The Nuclear Moments of Se^{79}†

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Microwave measurements of the $J=2\rightarrow3$ rotational transition of OCSe containing the radioactive-nucleus Se^{79} have established the Se^{79} spin as 7/2 and the Se^{79} quadrupole moment as 0.7×10^{-24} cm$^2\pm20$ percent. The quadrupole coupling constant eqQ is 752.09 ± 0.05 Mc/sec. The magnetic moment of Se^{79} has been determined as -1.015 ± 0.015 nuclear magnetons by observation of the Zeeman splitting of one hyperfine component. The 7/2 spin and the large positive Q are inconsistent with the single-particle nuclear-shell model, but suggest the configuration $(g_{9/2})^7{}_{7/2}$. This assignment is substantiated by the negative magnetic moment.

Measurement of isotopic shifts gives a value for the Se^{79} mass, and an odd-even mass difference of 2.4 millimass units for this nucleus.

(A) INTRODUCTION

IT is well known that the jj-coupling nuclear-shell model proposed by Mayer[1] and by Haxel, Jensen, and Suess[2] fails to account for the spins of several nuclei when used as a single-particle model in which the spin of a nucleus in its ground state is determined by the angular momentum of the last added odd nucleon.[1,2] For these exceptional nuclei, it is necessary to assume that several nucleons outside a closed shell contribute to the angular momentum, and that the resultant nuclear configuration is one in which the particles do not couple in pairs to give zero angular momentum for each pair. It is of especial interest to examine the configurations of these nuclei by study of their moments, or, indeed, by any other available means.

The nucleus $_{34}Se^{79}{}_{45}$ would be predicted from the single-particle version of the shell model to have the spin 9/2 or 1/2 corresponding to the assignment of the last odd neutron to a $g_{9/2}$ or possibly a $p_{1/2}$ level. The observed spin of 7/2 is a clear exception. Measurements of the magnetic dipole and electric quadrupole moments of this nucleus, discussed below, allow a fairly unique interpretation of the configuration of Se^{79}. This configuration is consistent with those found for other known exceptional nuclei, and helps to demonstrate a general favoring of states with positive quadrupole moments.

The spin and quadrupole moment of Se^{79} were measured by observation of the hyperfine pattern of the $J=2\rightarrow3$ microwave rotational transition of the molecule $OCSe^{79}$. This hyperfine structure is due to the electrostatic quadrupole interaction energy eqQ of the nuclear quadrupole moment, Q, in the molecular electric field gradient, q.[3] In the presence of an external magnetic field, there is an additional Zeeman splitting from which the nuclear magnetic moment may be determined.[4,5]

The ground state of Se^{79} is unstable, the nucleus decaying to Br^{79} with the emission of a β particle of about 160 kev with a half-life of 6.5×10^4 years. The 7/2 spin, predicted by Goldhaber and Sunyar from an analysis of this isomeric decay, was reported in an earlier note on the microwave absorption spectrum of $OCSe^{79}$.[6,7] Unfortunately, the amount of Se^{79} available in these earlier microwave measurements was less than one microgram, and hence so limited that extended measurements of high precision were difficult. A considerably enriched sample containing 270 micrograms of Se^{79}, representing an abundance of 1.2 percent, was subsequently made available by the Oak Ridge National Laboratory. This has permitted more accurate measurements of the molecular parameters of $OCSe^{79}$ and also the determination of the nuclear magnetic moment, both of which are reported here.

(B) SPECTROSCOPY ON $OCSe^{79}$ WITHOUT ZEEMAN EFFECTS

The Se^{79} sample was put into the molecular form OCSe and the previous microwave measurements were repeated. The spectrometer used was a conventional Stark modulation spectrometer of high sensitivity and good resolution. The 7/2-spin assignment was amply verified by the measurement of nine lines in the quadrupole hyperfine pattern, but only five were chosen for the determination of the molecular parameters. These five, listed in Table I, were of good intensity

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[1] Maria Goeppert Mayer, Phys. Rev. **78**, 16 (1950).

[2] Haxel, Jensen, and Suess, Phys. Rev. **75**, 1766 (1949); Z. Physik **128**, 295 (1950).

[3] J. Bardeen and C. H. Townes, Phys. Rev. **73**, 627 (1948).

