crystal was bombarded by ~15 mC of polonium α's, a spectrogram showing an emission band at ~4500A was obtainable within two days. The emission band along with the calibration lines of a mercury arc are drawn in Fig. 1.

A crystal of thoria was irradiated by 15 mC of polonium α's for a period of five minutes. A fast decaying alpha-particle excited phosphorescence, superposed upon the "natural" luminescence, was observed as shown in Fig. 2, curve A. Subtraction of the natural luminescent intensity arising from the internally emitted nuclear radiations yields curve B, the decay curve of the rapidly decaying α-particle induced phosphorescence. Since the curve assumes no constant slope in the time interval covered by the observations, a likely interpretation is that the decay curve is a composite one formed by a superposition of two or more power laws.

Numerous auxiliary experiments were performed to eliminate the possibility that the measured natural luminescence be generated by irradiation of air surrounding the thoria or by bombardment of the glass envelope of the phototube.

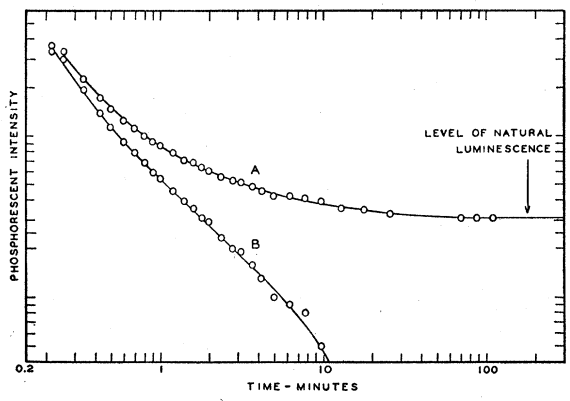

FIG. 2. Decay of the alpha-particle induced phosphorescence of thoria. Curve A is a plot of the observed emission; curve B, phosphorescent decay corrected for the presence of thoria's "natural" luminescence.

It is to be expected that radioactive uranyl salts also possess an intrinsic luminescence. Uranyl nitrate was observed to emit light resulting from interval emission of α-, β-, and γ-rays. Its light emissions seem, however, to be confined to fluorescence or a very short-lived phosphorescence. Measurements commenced a few seconds after cessation of irradiation by polonium alpha-particles and ultraviolet light gave no evidence of any appreciable phosphorescence.

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[1] The autoexcited luminescence of *radium* compounds was studied by early investigators. See, for example, J. A. Rodman, Phys. Rev. **23**, 478 (1924). References to still earlier measurements are contained in this paper.

[2] The luminescence of ThO_2 activated by Pr, Sm, and Tb has been studied under x-ray, cathode ray, ultraviolet light, and hydrogen flame excitation by F. G. Wick and C. G. Throop, J. Opt. Soc. Am. **25**, 57 (1935). These authors do not comment upon any self-induced luminescence nor do they appear to have studied the afterglow in particular. A spectrographic analysis of the thoria employed by the writers showed that Al, Be, Ce, Cr, Cn, La, Si, Ti, Yt, and Zr were all present simultaneously in activator quantities.

Angular Correlations from Liquid Sources

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IN a previous note, discrepancies between expected and observed angular correlations, such as that of the $\alpha-\gamma$ cascade of radiothorium, were shown to be attributable to the coupling of the nucleus in its intermediate state to crystalline electric fields.[1] Results more nearly like those expected are found when the source is put into the liquid state, usually as an aqueous solution. The reasons for this can be understood in terms of the analogous difference that exists between the liquid and solid states in nuclear paramagnetic resonance.[2] For example, "pure quadrupole" resonance in the absence of an applied magnetic field can only be observed in the solid state. This note will show that discrepancies between expected and observed angular correlations from liquid sources, such as that reported for Rh^{106} by Kraushaar and Goldhaber,[3] can result from the electric quadrupole moment in the intermediate state of the nucleus.

The liquid state characteristically lacks more than very short-lived spatial configurations of its component molecules. The effect of continual rearrangements, resulting from "Brownian motions," would be continuous reorientation, in a random manner, of the normal axes of any electric field gradient that would interact with the nuclear quadrupole moment. For simplicity the field gradient may be supposed axially symmetric and of constant magnitude $\partial^2V/\partial z'^2$, where z' is taken along the symmetry axis. With respect to a stationary coordinate system, the quadrupole interaction, then, has time-dependent off-diagonal matrix elements through the time dependence of the functions of the relative angles of orientation of the coordinate systems, as given by Eq. (18) of reference 2. This time dependence can be expressed by the correlation function of the random functions, taken as their mean squared values multiplied by the usual factor $\exp(-t/\tau_c)$, where τ_c is called the "correlation time." If the nuclear lifetime $\tau_N \gg \tau_c$ and if $eQ\tau_c(\partial^2V/\partial z'^2)/\hbar \ll 1$, no preferred direction other than that introduced by the first counter can exist. Thus the direction to the counter can be taken as the direction of quantization. The electric quadrupole interaction can then be regarded as a "relaxation" mechanism whereby the unequal probabilities of the magnetic substates of the intermediate nucleus, initially set by the detection of a decay by the counter, are altered toward eventual equality.

