It is unfortunately not possible to obtain the quadrupole moment of $Be^9$ from the observed splitting since the electric field gradient at the nucleus is unknown. Since the observed quadrupole interaction energy $eQ\partial^2V/\partial z^2$ is about ten times smaller for Be than Al, and since the nuclei occupy fairly similar positions in the crystal,[2] it seems reasonable to suppose that the quadrupole moment of $Be^9$ is appreciably smaller than that of $Al^{27}$ and probably of the order of $0.02\times10^{-24}$ $cm^2$.

In addition to the lines due to Al and Be, a very weak resonance was also observed at a field corresponding to a $g$ factor of 1.11. As there was no detectable shift of the resonance on rotation of the crystal axis with respect to the magnetic field it was due to a nucleus with very small or zero quadrupole moment. We have also observed the same resonance in two specimens of glass and we think it is probably the result of $Si^{29}$. According to the theory of Mayer[3] the spin of $Si^{29}$ should be $\frac{1}{2}$, and experiments by Townes et al.[4] have shown that the quadrupole moment is small or zero. If we assume $I=\frac{1}{2}$, the magnetic moment is 0.55 nuclear magnetons which is in very good agreement with the value predicted for $Si^{29}$ by the theory of Schawlow and Townes.[5]

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## The Effect of Scattering on Angular Correlation Measurements

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THE purpose of this note is to describe a simple method for correcting measurements of angular correlations (involving electrons) for multiple scattering in the source and for the finite solid angle of the detectors, which will allow the experimenter to determine specific activities needed for such measurements.

Consider an $e$-$\gamma$-experiment, where $W(\theta)$ is the correlation function and $F(\alpha)$ is the scattering function. The probability that a $\gamma$-ray will enter $d\Omega_1$ and that any electron correlated to it by $W(\theta)$ will be scattered through an angle $\alpha$ and enter $d\Omega_2$ is

$$P=d\Omega_1d\Omega_2\int d\Omega_\theta W(\theta)F(\alpha). \qquad (1)$$

The experimental correlation may be determined by the tedious process of evaluating $F(\alpha)$ numerically, expressing $\alpha$ in terms of $\theta$, $\varphi$, etc., and carrying out the integral (1) numerically. However, in general,

$$W(\theta)=(1/2\pi)\Sigma\tfrac{1}{2}(2l+1)a_lP_l(\cos\theta) \qquad (2)$$

$$F(\alpha)=(1/2\pi)\Sigma\tfrac{1}{2}(2k+1)b_kP_k(\cos\theta). \qquad (3)$$

By expressing $P_k(\cos\alpha)$, via the addition theorem, in terms of $\theta$ and of $\beta$, the angle between $d\Omega_1$ and $d\Omega_2$, one obtains

$$P=d\Omega_1d\Omega_2[(1/2\pi)\Sigma\tfrac{1}{2}(2l+1)a_lb_lP_l(\cos\beta)]. \qquad (4)$$

Similar expansions of $P_l(\cos\beta)$ and integrations over $d\Omega_1$ and $d\Omega_2$ yield:

$$P=S_1S_2(1/2\pi)\Sigma\tfrac{1}{2}(2l+1)a_lb_lg_lh_lP_l(\cos\theta), \qquad (5)$$

where now $\theta$ is the angle between the centers of two circular counters of solid angle $S_1$ and $S_2$ and half-angles $g_0$ and $h_0$ respectively, and

$$g_l\equiv\int_0^{g_0}P_l(\cos\alpha)d(\cos\alpha)\Big/\int_0^{g_0}d(\cos\alpha) \qquad (6)$$

with a similar definition for $h_l$. We note that $S_1g_l$ is the coefficient in (3) for $F(\alpha)=1$, $0\le\alpha\le g_0$; $F(\alpha)=0$, $g_0\le\alpha\le\pi$, so that the solid angle correction is identical with a scattering correction. The bracket in (4) represents a new correlation function so that similar treatment extends the result to many "scatterings." Thus, given $n$ events such that the $k+1$th event is correlated to the $k$th event by $W_k(\theta_k)=(1/2\pi)\Sigma\tfrac{1}{2}(2l+1)a_{lk}P_l(\cos\theta)$, then the correlation between the first and the $n$th event is just

$$W_n(\theta_n)=\frac{1}{2\pi}\Sigma\frac{2l+1}{2}\Big(\prod_{k=1}^{n-1}a_{lk}\Big)P_l(\cos\theta_n) \qquad (7)$$

where $\theta_n$ is the angle between the first and the $n$th events.