[4] Eschbach, Hillger, and Strandberg, Phys. Rev. **85**, 532 (1952).

[5] C. K. Jen, Phys. Rev. **74**, 1396 (1948).

[6] M. Goldhaber and A. W. Sunyar, Phys. Rev. **83**, 906 (1951).

[7] Hardy, Silvey, and Townes, Phys. Rev. **85**, 494 (1952).

and were not distorted by weak Stark splitting or by the Stark components of neighboring lines. The molecular parameters calculated from these lines are also listed in Table I.

Two nuclear interactions were considered in the calculations. The most important is the quadrupole interaction depending on eqQ, and this was calculated from the matrix elements given by Bardeen and Townes, including second-order corrections.[3] For refinement, the interaction $c\mathbf{I}\cdot\mathbf{J}$ was also included. This represents a perturbation on the quadrupole hyperfine structure arising from the interaction of the Se^{79} magnetic moment with the magnetic field at the nucleus due to the molecular rotation. Its effect is extremely small, being of the order of the 5-kc/sec uncertainty in the frequency measurements. In Table I the deviations between the measured line frequencies and those calculated from the quoted molecular parameters are given both for $c=-1.3$ kc/sec and for $c=0$. Although the value $c=-1.3$ kc/sec gives a minimum deviation for the data, it is clear from the size of these deviations that this value of c is not very reliable. However, the negative sign which is obtained is consistent with the negative magnetic moment of Se^{79} and the direction of the internal molecular magnetic fields observed in most molecules.

The nuclear quadrupole moment, Q, is not directly obtainable from the measured quadrupole coupling constant, eqQ, but is approximated by making a reasonable estimate of the molecular field gradient, q, following the method of Townes and Dailey.[8] In the first note on the microwave spectrum of $OCSe^{79}$, Q was estimated as 1.2×10^{-24} cm$^2\pm50$ percent.[7] However, recent work on sulfur bonds by Bird and also by Dehmelt indicates that eqQ for the nucleus S^{33} in a pure p bond would be 48 Mc/sec.[9,10] The measured eqQ for OCS^{33} is 29 Mc/sec, so the fractional importance of the pure p bond in the OCS^{33} molecular structure must be 60 percent. OCS and OCSe would be expected to have similar bonding structures, and, making only this assumption, the quadrupole moment of Se^{79} may be calculated as 0.7×10^{-24} cm^2 with a probable error of less than 20 percent.

TABLE I. Measured hyperfine lines in the $J=2\rightarrow3$ rotational spectrum of $OCSe^{79}$ and calculated frequencies using the molecular parameters determined.

Transition $F\rightarrow F'$		Measured frequency in Mc/sec	Calculated frequency in Mc/sec ($c=-1.3$ kc/sec)	Deviation in kc/sec	Calculated frequency in Mc/sec ($c=0$)	Deviation in kc/sec
7/2	7/2	24 153.204	24 153.209	−5	24 153.205	−1
11/2	13/2	24 170.194	24 170.193	1	24 170.198	−4
7/2	9/2	24 190.787	24 190.781	6	24 190.783	4
3/2	3/2	24 204.692	24 204.688	4	24 204.684	8
5/2	7/2	24 234.329	24 234.333	−4	24 234.334	−5

$\nu_0=24\,179.097\pm0.004$ Mc/sec
$eqQ=752.09\pm0.05$ Mc/sec
$c=-1.3\pm2.0$ kc/sec
$I(Se^{79})=7/2$
$\dfrac{m^{79}-m^{78}}{m^{80}-m^{78}}=0.50081\pm0.00010$

The rotational transition frequency of $OCSe^{79}$, assuming no hyperfine structure, is calculated as

$$\nu_0=24\,179.097\pm0.004\ \text{Mc/sec}.$$

From this and the rotational frequencies of other OCSe isotopic molecules the Se^{79} mass difference ratio may be determined as[11]

$$\frac{m^{79}-m^{78}}{m^{80}-m^{78}}=\frac{M^{79}}{M^{80}}\left(\frac{\nu^{80}}{\nu^{79}}\right)\left(\frac{\nu^{78}-\nu^{79}}{\nu^{78}-\nu^{80}}\right)$$
$$=0.50081\times0.00010.$$

