Decay of Nb^{92}†

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The decay scheme of Nb^{92} has been reexamined. Levels at 0.934 Mev (97.4% per disintegration) and 1.82 Mev (2.6%) were found. The 1.82-Mev state decays by 32% to the ground state and 68% to the 0.934-Mev state. This is in agreement with the work of Hayward, Hoppes, and Ernst. In addition a weak positron branch of $(5.6\pm0.6)\times10^{-2}$% per disintegration was found going to the 0.934-Mev level. Also, the angular correlation of the gamma-ray cascade was measured and found to be uniquely consistent with a level assignment of 2^+, 2^+, 0^+, with essentially pure $M1$ radiation ($E2$ admixture <0.2%) for the 2^+, 2^+ transition. The large amount of $M1$ radiation in this type of transition is quite exceptional. Simple theoretical considerations indicate the gamma-ray transitions to be of the single-particle type.

I. INTRODUCTION

THE latest work on Nb^{92} is that of Hayward, Hoppes, and Ernst.[1] Gamma rays of 0.934 Mev (97.8%), 0.900 Mev (1.3%), and 1.83 Mev were found all in coincidence with x-rays. The 0.934- and 0.900-Mev gamma rays were found to be in coincidence. The anisotropy of the angular correlation of the 0.900- and 0.934-Mev gamma rays was 0.21. The half-life was 10.1 days. In addition, the β^+ intensity was less than 0.01%. A comprehensive list of references to the work on Nb^{92} is to be found in *Nuclear Level Schemes*.[1] On the basis of this work, one can construct a simple scheme with levels at 1.83 and 0.934 Mev. The angular correlation would be consistent with spins of 2^+, 2^+, 0^+, with quadrupole mixing in the upper transition. The present work was prompted by the fact that the angular correlation work appeared incomplete, and by the lack of positrons in a situation where they would be expected from the decay energy. In the course of carrying out these measurements, the coincidence work was repeated. The results of the work in this paper are summarized in Fig. 1.

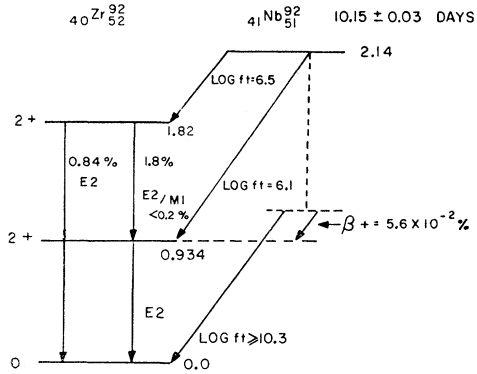

FIG. 1. Decay scheme of Nb^{92}.

II. APPARATUS

The coincidence work was done on a fast-slow coincidence system. The fast coincidence circuit, similar to that described by McGowan,[2] was capable of a resolving time $2\tau\sim2\times10^{-9}$ sec. However, to avoid possible loss of true coincidences, it was never run below $2\tau\sim3\times10^{-8}$ in these experiments. When necessary, the slow output of one of the detectors could be recorded in coincidence on a 256-channel pulse-height analyzer[3] (Argonne type) made by Radiation Instrument Development Laboratories.

The gamma-ray detectors were NaI(Tl) cystrals $1\frac{3}{4}$ in. diameter$\times2$ in. long mounted on RCA 6655 photomultipliers. The x-ray detector was a NaI(Tl) crystal $\frac{1}{8}$ in.$\times1\frac{1}{2}$ in. diameter with a window of 15-mil beryllium with a 0.5-mil aluminum reflector. For the x-ray energies ($\sim$15 kev) used in these experiments, all x-rays that hit the NaI(Tl) crystal were stopped and presumably detected. Hence the detection efficiency depended on the window attenuation and geometry, which was readily calculable. The efficiencies of the gamma-ray detectors could not be obtained as easily and were determined as follows:

1. Photopeak efficiencies were measured in various geometries using 4π-counted sources of Na^{22}, Cs^{137}, and Na^{24}.

2. Total detection efficiency as a function of energy and geometry was calculated on an IBM 650 digital calculator. The absorption coefficients used were those of White[4] with coherent scattering removed.

3. The directly measured photo efficiencies were divided by the calculated total efficiencies to give a curve of their ratio, which was found to be reasonably independent of changes in geometry.