(1) Equation (7) extends (5) to $e$-$e$ angular correlations. (This formula is valid only if the correlation between the $k+1$th and $k$th events, $W_k$, is independent of the previous events. Thus it should not give the angular correlation between the first and last events of a cascade transition.)

(2) The form of the correlation is unaffected by the presence of scattering or finite $\varphi$-symmetric detectors. For example, if only $P_2$ appears in the experimental data, (say $W(\theta)=1+A\cos^2\theta$ $=1+aP_2$) then only $P_2$ is present in the correlation function. This is of interest since often the highest power of $l$ appearing in $W(\theta)$ is of importance even when the $a_l$ are not accurately known. (Where lens spectrometers are used to detect the electrons the form is still unaltered but $g_1$ and $g_2$, the acceptance angles of the spectrometer, replace 0 and $g_0$ in the limits in (6).)

(3) The multiple scattering coefficients $b_l$ are just the correction factors for $a_l$ so that one need not evidence $F(\alpha)$ explicitly. Usually only $b_2$ or $b_2$ and $b_4$ are needed. In the Goudsmit and Saunderson[1] treatment of multiple scattering

$$b_l=\exp[-q(1-C_l)/b_1]\equiv\exp(-ml) \qquad (8)$$

where $q=Nst$ ($N=$ atomic density; $s=$ total single scattering cross section; $t=$ effective source thickness) and $c_l$ is just the coefficient of the $P_l$ expansion of $f(\theta)$, the single scattering function. The reader is referred to this treatment for a discussion of assumptions inherent in (8) and for simple expressions for $b_l$ in terms of electron energy, source thickness, atomic number, etc.

(4) Electrons originating near the surface of a source are scattered less than Eq. (8) indicates. (8) applies to a collimated electron beam traversing a foil. A first-order approximation valid when (8) is valid and applicable to thin sources would replace $b_l$ by $(1-b_l)/ml$.

(5) Order of magnitude results using the above approximations: for a source thickness of 200 micrograms ($Z=52$; $A=120$; $E=100$ kev) $b_2=0.9$, $b_4=0.77$. For a half-angle of $18°$ $g_2=0.9$, $g_4=0.75$.

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## Emission of Long-Range Particles in the Fast Neutron Ternary Fission of U-238 and Th-232

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FOLLOWING a detailed investigation of the long-range particles emitted in the slow neutron ternary fission of U-235 by the photographic plate method,[1] experiments were undertaken to determine whether similar phenomena occur in the fast neutron fission of U-238 and Th-232. Although Tsien et al.[2] reported that U-238 gave no such long-range particles when irradiated by neutrons from the bombardment of beryllium by 6.7-Mev deuterons and Tsien and Faraggi[3] obtained a similar result for Th-232, yet the observation of such a mode of photofission in uranium by Titterton and Goward[4] and in thorium by Titterton and Brinkley[5] threw doubt on the validity of the argument used by the French group to explain the absence of the long-range particles in their experiments.

In the present experiments two sets of plates, each including Ilford $C_2$ and $D_1$ emulsions, were loaded with uranium acetate and thorium nitrate respectively, as described elsewhere[4,5] and were exposed to neutrons of energy 2.5 Mev obtained from the

Harwell 200-kev $D-D$ source. Because of the low values of the fission cross sections concerned, long irradiations ($\sim$8 hours) were necessary and, as both types of emulsion were used under conditions where they recorded protons of 2.5-Mev energy, a large background of recoil protons and natural radioactive $\alpha$-particles was present in the processed emulsions. A high rate of chance superposition of tracks was therefore to be expected. However, since the maximum range of the recoil protons was 56$\mu$ while the maximum $\alpha$-particle range in the uranium case was 39$\mu$ and in the thorium case 48$\mu$, it was certain that any fission events having light fragments of range in excess of 60$\mu$ could not be due to a chance juxtaposition of tracks.

As normal isotopic uranium was used in the experiment, the plates loaded with this material were wrapped in thin cadmium foils to reduce the chance of slow neutron fission in the U-235 component resulting from the slight background of scattered neutrons. The fission cross sections of U-235 and U-238 at 2.5 Mev are such that fission events resulting from the rarer isotope could not be more than a percent or two of those resulting from the U-238. Search of the uranium loaded emulsions yielded 8 cases of ternary fission with the emission of a light, charged fragment of range greater than 60$\mu$ among 12,000 binary fissions. The greatest range observed was 202$\mu$. In addition there were 8 events having light particles lying in the range interval 20 to 60$\mu$ and which, in the light of experience gained in earlier experiments,[1,4,5] appeared to be ternary fission.