Here m is the nuclear mass, M the molecular mass, and ν the rotational frequency. For each of these the superscript designates the isotope of selenium used. Geschwind has shown that the error in the selenium mass ratios derived from this formula is less than 0.01 percent.[11] This ratio gives the odd-even mass difference of Se^{79} as 2.4-millimass units and may be compared with the 2.0-millimass units difference of Se^{77} determined by Geschwind, Minden, and Townes.[12] These authors measured the rotational frequencies of all the naturally abundant isotopes of selenium in OCSe and express their data in terms of the masses of Se^{76} and Se^{80}, which they assume from a Bohr-Wheeler type formula. This assumption would give the mass of Se^{79} as 78.9494 ± 0.0002-mass units. The $OCSe^{78}$ rotational frequency was remeasured and found to agree within 2 kc/sec with that measured by Geschwind *et al.*

(C) THEORY OF THE ZEEMAN EFFECT

The part of the Hamiltonian giving the interaction of the molecule with an external magnetic field $\mathbf{H}$ is

$$\mathcal{H}_m=-\mu_0 g_J(\mathbf{H}\cdot\mathbf{J})-\mu_0 g_I(\mathbf{H}\cdot\mathbf{I}).$$

Here μ_0 is the nuclear magneton, g_J the molecular g factor due to the rotation of the molecule, and g_I the nuclear g factor. The nuclear term will have a negligible effect upon the observed rotational spectrum unless the nuclear spin is coupled to the molecule by an interaction energy larger than the line width. In the case of Se^{79} this interaction is provided by the quadrupole coupling. The appropriate quantum numbers when such a coupling is present are I, J, F, and M with $\mathbf{F}=\mathbf{J}+\mathbf{I}$ and M the projection of $\mathbf{F}$ on the axis of quantization. The matrix evaluation of $\mathcal{H}_m$ in this representation has been given by a number of authors.[4,5,13] We give here only the first-order diagonal terms so as to show the structure of the Zeeman pattern for the

[8] C. H. Townes and B. P. Dailey, J. Chem. Phys. **17**, 796 (1949).
[9] George Bird (private communication).
[10] H. Dehmelt, Phys. Rev. **91**, 313 (1953).
[11] S. Geschwind, thesis, Columbia University, 1951 (unpublished).
[12] Geschwind, Minden, and Townes, Phys. Rev. **78**, 174 (1950).
[13] F. Coester, Phys. Rev. **77**, 454 (1950).

case where the interaction between the nucleus and the external magnetic field is considerably less than that between its quadrupole moment and molecular electric field ($\mathcal{H}_m \ll \mathcal{H}_Q$).

$$E_m = -\mu_0 HM(g_J \alpha_J + g_I \alpha_I).$$

The α's are cosine terms (obtainable from the vector model) with

$$\alpha_J = \frac{F(F+1)-I(I+1)+J(J+1)}{2F(F+1)},$$

$$\alpha_J + \alpha_I = 1.$$

For the typical case of plane polarized radiation in a rectangular wave guide, we may distinguish two types of Zeeman transitions depending on whether **H** is parallel or perpendicular to the microwave electric vector, **E**:

(a) **H** parallel to **E**: ($\Delta F = 0, \pm 1$; $\Delta M = 0$),

$$\Delta\nu^0 = \mu_0 HM(g_J - g_I)(\alpha_{J1} - \alpha_{J2}).$$

(b) **H** perpendicular to **E**: ($\Delta F = 0, \pm 1$; $\Delta M = \pm 1$),

$$\Delta\nu^{\pm 1} = \Delta\nu^0 \mp \mu_0 H(g_J \alpha_{J2} + g_I \alpha_{I2});$$

$\Delta\nu$ is the Zeeman shift, and α_{J2} and α_{J1} are the cosines of the upper and lower states, respectively.