4. An unknown photopeak efficiency was then obtained from the product of the photo-to-total ratio and the total efficiency.

† This work was performed under the auspices of the U. S. Atomic Energy Commission.

[1] Hayward, Hoppes, and Ernst, Phys. Rev. **98**, 231(A) (1955), and verbal report in *Nuclear Level Schemes, A=40—92*, compiled by Way, King, McGinnis, and van Lieshout, U. S. Atomic Energy Commission Report TID-5300 (U. S. Government Printing Office, Washington, D. C., 1955).

[2] F. K. McGowan, Phys. Rev. **93**, 163 (1954).

[3] R. W. Schumann and J. P. McMahon, Rev. Sci. Instr. **27**, 657 (1956).

[4] G. R. White, National Bureau of Standards Report, NBS-1003, 1952 (unpublished).

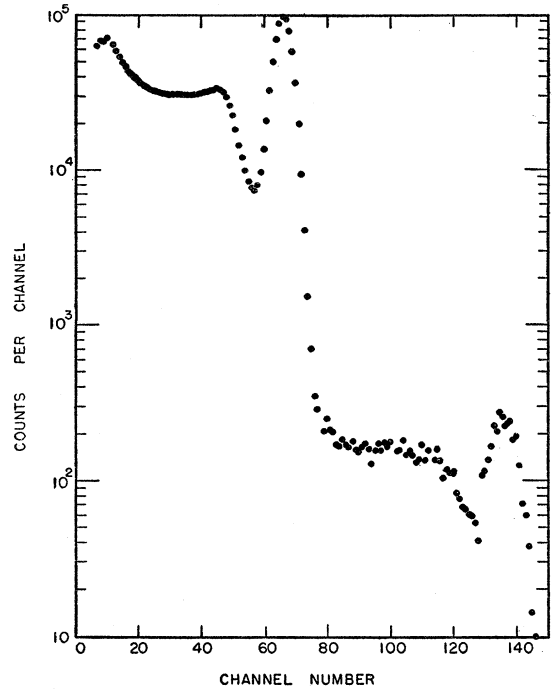

FIG. 2. NaI pulse-height spectrum of the gamma rays in the decay of Nb^{92}.

III. SOURCES

The sources were prepared by a $(d,p2n)$ reaction on niobium foil in the Berkeley 60-in. cyclotron. Chemical separation removed all activities except those of niobium. A sample was integral counted on a scintillation spectrometer for 20 days. The decay curve gave a half-life of 10.5 days and showed no evidence of a second decay component. After 2 months, scintillation spectra showed nothing but the Nb^{92} radiation so that it is believed contaminants could not have affected the results. Dr. H. Tewes and Dr. N. Bonner of this Laboratory made available data on four samples of Nb^{92} that had been followed for 36 days. Least-squares analyses of these data gave a half-life of 10.15 ± 0.03 days.

IV. GAMMA-RAY SPECTRUM

A typical pulse-height spectrum taken with the detector at 16 in. is shown in Fig. 2. Gamma rays are found at 0.934 Mev and 1.82 Mev. The rise in intensity of the spectrum below 0.3 Mev is due to scattering from the surroundings. Spectra taken in close geometry were flat from this energy back to the origin. The data in Fig. 2 were taken with a large source distance to insure that there was no possibility that simultaneous detection of cascaded gamma rays could give the 1.82-Mev gamma ray. In order to be sure the peak was not due to counting-rate pileup, the equipment was checked with an intense Cs^{137} source and the results used to correct the Nb^{92} spectrum. The correction to the 1.82-Mev peak was only 3%. After correcting for detection efficiency, the ratio of 1.82- to 0.934-Mev intensities was found to be $(8.4\pm1)\times10^{-3}$, from the average of three runs.

The photo- and pair-peaks from the 2.6143-Mev gamma ray[5] of ThC″ were used for a calibration of the scintillation spectrometer from which the high-energy gamma ray was found to have an energy of 1.82 ± 0.01 Mev.

The energy of the first excited state was measured in a thin lens spectrometer using a 0.5-mil Pb radiator. The spectrum is shown in Fig. 3. The 625-kev conversion electrons from Ba^{137m} were used for energy calibration. The average of the results obtained from the K and L conversion lines in lead gave 0.934 ± 0.001 Mev, in agreement with Hayward *et al.*[1] The sources did not have sufficient activity for internal conversion electron measurements.