In the case of the thorium-loaded emulsion 14,000 fission events were examined; all of these were fast neutron induced since the threshold is at $1 \cdot 1$ Mev. Seven events were found having light fragments of range 60$\mu$ and five where the range of the light fragment lay between 20 and 60$\mu$. The longest range observed in this case was 243$\mu$.

The general character of the events in all cases was similar to those observed in the slow neutron[1] and photofission experiments[4,5] i.e., the light particle appears to be an $\alpha$-particle and is emitted preferentially near to 90° from the heavy fragments.

Deductions as to the relative frequency of binary and ternary fission in these experiments cannot be drawn with confidence since, with such a high background of tracks, it is not certain that the observers would find all ternary events. However, it appears that the frequency of ternary fission is similar to that observed in the slow neutron fission of U-235.

These experiments therefore throw further doubt on the theory advanced by Tsien[6] which suggests that the emission of the long-range fragments is connected with the excitation of the compound nucleus, being less favored the greater the value of the excitation energy.

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## Energy Storage and Light Stimulated Phosphorescence in Activated NaCl Crystals Induced by Gamma-Rays*

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IN a previous paper[1] experiments on fluorescence, phosphorescence, and light stimulation in sodium chloride crystals activated with 1 percent silver chloride were described. Three different decay times occur with these crystals. First, immediately after excitation by high energy radiation, the emitted light decays quite slowly with a period (designated by lifetime of instantaneous phosphorescence) of minutes, hours, or even days, depending on the period, rate, and type of high energy radiation. Second, if such a crystal is then irradiated with light of the near ultraviolet or the visible region, even after its phosphorescent light emission has considerably decreased, a new light emission is stimulated mostly in the ultraviolet region around 2400 to 3000A which again decays rather slowly after the stimulating light has been switched off (designated by lifetime of stimulated phosphorescence). Third, if the stimulation of the crystal is deferred for a considerable period of time it should be expected that the amount of stimulated light decreases since the storage qualities of the crystal may not be perfect (designated by lifetime of storage).

This letter is concerned principally with experiments trying to link these processes to the phenomenon of color centers in alkali-halide crystals. It was found that the lifetime of instantaneous phosphorescence and that of stimulated phosphorescence are closely connected to each other and probably originate from the same energy levels. The lifetime of the instantaneous phosphorescence increases considerably with increasing time of irradiation applied at the same rate. This lifetime is also considerably longer if the same total amount of high energy radiation is applied during a long period than during a short period of irradiation. The same is true for the phosphorescence of the stimulated light. If the same total amount of stimulating light is applied during a short period. the decay of the stimulated light is shorter than the decay when the same stimulation is applied during a longer period. For instance, with a short-time gamma-irradiation (5 minutes) the instantaneous phosphorescence decreased to 14 percent of its original value within eight minutes, with a long-time irradiation (12,000 minutes) applied at the same rate the same percentage decrease was reached only after eight thousand minutes.

These increased lifetimes with extended periods of irradiation indicate that electron traps of different depths are responsible for this phosphorescence. The deeper traps which give a longer lifetime are filled to an equilibrium value only after the time of irradiation is extended for a time longer than the lifetime associated with these traps. Thus, with increased times of irradiation the deeper traps are filled to a higher degree and the lifetime is thus extended, whereas the shallower traps are already filled to an equilibrium level after a shorter time of irradiation.

It is noteworthy that the amount of stimulated light, however, is essentially independent of the time of irradiation by high energy radiation but depends mostly on the total dosage. This indicates that in those traps responsible for the observed phenomenon of long-time decay only a relatively small part of the energy which can be released as light is stored.

The third lifetime, namely, that of storage could not yet be determined very accurately. The amount of energy stored, which is indicated by the intensity of the stimulated light, does not decrease by more than two or three percent during one day under normal laboratory conditions according to our observations. This means a lifetime of the order of weeks or longer.

The idea presents itself that this long-time storage is in some way connected to the formation of color centers in alkali-halide crystals since it is known that these persist for long periods of time. It was observed that the crystals of high storage qualities show a considerable coloration after a gamma-dose of 1000 roentgens and more. The color was in this case brownish; the spectrum is similar to the absorption spectrum of the pure colored centered sodium chloride crystals.[2] This coloration increased with increasing doses and was thus as indicated above parallel to the stimulability of the crystal, and the color disappeared under constant irradiation with visible light as did the stimulability. Other crystals of the same kind but made differently, which also show a considerable fluorescence but a much smaller stimulability, exhibited a much smaller coloration. Repeated gamma-irradiation of the crystal up to 10,000 roentgens makes the crystal quite brown, but this color can be made to disappear by continued irradiation by the stimulating light, at which time the light stimulated intensity is very small.