Because the Zeeman pattern is symmetric for either positive or negative M and ΔM, the sign of M for an individual transition cannot be determined and consequently g_J and g_I are not uniquely determined by measurements of the Zeeman splitting for the two field conditions. It is possible to determine M assignments for the pattern by the use of circularly polarized radiation to select M components, but this was not feasible in this experiment due to the poorer sensitivity of the circular polarization apparatus and the low abundance of the isotope with nuclear spin. The molecular g factor, g_J, may be determined independently of g_I by examining the Zeeman splitting in an isotopic molecule in which the substituted nucleus has no nuclear spin and hence possesses no nuclear rotational interaction. Here the Zeeman pattern simplifies and the sign of g_J may be readily determined by circular polarization techniques. When g_J is known, g_I may be completely determined by measurements of the hyperfine splitting under the two field conditions given above.

(D) MEASUREMENTS OF ZEEMAN EFFECTS

The wave-guide absorption cell used in this work consisted of a conventional Stark septum wave guide three feet in length which could be rotated with respect to a magnetic yoke running the length of the guide. Actually two identical yokes were used: one in which the wave guide was inserted, and one in which the magnetic field was measured by means of a flip-coil. These yokes were carefully calibrated so that the error due to the field measurement was of the order of 0.5 percent.

As indicated above, the molecular g factor, g_J, was determined in an isotopic molecule which did not have hyperfine structure. The magnitude of g_J was measured by the normal Zeeman splitting for the $J=2\rightarrow 3$, $\Delta M = \pm 1$ transition of the molecule $OCSe^{80}$. The separation of the two components was determined as 92 kc/sec in a field of 6300 oersteds by matching the observed line shape with that obtained by adding two lines of equal intensity and of the same shape as the unsplit line. The width of the unsplit line at half maximum intensity was 120 kc/sec. Further, the g factor was determined as negative by the use of circularly polarized microwave radiation in a special wave guide of square cross section oriented in a longitudinal magnetic field. This apparatus and the technique involved has already been described.[4,14,15] The molecular g factor is thus determined as

$$g_J = -0.019 \pm 0.002.$$

Although this is the g factor for $OCSe^{80}$, it will differ from that of $OCSe^{79}$ only by the ratio of the rotational frequencies of these molecules, and this correction is therefore not significant.

For the hyperfine lines, the dependence of the α cosines given above on F indicates the necessity for using low F transitions to insure a splitting sufficient to distinguish the Zeeman components and measure them accurately in the available fields. Of the hyperfine lines measured, the $F=3/2\rightarrow 3/2$ line was selected as best meeting this requirement, although its intensity is only 17 percent of that of the strongest hyperfine component, the $F=11/2\rightarrow 13/2$ line. The absolute absorption of the $F=3/2\rightarrow 3/2$ line in the 1.2-percent abundant sample is 7.3×10^{-9} cm^{-1}, and the strongest Zeeman component in the $\Delta M = \pm 1$ transition is only one-fifth as intense with an absorption of 1.5×10^{-9} cm^{-1}. Because of this low intensity, the 2K33 klystron frequency was stabilized with respect to a microwave frequency standard harmonic by mixing the two signals in a crystal and detecting the difference with an FM receiver. The discriminator output was then used to control the repeller voltage of the klystron and thus effect stabilization. Slow sweeping of the klystron through the line frequency was achieved simply by tuning the receiver, and the absorption line was displayed on an Esterline Angus recording meter together with frequency markers obtained from the receiver dial calibration. The observed line intensities in the three-foot wave guide were three to four times the noise level at a guide temperature of -50°C.

The separation between the components $M=-3/2\rightarrow -3/2$ and $M=3/2\rightarrow 3/2$ was determined from ten

[14] J. R. Eschbach and M. W. P. Strandberg, Rev. Sci. Instr. **23**, 623 (1952).

[15] Bernard Burke, thesis, Massachusetts Institute of Technology, 1953 (unpublished).

pairs of recorder traces at fields ranging from 3100 to 6100 oersteds. From these data,

$$|g_I - g_J| = 0.271 \pm 0.002.$$

The $\Delta M = \pm 1$ transitions must thus distinguish between the two possibilities:

$$g_I = +0.252, \quad -0.290.$$

For the $\Delta M = \pm 1$ transitions the separations were measured between the $M = -1/2 \rightarrow 1/2$ and $M = 1/2 \rightarrow -1/2$ components from three pairs of traces. Table II compares the measured separation with that calculated for the two possible values of g_I, and establishes the negative value as correct, since the positive value is outside the experimental error. Alternately, the $\Delta M = \pm 1$ data may be used to calculate g_J. For $g_I = +0.252$, $g_J = 0.016 \pm 0.016$, while for $g_I = -0.290$, $g_J = -0.016 \pm 0.016$. Again, the positive value of g_I is excluded.