V. COINCIDENCE MEASUREMENTS

The coincidence measurements were interpreted on the basis of the level scheme in Fig. 1. In order to determine the intensity of the 0.89-Mev gamma ray, gamma-gamma coincidence measurements were made with the slow channels of the coincidence system set from about 0.80 to 1.10 Mev. Back-to-back coincidence runs with a source-to-detector distance of 3 cm gave 1.8% per disintegration. A correction of 15% was made for angular correlation effects. A second set of data, obtained from the angular correlation experiments, gave 1.79% per disintegration, in agreement with the first measurement.

X-ray coincidences with the 0.93-Mev gamma ray were studied. In these measurements the coincidence circuit was operated with $2\tau=0.1$ μsec. Varying this

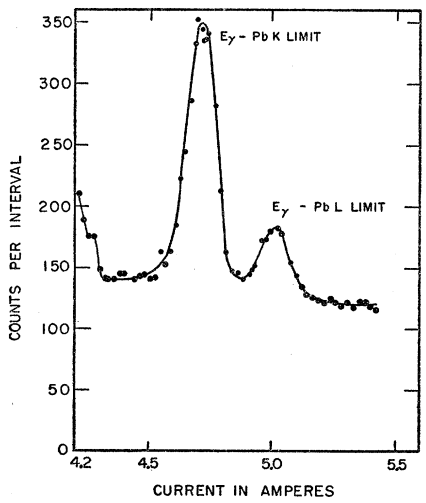

FIG. 3. Energy spectrum of the conversion electrons ejected from a 0.5-mil Pb radiator by the gamma rays in Nb^{92} decay, observed by a thin lens spectrometer.

[5] G. Lindström, Phys. Rev. 87, 678 (1952).

time did not appreciably change the coincidence rate, so it is believed there was no coincidence loss due to too short a resolving time. For the fraction of electron capture to the ground state, a straightforward analysis gives

$$\delta=1-\alpha_1+\alpha_2-\frac{N_{x\gamma}}{N_x}\frac{1}{g_\gamma\xi_\gamma},$$

and

$$\delta=1-\alpha_1+\alpha_2-\frac{N_\gamma}{N_x}\frac{g_x\xi_x w_k}{g_\gamma\xi_\gamma}\frac{1}{1+L_I/K},$$

where α_1 is the number of 1.82-Mev gamma rays per Nb^{92} decay, α_2 is the number of 0.89-Mev gamma rays, N_x, N_γ, and $N_{x\gamma}$ are the respective counting rates, g_x and g_γ are the counter geometries, ξ_x and ξ_γ are the counter efficiencies, w_k is the K-shell fluorescence yield (0.70, Siegbahn,[6] p. 630), and L_I/K is the L_I-to-K electron capture ratio[7] (0.11).

The first equation (based on a coincidence count) gave $\delta=0.0\pm0.05$. The second equation (based on singles rates) gave $\delta=-0.18\pm0.15$.

Almost all of the error in the second result is due to the uncertainty in ξ_x. The calculated window attenuation of the x-ray detector was probably in error by only a few percent. The main error is probably source attenuation, as the source was not carrier free. No correction for this effect was made in the above result.

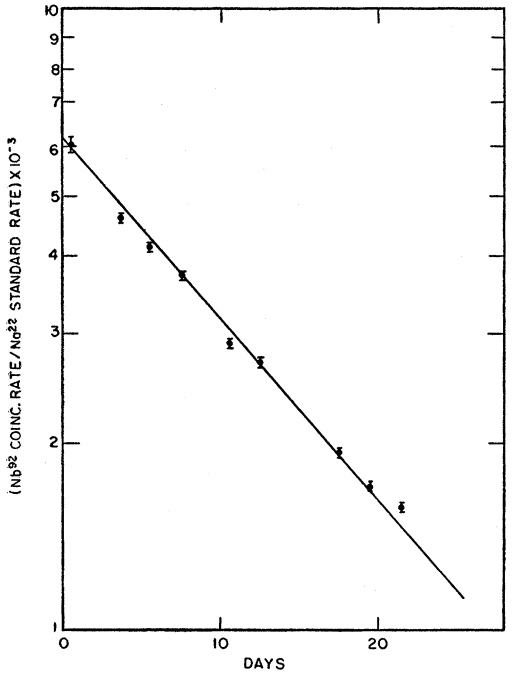

FIG. 4. Positron decay observed by 511–511 kev gamma-ray coincidences in two NaI crystals. The indicated decay curve has the 10.15-day Nb^{92} half-life.

