which depend upon the size and the shape of the container, but in the limit of large volume, the results obtained for Landau diamagnetism and the Haas-van Alphen effect agree with those obtained by many previous authors. This last result should not appear to be surprising. One of these authors,[1] however, criticizes the procedure in previous calculations of ignoring the contributions of surface electrons to the partition function, on the grounds that completely different results could be obtained by methods which one has no *a priori* reason for rejecting. More specifically, reference is made to the discrepancy between the results obtained by making the approximation of neglecting surface states before or after differentiating the partition function with respect to the magnetic field. This discrepancy has been discussed by Teller[3] and Van Vleck,[4] who concluded that while the contribution of the surface states to the partition function is negligible in the limit of large volume, the direct contribution of these electrons to the magnetic moment must be included if the procedure is followed of summing over states after differentiating the partition function. Osborne rejects this explanation by pointing out that Van Vleck omitted certain states, and by stating that if these states are included, completely unreasonable results are obtained. It is the purpose of this letter to indicate that a consistent inclusion of effects, of the order of those contributed by the omitted states referred to, leaves the results of Van Vleck unaltered.

Van Vleck considers the electrons to be enclosed in a container of cylindrical shape, the axis of the cylinder being parallel to the magnetic field. The inner electrons are treated as being completely free, and the Schrödinger equation for the motion of a free electron in a plane perpendicular to the magnetic field is solved in polar coordinates, with the result that the energy levels are given by

$$W=(n_1+|n_1|+2n_2+1)h\nu, \tag{1}$$

where n_1 is the azimuth quantum number, n_2 the radial quantum number, and ν the Larmor frequency. The partition function is taken to be

$$Z=\sum_{n_1}\sum_{n_2=0}^{\infty}\exp[-(n_1+|n_1|+2n_2+1)h\nu/kT], \tag{2}$$

where n_1 is to be summed over only those values of n_1 corresponding to inner electrons. Van Vleck takes the lower limit on this summation to be $n_1=-\pi eHR^2/hc$, R being the radius of the container; this value for the limit is obtained by considering the semiclassical equation

$$n_1=\pi eH(r^2-d^2)/hc \tag{3}$$

(r being the radius of the circular orbit and d the distance of its center from the origin) and by ruling out values of n_1 which would give $d>R$, on the assumption that $R\gg r$. The upper limit is taken to be $n_1=-1$, since, if $R\gg r$, only a negligible number of orbits encircle the origin (have positive n_1). It is this last assumption to which objection has been raised by Osborne. It is true that the sum in (2) includes many states for which the assumption $R\gg r$ is not valid, and hence states of positive n_1 should be included. For these states, however, the r^2 term in Eq. (3) cannot be ignored, and it is easy to see that the consistent inclusion of states of positive n_1, i.e., the correction of both the upper and lower limits on n_1, leads to results identical with those given by Van Vleck. If one introduces the principal quantum number $n=(n_1+|n_1|+2n_2)/2$, Eq. (1) becomes

$$W=(2n+1)h\nu, \tag{4}$$

and (2) becomes

$$Z=\sum_{n=0}^{\infty}\sum_{n_1}\exp[-(2n+1)h\nu/kT]. \tag{5}$$

It is clear that the upper limit on n_1 should be taken to be n. However, since the classical radius of the orbit is given by

$$r^2=hcn/\pi eH, \tag{6}$$

Eq. (3) can be written as

$$n_1=n-\pi eHd^2/hc, \tag{7}$$

and Van Vleck's criterion gives for the lower limit $n_1=n-\pi eHR^2/hc$. Thus, the correction of both the limits leads to all the results given by Van Vleck. It is thus seen that the inclusion of the orbits which enclose the origin does not lead to unreasonable results.

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Activation Cross Sections Measured with Antimony-Beryllium Photoneutrons. II

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ADDITIONAL measurements of activation cross sections using Sb–Be photoneutrons (energy≅25 kev) have been made using the technique described by Hummel and Hamermesh.[1]

Table I contains a list of these cross sections relative to Seren's[2] thermal cross section for the given element.

TABLE I. Natural atom cross sections for (Sb–Be).