The Zeeman components displaced by Stark effect as well as those which were undisplaced by Stark effect were used in the evaluation of the data. Further, independent estimates were made at both MIT and Columbia of the separations as determined from the estimated center frequencies of the weak lines on the recorder traces. Both groups obtained exactly the same average g_I, although individual line separations varied by as much as 1 percent. Second-order perturbations representing a magnetic decoupling of I from F were calculated but are of the order of magnitude of the experimental uncertainties, being about 30 kc/sec. In any case they do not affect the net separation of the observed Zeeman components. Finally, the value given for the magnetic moment has not been corrected for the molecular diamagnetic susceptibility. Such a correction would be approximately 0.3 percent, and hence appreciably less than the experimental error.[16] The values obtained from an average of all the experimental measurements are

$$g_I = -0.290 \pm 0.004,$$

$$\mu(Se^{79}) = g_I I = -1.015 \pm 0.015 \text{ nuclear magnetons.}$$

The 1.5-percent experimental error is the sum of both frequency and field calibration errors.

Recorder traces are shown in Fig. 1 for a $\Delta M = 0$ and for a $\Delta M = \pm 1$ transition, illustrating the experimental signal-to-noise ratio. The valley on the left side of the peak in each figure represents absorption by a Zeeman component during the time when the Stark field was on, and the peak represents absorption by the same Zeeman component in the zero Stark field. The calculated Zeeman pattern is shown in Fig. 2. Of ten possible lines, only the strongest pair in each type of M transition was observed. Unfortunately, the current required to establish the strong magnetic field necessary for the $\Delta M = \pm 1$ transitions heated the wave guide to the extent that the OCSe dissociated and, because the amount of $OCSe^{79}$ was limited, precluded additional measurements.

TABLE II. Comparison of calculated and measured separations between $M = \frac{1}{2} \rightarrow -\frac{1}{2}$ and $M = -\frac{1}{2} \rightarrow \frac{1}{2}$ Zeeman components for the two possible g_I.

g_I	Calculated separation in Mc/sec	Measured separation in Mc/sec	Deviation in kc/sec
+0.252	1.956	2.144±0.050	188±50
−0.290	2.163	2.144±0.050	−19±50

[16] P. F. A. Klinkenberg, Revs. Modern Phys. **24**, 63 (1952).

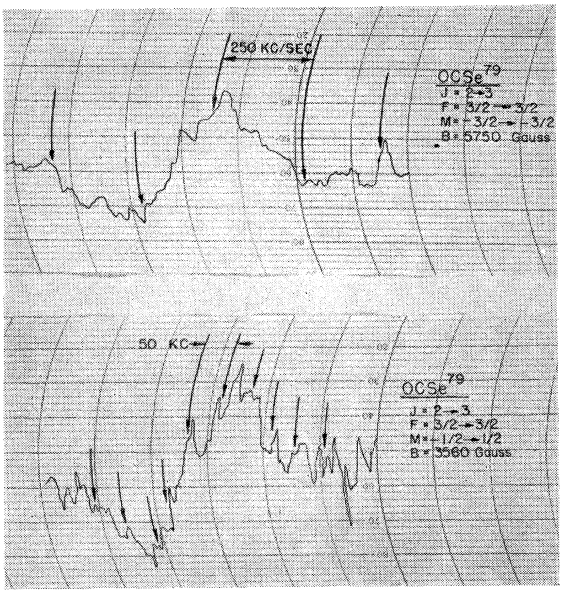

FIG. 1. Typical recording traces for a $\Delta M = 0$ and a $\Delta M = +1$ Zeeman component. The line is the positive hump on the trace and the valley at the left represents absorption during the presence of the Stark field. Frequency markers are shown above the lines.

(E) CHEMISTRY INVOLVED IN MAKING $OCSe^{79}$

Selenium metal containing 1.2-percent Se^{79} was converted to OCSe by introducing carbon monoxide to a pressure of one-half atmosphere into a reaction vessel containing the selenium. The vessel was sealed and heated to 500°C for fifteen minutes. The resulting OCSe was pumped into a trap cooled with liquid nitrogen and was collected.