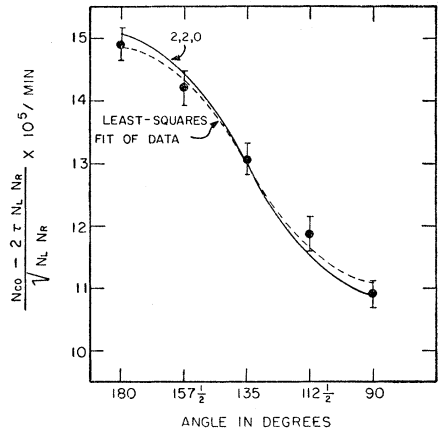

FIG. 5. Angular correlation data (Nb_2O_5 in HF solution) compared with the correlation expected for unmixed radiations in a 2, 2, 0 cascade. The theoretical correlation has been reduced by the counter angular resolution.

VI. POSITRON SEARCH

Previous workers[1] have not been able to detect positrons in Nb^{92} although there is evidently sufficient decay energy. In the present work, use was made of a back-to-back coincidence arrangement. The distance from the source to the gamma-ray detectors was 15 cm. At this distance, with the slow channels set to detect only annihilation photopeaks, the ratio of the in-line to out-of-line coincidence rates was greater than 10/1.

Before each run, the system was checked with a 4π-counted standard Na^{22} source. Data shown in Fig. 4 taken over a period of 3 weeks show decay with the characteristic half-life of Nb^{92}. On the basis of this measurement, $(5.6\pm0.6)\times10^{-4}$ positrons/disintegration were obtained.

Simple theoretical considerations indicate that the positron decay is to the 0.93-Mev state. To verify this, a triple coincidence experiment was carried out. Two crystals, back-to-back, detected the positrons (channels set at about 450–550 kev), and a third detected possible gamma rays in coincidence. Each crystal was approximately 1 inch from the source. A fast-slow triple coincidence system was used, and the output of the third crystal was pulse-height analyzed. The result was the characteristic pulse-height distribution of the 0.93-Mev gamma ray. The agreement between positron intensities in this experiment and the back-to-back coincidence experiment is within the 15% statistical error of the triple coincidence experiment.

VII. ANGULAR CORRELATION

For these measurements, the slow channels of the coincidence system bracketed the photopeaks of both 0.9-Mev gamma rays. Data were taken at every $22\frac{1}{2}°$ from 90° to 180°. The chance coincidence rate was

[6] *Beta- and Gamma-Ray Spectroscopy*, edited by Kai Siegbahm (Interscience Publishers, Inc., New York; North-Holland Publishing Company, Amsterdam, 1955).

[7] M. E. Rose and J. L. Jackson, Phys. Rev. **76**, 1540 (1949).

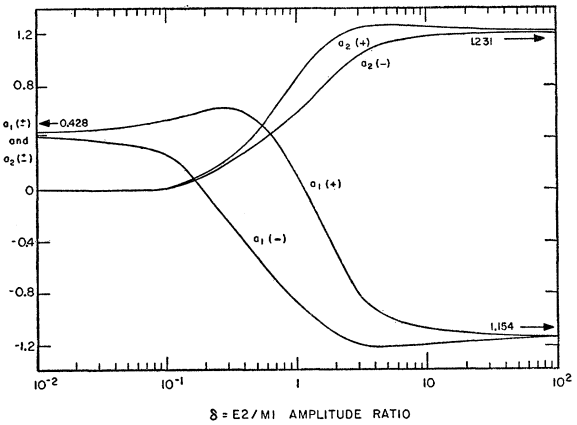

FIG. 6. Angular correlation coefficients for the spin sequence 2, 2, 0. δ equals the $E2/M1$ amplitude ratio as defined by Ferentz and Rosenzweig. The correlation is given by $W(\theta)=1+a_1^{(\pm)}\cos^2\theta+a_2^{(\pm)}\cos^4\theta$.

measured every hour by inserting 0.16-μsec delay in the fast output of one of the detectors. During the course of the experiments ($\sim$50 hours) the resolving time of the coincidence system varied by 20%, as measured by the observed chance rates. However, because of the hourly checks on chance rate, the resolving time was always known to 5%.

