \rightarrow 2')/I_\gamma(4-2) < 1.3 \times 10^{-3}$. We therefore believe that the 174-keV line observed by Johns and Nablo is not present in the ^{192}Ir decay. Using the above limit on the $I_\gamma(4 \rightarrow 2')$ and the measured $\tau(4+)$ we find that the transition probability for the $4 \rightarrow 2'$ transition is enhanced by less than a factor 7 relative to the Weisskopf estimate and that $B(E2;\ 4 \rightarrow 2')/B(E2;\ 4 \rightarrow 2) < 0.23$. This result does not seem particularly surprising.

[15] J. M. Cork, J. M. LeBlanc, A. E. Stoddard, W. J.Childs, C. E. Branyan, and D. W. Martin, Phys. Rev. **82**, 258 (1951).
[16] M. W. Johns and C. V. Nablo, Phys. Rev. **96**, 1599 (1954).

Errata

Measurement and Statistical Theory Analysis of $Fe^{56}(He^3,p)$ and $Cu^{63}(He^3,p)$ Energy and Angular Distributions—Nuclear Shell Effects, JEAN-PIERRE HAZAN AND GEORGE MERKEL [Phys. Rev. **139**, B835 (1965)]. Equation (3), p. B839 should read

$$a = 0.0748(\vec{j}_n + \vec{j}_p + 1)A^{2/3}$$

instead of

$$a = 0.0748(\vec{j}_n + \vec{j}_p + 1).$$

Analysis of Triple Correlation Measurements, GALE I. HARRIS, HANS J. HENNECKE, AND D. D. WATSON [Phys. Rev. **139**, B1113 (1965)]. The coefficient in the denominator of Eq. (5) should read

$$\bar{Z}_1(\Lambda_2 J_2 \Lambda_2 J_2;\ \mathcal{J}_3 M) \quad \text{instead of} \quad \bar{Z}_1(\Lambda_2 J_2 \Lambda_2 J_2, \tau_3 M).$$

In Eq. (7), the quantum number in the second row, second column of the 9-J symbol should be L_1' instead of J_1'.