The selenium metal was part of a larger sample isolated in June, 1949, in a search for a long-lived selenium activity in fission. It was derived from pile-irradiated uranium metal which had been subjected to the highest available neutron flux for a period of one year. The initial separation from uranyl chloride solution involved the usual reduction to elementary selenium in strong hydrochloric acid by means of SO_2 gas. Equilibration with chemical selenium was effected by the addition of the carrier at the end of the dissolution of the metal and prior to oxidation of UCl_4 to UO_2Cl_2.

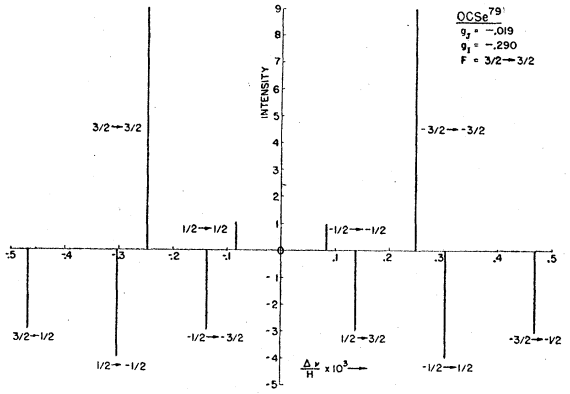

FIG. 2. Calculated Zeeman pattern for the observed $F=\frac{3}{2}\rightarrow\frac{3}{2}$ hyperfine component of $OCSe^{79}$ showing relative intensities. $\Delta M=0$ transitions extend upwards from the base line and $\Delta M=\pm 1$ transitions are indicated downwards.

The crude filtered product was dissolved in a few drops of nitric acid and purified by repeated distillations with 48-percent HBr followed by SO_2 reduction, each in the presence of hold-back carriers of As, Sb, and Tc. Finally, when the ratio of selenium activity to mass of selenium was no longer altered by chemical treatment, portions of the sample were electrolytically co-deposited with copper on platinum disks for counting. In order to obtain pure elementary selenium for this experiment, the plate was redissolved in a drop of nitric acid, fumed with HCl, reduced in $6N$ HCl with SO_2, centrifuged, dried, and weighed.

Since the mass analysis obtained was considered only qualitatively reliable, the apparent abundance in mass-79 has been estimated from the smooth-curve fission yield and the percentage of Se^{79} in the total selenium. From the known number of fissions in the uranium, a total yield of 2.7 milligrams of selenium was produced. Of this material, 10 percent or 270 micrograms was Se^{79}. When equilibrated with 20 milligrams of carrier containing no Se^{79}, this results in a final concentration of 1.2 percent.

(F) DISCUSSION

In addition to Se^{79} there are two other exceptional nuclei Na^{23} and Mn^{55}, whose spins differ from predictions of the single-particle model. All of these nuclei show a spin that is one less than that which would be expected on the single-particle version of the shell model, indicating that two nucleons fail to pair to give zero angular momentum, but give one instead.[16–18] For Se^{79} the two most reasonable configurations which would allow the 7/2 spin are thus $(p_{1/2})^2(g_{9/2})^5$ and $(g_{9/2})^7$, although it is conceivable that the 7/2 spin is due to a single $g_{7/2}$ neutron. However, while the negative sign of the measured magnetic moment is consistent with the two configurations given above, it definitely rules out the possibility of the single $g_{7/2}$ neutron. This follows because the g factor of any configuration whose moment is derived solely from $j=l+1/2$ neutrons, such as the two above, should be the same as for a single $j=l+1/2$ neutron, and hence negative. The g factor produced by a $j=l-1/2$ neutron should be positive. The measured magnetic moment, -1.015 nuclear magnetons, is in reasonable agreement with the value -1.50 nuclear magnetons calculated from a configuration of $j=l+1/2$ (and hence $g_{9/2}$) neutrons. The difference is in the same direction and of about the same magnitude as is generally found for deviations of magnetic moments from the Schmidt limits.[16]

It can be shown that there is only one properly antisymmetrized state corresponding to the configuration $(g_{9/2})^7$.[18] This state has an exceptionally large positive quadrupole moment of magnitude 1.34 times larger than the maximum quadrupole moment produced by any state conforming to the single-particle model. The configuration $(p_{1/2})^2(g_{9/2})^5$, on the other hand, is doubly degenerate and no combination of the degenerate states can produce more than a small quadrupole moment (one-seventh as large).[18] Hence, the measured large positive quadrupole moment is good evidence that the Se^{79} nucleus is best represented by a $(g_{9/2})^7$ configuration.