Two separate runs were made. In the first run, a Nb_2O_5 source was used with source-to-detector distances of 8.3 cm. In the second run the Nb_2O_5 was in a HF solution, with source-to-detector distances of 7.0 cm. These sources could have strong nuclear field gradients which would attenuate the angular correlation unless the lifetime of the intermediate state is very short. This lifetime has been measured by Stelson and McGowan,[8] using Coulomb excitation and assuming pure $E2$ radiation. They obtained 5.5×10^{-12} sec, which is not expected to affect the angular correlation.

A function of the form $A+B\cos^2\theta$ was fitted to the data by a least-squares analysis. The results are $W(\theta)=1+(0.414\pm0.02)\cos^2\theta$ for the Nb_2O_5 source, and $W(\theta)=1+(0.383\pm0.02)\cos^2\theta$ for the Nb_2O_5 in HF solution. If a $\cos^4\theta$ term is included in the analysis, the data from the HF solution give $W(\theta)=1+0.395\cos^2\theta-0.015\cos^4\theta$. These results have been corrected for the finite angles subtended by the detectors by the calculational method of Rose.[9] The data obtained from the HF solution are shown in Fig. 5.

The angular correlation results, in combination with the known internal conversion of the 0.934-Mev gamma ray and the gamma-ray transition probabilities, give a unique determination of the spins of the Zr^{92} states. (The ground state is assumed to have zero spin.) Stähelin and Preiswerk[10] have measured the total conversion coefficient for the 0.934-Mev state and obtained $(7.5\pm2.5)\times10^{-4}$. From the tables of Sliv,[11] the theoretical values which agree with this are $\beta_1=\alpha_2=7.2\times10^{-4}$. These values are in agreement with an $E2$ assignment from Coulomb excitation,[8] giving spin 2+ for the 0.934-Mev level.

The compilation of experimental lifetimes for gamma-ray transitions by multipole orders, given by Goldhaber and Sunyar[12] was used to estimate the gamma-ray transition probabilities. The results show that only spins 1 and 2 are possible for the 1.82-Mev state because of the large crossover intensity.

The angular correlation is determined by the spins of the states and by the multipole orders involved in the gamma-ray transitions. These effects are shown by the curves in Figs. 6 and 7, prepared from the tables of Ferentz and Rosenzweig[13] for the spin sequences 2, 2, 0, and 1, 2, 0. Comparison with the experimental results shows that only spin 2 is possible for the 1.82-Mev state, with a quadrupole-dipole intensity ratio of $<0.2\%$ for the 0.89-Mev gamma ray. Spin 3, with a multipole mixing ratio of 25%, also fits the data but is ruled out by the large crossover intensity. Therefore the spin sequence is 2, 2, 0. The 1.82-Mev state is assigned positive parity on the basis of the large crossover transition.

VIII. DISCUSSION OF DECAY SCHEME

The decay scheme as shown in Fig. 1 can be constructed. On the assumption of allowed transitions into the upper states, the total decay energy can be determined from the K-capture/positron ratio using the curves of Feenberg and Trigg.[14] The total decay energy

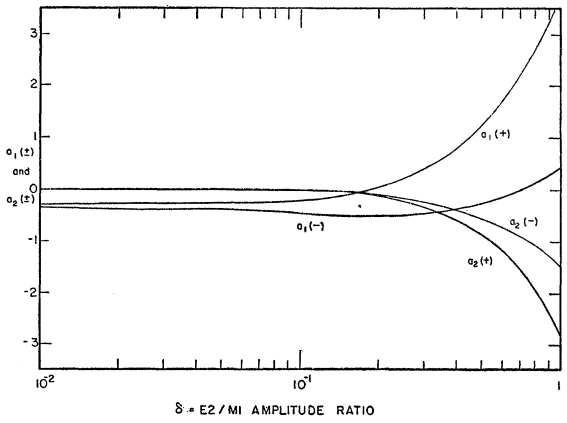

FIG. 7. Angular correlation coefficients for the spin sequence 1, 2, 0.