Isotope ($A+1$)	Half-life	Natural atom cross section (millibarns)	Percent error
Co^{60}	10.7 min	7.7[a]	30
Cu^{64}	12.8 hr	85	25
Ge^{75}	82 min	14	10
Ba^{139}	85 min	53	10
W^{187}	24.1 hr	119	15

[a] This value is an upper limit. The very small number of counts above background made it difficult to obtain good half-life values. The value in the table is obtained by assigning to the 10.7-min activity all counts above background corresponding to a half-life of less than thirty minutes.

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Influence of the Nuclear Quadrupole Moment on the $\alpha-\gamma$ Angular Correlation in Radiothorium

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IT is well known that the angular correlation between two nuclear radiations can be affected by magnetic fields, either atomic or applied, acting on the magnetic moment of the nucleus in its intermediate state. No attention seems to have been paid so far, in this connection, to the quadrupole moment of the nucleus. The influence of the quadrupole coupling on the angular correlations and the possibility of using this effect to measure the quadrupole moments of short-lived isomers are discussed in detail in a forthcoming paper by Abragam, Bloembergen, and Pound. The purpose of the present letter is to show that such coupling provides an explanation for the discrepancy between experimental and theoretical values of the $\alpha-\gamma$ correlation in the disintegration of radiothorium which has recently been investigated by two different groups.[1,2] Their results agree within experimental error.

The correlation is given in reference 1 as

$$W(\theta)=1+6.9\cos^2\theta-7.07\cos^4\theta,$$

or, if we rewrite it in terms of Legendre polynomials,

$$W(\theta)=1+0.30P_2-0.86P_4.$$

The theoretical correlation resulting from the most plausible disintegration scheme ($I_a=0$, quadrupole α-emission, $I_b=2$, quadrupole γ-emission, $I_c=0$) is $W=\cos^2\theta-\cos^4\theta$ or $1+(5/7)P_2-(12/7)P_4$. It is seen that the experimental correlation is weaker

than the theoretical one. The experimental coefficients of the second and fourth Legendre polynomials are, respectively, smaller than the theoretical ones by the factors $G_2=0.42$ and $G_4=0.50$.

Such a weakening can be produced by the interaction of the quadrupole moment in the intermediate state with the gradient of the electric field at the nucleus. If we assume that the field has axial symmetry and that all directions of its axis are equally probable (as for a crystalline powder), it can be shown that for a nucleus of spin 2,

$$G_2^{\text{theor}}=(1/35)[8(1+16x^2)^{-1}+12(1+9x^2)^{-1}+2(1+x^2)^{-1}+13],$$
$$G_4^{\text{theor}}=(1/63)[6(1+16x^2)^{-1}+16(1+9x^2)^{-1}+12(1+x^2)^{-1}+29].$$

In this formula $x=2\pi\nu\tau$, where τ is the lifetime of the intermediate state and $h\nu$ the energy difference between the states $M_h=0$ and $M_h=\pm1$ of the quadrupole moment in the axial field.

G_2 and G_4 are decreasing functions of x which vary very slowly for $x>1$.

$$G_2(0)=G_4(0)=1;$$
$$G_2(1)=0.45, \quad G_4(1)=0.59,$$
$$G_2(\infty)=0.37, \quad G_4(\infty)=0.46.$$

If we take $\tau=10^{-8}$ sec,[1,2] $x=1$ corresponds to a frequency ν of 15 Mc/sec. Much higher quadrupole interactions have been observed in nuclear resonance experiments, and values of x much higher than 1 are by no means unlikely.

It follows from this that G_2 and G_4, and therefore the correlation, are practically independent of the value of the gradient of the electric field as long as it is large enough (ν higher than 15 Mc/sec). This is particularly important in view of the fact that after the α-emission, the nucleus, which has a recoil energy higher than 100 kev, can occupy any position with respect to the surrounding atoms or molecules. Such circumstances are favorable for large electric field gradients with considerable variation in magnitude and direction from one radioactive nucleus to another. For $x>1$ the agreement with experiment is very good.

The near constancy of the G's for $x>1$ explains why both experimental groups obtain almost identical results using different source materials. A departure of the electric field from axial symmetry is not likely to affect the previous results drastically.