It is a striking fact that the quadrupole moments of the nuclei so far measured which are exceptions to the single particle version of the shell model are very large and positive. This includes Eu^{153}, as well as Na^{23}, Mn^{55}, and Se^{79} whose quadrupole moments have only recently been measured. Moszkowski and Townes discuss this and other evidence that a positive quadrupole moment tends to lower the energy of a nuclear state.[18]

Although the 7/2 spin of Se^{79} is an exception to the usual expectations, a spin of 7/2 in the $g_{9/2}$ shell is actually fairly common.[19] There is evidence[19] that it is the ground state of the odd-neutron nuclei Ge^{77}, Se^{79}, and Kr^{81}, and of the odd-proton nucleus Rh^{105}. Further, the 7/2 spin lies very close to the ground state in the odd-neutron nuclei Se^{77}, Se^{81}, Kr^{79}, Kr^{83}, and Sr^{85} and in the odd-proton nuclei Tc^{99}, Rh^{103}, Ag^{107}, and Ag^{109}. In these nuclei the 7/2 level shows strong competition with the $p_{1/2}$ level.

(G) ACKNOWLEDGMENT

The success of the above work is the result of the cooperative use of the facilities of a number of laboratories. The Se^{79} metal was prepared and purified at the Oak Ridge National Laboratory and converted to OCSe at Columbia University. The magnitude of g_J

[17] To this list Eu^{153} should probably be added. (See reference 18.)
[18] S. A. Moszkowski and C. H. Townes, Phys. Rev. (to be published).
[19] M. Goldhaber and R. D. Hill, Revs. Modern Phys. 24, 179 (1952).

for $OCSe^{80}$ was determined at Brookhaven National Laboratory and the sign in the apparatus for circular polarization at MIT. Final Zeeman measurements on $OCSe^{79}$ were made with a Columbia University spectrometer using an MIT Zeeman cell and magnet. Certain preliminary measurements were carried out at Brookhaven. The remainder of the measurements were done at Columbia.

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"Nonmesonic" Bound V-Particle Decay*

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A theoretical treatment is presented of the apparent relative stability of V particles in nuclear matter in terms of the process of bound V-particle nonmesonic decay. Mean lives for nonmesonic decay of V particles imbedded in nuclear fragments such as He, Li, $\cdots$O, are estimated as $\approx 10^{-11}-10^{-12}$ sec. A very brief discussion is given of the bearing of such relatively long mean lives on possible mechanisms of V-particle production.

INTRODUCTION

RECENTLY, cosmic-ray evidence has suggested the existence of unstable nuclear fragments ($Z \geqq 2$) emitted in high-energy events.[1] These fragments are observed to come to rest in emulsions in about 10^{-12} sec and then to decay with a visible energy release of 50–150 Mev. Since the mean life for the emission of a nucleon from a nuclear fragment having an excitation energy ≈ 100 Mev is $\approx 10^{-20}$ sec, it has been assumed[2] that all the "excitation energy" in such a fragment is concentrated on a single nucleon, i.e., that one of the nucleons in the fragment is a V particle; it is further assumed that this V particle (considered as an elementary fermion) is still bound to the other nucleons in the fragment by "nuclear forces" about as strong as those acting among the nucleons themselves. It is the purpose of the present note to relate the mean life for the decay (mesonic or nonmesonic) of such a "V-particle nuclear fragment" to the mean life for the mesonic decay of a free (unbound) V particle (free $V \to p+\pi^-$ +35–40 Mev, in about 10^{-10} sec).[3] In fact, the V particle bound in such a fragment may decay without the emission of a π meson, the appropriate energy and momentum balance being insured by the appearance of an ejected nucleon and a recoiling, in general excited, residual fragment. It is reasonable to suppose that this nonmesonic decay of a "V-particle nuclear fragment" is a process formally analogous to the nonradiative deexcitation of a nucleus in an ordinary excited state (internal conversion); the general basis of the analogy may be considered by postulating an appropriate Hamiltonian density H for the system of nucleons, V particles, and π mesons. We take