[8] P. H. Stelson and F. K. McGowan, Bull. Am. Phys. Soc. Ser. II, **2**, 69 (1957); and verbal report, New York Meeting of the American Physical Society, 1957.
[9] M. E. Rose, Phys. Rev. **91**, 610 (1953).
[10] P. Stähelin and P. Preiswerk, Nuovo cimento **10**, 1219 (1953).
[11] L. A. Sliv and I. M. Band, Leningrad Physico-Technical Institute Report, 1956 [translation: Report 57 ICCKl, issued by Physics Department, University of Illinois, Urbana, Illinois (unpublished)].
[12] See reference 6, Chap. XVI.
[13] M. Ferentz and N. Rosenzweig, Argonne National Laboratory Report ANL-5324, 1954 (unpublished).
[14] E. Feenberg and G. Trigg, Revs. Modern Phys. **22**, 399 (1950).

is of the order of 2.14 Mev, giving logft values[15] of 6.5 for the 1.82-Mev level, and 6.1 for the 0.934-Mev level. The positron experiments show that no more than 20% of the positrons could go to the ground state. This gives a lower limit for the ground-state transition of logft=10.3.

An attempt was made to use the shell model of Mayer and Jensen[16] to determine the ground-state configuration of $_{41}Nb^{92}$. The allowed states for the 41st proton are $g_{9/2}$ and $p_{1/2}$. For the 51st neutron, the states are $d_{5/2}$ and $g_{7/2}$. Then the possible states for J, where J is given by Nordheim's[17] empirical rules, are:

$$g_{9/2}d_{5/2}(J=2-7),\quad g_{9/2}g_{7/2}(1^+),\quad p_{1/2}d_{5/2}(2^-),$$

and

$$p_{1/2}g_{7/2}(3^-\text{ or }4^-).$$

The 51st neutron is usually found to be $d_{5/2}$ rather than $g_{7/2}$ as first expected from the model. On the basis of the above, the first and third configurations are to be favored. The ft values make the first preferable because it makes the ground-state transition second forbidden. The third case would make all the transitions first forbidden.

Previous investigations of the $(2^+,2^+,0^+)$ level structure have produced the following results: (I) Between a second and first excited state, the transition is usually mainly $E2$ with only a small $M1$ admixture. (II) The transition probability of the $E2$ part of this transition relative to the ground state (crossover) transition is much higher than is to be expected on the basis of the single-particle model. Both these rules were pointed out by Kraushaar and Goldhaber.[18] Scharff-Goldhaber and Weneser[19] have further studied the systematics of this decay and pointed out a third rule, namely, (III) that the ratio of the energies of the second to first excited states is of the order two.

Mottelson[20] describes the $(2^+,2^+,0^+)$ structure as due to nuclear quadrupole vibrations. Since the fundamental excitation mode involved is a quadrupole motion even though $\Delta J=0$, the $M1$ matrix element vanishes.

Clearly, in the present case, only rule III is satisfied. The present $(2^+,2^+,0^+)$ case has the least $E2$ admixture for its upper transition of any case known to the authors. The literature has revealed a second case which is largely $M1$ and that is the $(2^+,2^+,0^+)$ decay of Ir^{194} ($M1=98\%$) measured by Kraushaar and Goldhaber.[18]

Assuming the energy dependence of the single-particle model given by Moszkowski[21] and the lifetime of the 0.934-Mev state as measured by Stelson and McGowan,[8] a transition probability for the 1.82-Mev ground-state transition equal to 7.8×10^{12} sec^{-1} is obtained. Using this value and the observed branching ratio, 1.7×10^{13} sec^{-1} is obtained for the 1.82- to 0.934-Mev transition. The single-particle estimate for $M1$ radiation from Moszkowski's theory (statistical factor S taken as 1) is 2.1×10^{13} sec^{-1}. This, however, is 10–100 times faster than most of the experimental $M1$ transitions listed by Goldhaber and Sunyar.[12] In the light of all considerations it is concluded that the transitions are essentially of the single-particle type.

ACKNOWLEDGMENTS

Discussions with Professor Walter E. Meyerhof were helpful in the analysis of the data. We also wish to thank the crew of the Berkeley 60-in. cyclotron for source irradiations.

[15] S. A. Moszkowski, Phys. Rev. **82**, 35 (1951).
[16] Considerations based on Chaps. XV and XVI of reference 6.
[17] L. W. Nordheim, Revs. Modern Phys. **23**, 322 (1951).
[18] J. J. Kraushaar and M. Goldhaber, Phys. Rev. **89**, 1081 (1953).
[19] Gertrude Scharff-Goldhaber and J. Weneser, Phys. Rev. **98**, 212 (1955).
[20] B. R. Mottelson, Revs. Modern Phys. **29**, 186 (1957).
[21] See reference 6, Chap. XIII.