The fact that G_4 is larger than G_2, theoretically and experimentally, suggests very strongly that the influence of atomic magnetic fields on the correlation is very small. It can be shown[3] that a magnetic field, whether atomic or applied, affects the higher harmonics most strongly and would lead to $G_4 \ll G_2$.

The nuclear electric quadrupole interaction in the intermediate state appears to offer explanation of discrepancies observed in many other angular correlation experiments. Other examples will be discussed in the later paper.

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Neutron Capture Cross Sections for Production of Sc^{46} and Sr^{85}†

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CONSIDERABLE uncertainty exists in the literature concerning the thermal neutron capture cross section for production of both 85-day Sc^{46} and 65-day Sr^{85}. Tabulated nuclear data[1] give conflicting values for Sc^{46} and none for Sr^{85}.

Bethe[2] has reported >13 barns for the reaction $Sc^{45}(n,\gamma)Sc^{46}$. Seren *et al.*[3] report 22 b. Recently Pomerance[4] has measured the capture cross section for pile neutrons using the pile oscillator. He finds 23±1.5 barns.

Samples of spectroscopically pure Sc_2O_3 together with weighed pieces of Al–Mn alloy of known Mn concentration were irradiated in the Oak Ridge National Laboratory graphite reactor for eight hours. Upon removal from the reactor the decay of the monitor metal was followed in a calibrated high pressure ionization chamber, and the activity of the product 2.59-hour Mn^{56} was determined. The neutron flux was then calculated using the expression

$$A=Nf\sigma(1-e^{-\lambda t}),$$

where $\sigma=13$ barns.

Samples of the irradiated Sc_2O_3 were then weighed on an analytical balance, and the activity of the daughter Sc^{46} determined from ion chamber measurements. After correction for decay from pile discharge time, the pile neutron cross section for Sc^{46} was calculated as above and found to be 21.6±2 barns. Goldhaber and Muehlhause[5] have reported a 20-sec isomer of Sc^{46} which has an activation cross section of 10±4 barns. Thus the cross section for direct production to the ground state 85-day activity is 12 barns, and the value of 22 barns is the "effective" production cross section for the longer-lived activity.

Sr^{85} is a K electron capturing nuclide whose decay scheme has only recently been completely elucidated by Sunyar *et al.*[6] These workers have established that Sr^{85m}, which is the 70-min excited state initially produced, decays to Sr^{85} (65-day) in 86 percent of the disintegrations. Recently Harrison and Seymour[7] have reported an "effective" production cross section of Sr^{85} of 0.3±0.1 measured relative to the 5-mb cross section for the Sr^{89} 53-day activity.

The thermal neutron cross section for production of Sr^{85} has been obtained by use of $SrCO_3$ enriched to a Sr^{84} concentration of 45.95 percent.[8] Samples of $SrCO_3$ together with cobalt monitor metal were irradiated in the Oak Ridge National Laboratory graphite reactor for two weeks. After cooling one week, the $SrCO_3$ and Co metal were weighed, and the activity produced in them was read on the calibrated high pressure ionization chamber. By use of the decay scheme noted above, the activity of product Sr^{85} was calculated. The "effective" isotopic capture cross section for the production of Sr^{85} was then calculated and found to be 1.2±0.1 barns.

To establish that the γ-activity observed was due solely to radiation from the primary product nuclides, portions of the irradiated material were examined on a NaI(Tl) crystal γ-ray spectrometer equipped with a linear amplifier and differential and integral pulse-height selector. The γ-spectra so obtained indicated the activities to be pure Sc^{46} and Sr^{85}.

Table I is a summary of the results.

TABLE I. Capture cross sections for pile neutrons.

Target atom	Product atom	"Effective" isotopic capture cross section (barns)	Atomic capture cross section (barns)
Sc^{45}	Sc^{46}	21.6±2	21.6±2
Sr^{84}	Sr^{85}	1.2±0.1	0.0066±0.0006

† Based on work performed by the U. S. Atomic Energy Commission.
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Angular Distribution of Particles from Stars*

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IN our recent communications[1,2] we have described the experimental arrangement and some preliminary results obtained on stars induced by high energy neutrons in 200-μ Ilford G5 plates.