$$H=H(\psi_n)+H(\psi_V)+H(\varphi_\alpha)+H_{\text{prod}}(\psi_n, \psi_V, \varphi_\alpha, \cdots) + \frac{g}{2\kappa_n}(\psi_n^*\boldsymbol{\sigma}\tau_\alpha\psi_n)\cdot\nabla\varphi_\alpha+\frac{g}{2\kappa_V}(\psi_V^*\boldsymbol{\sigma}\tau_\alpha\psi_V)\cdot\nabla\varphi_\alpha + \left\{\frac{\eta}{\kappa_n+\kappa_V}(\psi_n^*\boldsymbol{\sigma}\tau_\alpha\psi_V)\cdot\nabla\varphi_\alpha+\text{h.c.}\right\}, \quad (1)$$

where

$\psi_n, \psi_V, \varphi_\alpha$ = quantized field amplitudes for the nucleon, V particle, and π-meson fields, respectively;

$H(\psi_n), H(\psi_V), H(\varphi_\alpha)$ = Hamiltonian densities for isolated nucleon, V particle, and π-meson fields, respectively;

κ_n, κ_V = inverse Compton wavelengths of the nucleon and V particle;

g = coupling constant between nucleon and π-meson fields;

η = coupling constant among nucleon, V particle, and π-meson fields ($\eta \ll g$ to account for the relatively long mean life of a free V particle against decay into a nucleon and π meson);

$H_{\text{prod}}(\psi_n, \psi_V, \varphi_\alpha, \cdots)$ = relatively large interaction term describing V-particle production in nucleon-nucleon and/or π-meson nucleon collisions, and contributing a major part of the V-particle nucleon

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[1] M. Danysz and J. Pniewski, Phil. Mag. **44**, 348 (1953); Tidman, Davis, Herz, and Tennent, Phil. Mag. **44**, 350 (1953); J. Crussard and D. Morellet, Compt. rend. **236**, 64 (1953); Freier, Anderson, and Naugle, preprint, Phys. Rev. (to be published).
[2] See M. Danysz and J. Pniewski, Phil. Mag. **44**, 348 (1953).
[3] Latest mean-life estimates in W. L. Alford and R. B. Leighton, Phys. Rev. **90**, 622 (1953); Fretter, May, and Nakada, Phys. Rev. **89**, 168 (1953); J. G. Wilson and C. C. Butler, Phil. Mag. **43**, 993 (1953); Bridge, Peyrou, Rossi, and Safford, Phys. Rev. **91**, 362 (1953).

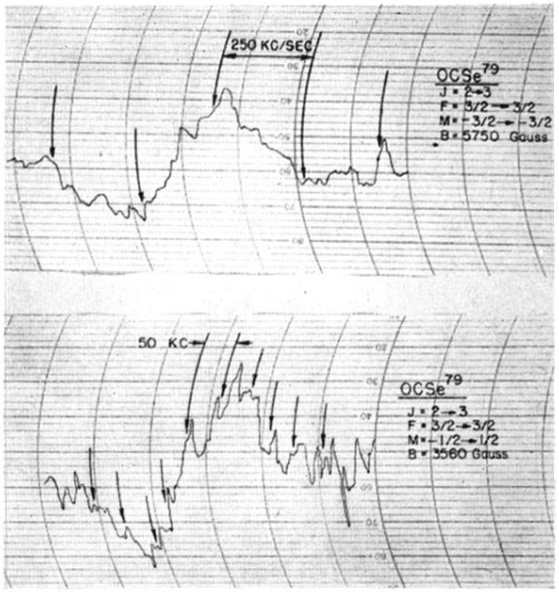

FIG. 1. Typical recording traces for a $\Delta M=0$ and a $\Delta M=+1$ Zeeman component. The line is the positive hump on the trace and the valley at the left represents absorption during the presence of the Stark field. Frequency markers are shown above the lines.