If the undisturbed angular correlation is expressed in the form $1+\Sigma_k A_k P_k(\cos\theta)$, this model results in a function $1+\Sigma_k G_{kI_B} \times A_k P_k(\cos\theta)$, where the factors G_{kI_B} may be regarded as attenuation factors and are independent of the nature of the radioactive transitions to and from the intermediate state. All the factors G_{kI_B} are of the form

$$G_{kI_B} = \{1+\lambda_{kI_B}[eQ(\partial^2V/\partial z'^2)/\hbar]^2\tau_N\tau_c\}^{-1},$$

where λ_{kI_B} depend only on k and I_B, the spin of the intermediate state. Table I gives values of λ_{kI_B} calculated from the model in a manner to be published in a later, more detailed paper.

TABLE I.

k \ I_B	1	3/2	2	5/2
2	9/40	1/5	17/160	63/1000
4			1/16	21/200

The $\gamma-\gamma$ correlation of Pd^{106} following β-emission of Rh^{106} shows, from the results of Kraushaar and Goldhaber,[3] $G_{22}=0.779$ and $G_{42}=0.864$. These lead, independently, to the remarkably consistent values of 2.66 and 2.53 for $[eQ(\partial^2V/\partial z'^2)/\hbar]^2\tau_N\tau_c$. Thus a value greater than 1160 Mc/sec for $eQ(\partial^2V/\partial z'^2)/h$ is indicated for τ_N less than 5×10^{-9} sec if τ_c is taken to be 10^{-11} sec. The failure by Steffen[4] to observe differences in the angular correlations with different solid samples is explained by such a large interaction. All samples are presumably in the condition $[eQ(\partial^2V/\partial z^2)\tau_N]/\hbar \gg 1$, and thus the correlations are independent of $\partial^2V/\partial z^2$ in the solid state.[1]

Although the atomic state of the Pd^{106} following the 2.44-Mev β-decay from Rh^{106} is not known, it is unlikely that $\partial^2V/\partial z'^2$ would be much larger than that of a pure p electron in this region of the periodic table. In the pure p state, I^{127} shows a value of

$(eQ\partial^2V/\partial z'^2/h)$ of 2500 Mc/sec and thus the magnitude of Q for the excited, spin 2, of even-even Pd^{106} is probably at least as large as 0.2×10^{-24} cm^2.

Finally, it might be remarked that for the factors GkI_B very near unity the attenuation factors for the solid lattice and for the liquid give the same results if τ_N^2 in the formulas for the solid are replaced by $\tau_N\tau_c$. On the other hand, the "relaxation" process involved in the liquid can truly be regarded as a "loss of memory." In contrast, the characteristic frequencies produced by static interactions in solids or by applied fields could be observed by the use of delayed coincidence techniques. Thus the term "loss of memory" in those cases is inappropriate.

[1] A. Abragam and R. V. Pound, Phys. Rev. **89**, 1306 (1953).
[2] R. V. Pound, Phys. Rev. **79**, 685 (1950).
[3] J. J. Kraushaar and M. Goldhaber, Phys. Rev. **89**, 1081 (1953).
[4] R. M. Steffen, Phys. Rev. **86**, 632 (1952).

The Use of the Tamm-Dancoff Method in Field Theory

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MANY authors[1] have discussed the application of the Tamm-Dancoff method[2] to problems of field theory. In this method the wave function of a system is represented by the amplitude $a(N)$ for finding a prescribed set N of occupation numbers. N is a set of integers giving the number of particles present in each of the normal modes of the noninteracting fields. Let E_N be the total energy of the free particles specified by N. The Schrödinger equation for a state of the interacting fields with energy E becomes

$$(E-E_N)a(N)=\Sigma_M H'(MN)a(M), \tag{1}$$

where $H'(MN)$ is the matrix element of the interaction operator H' between the states specified by N and M. The Tamm-Dancoff method consists in breaking off the infinite set of Eq. (1) by omitting all terms involving amplitudes $a(M)$ with more than a fixed number of particles. The finite set of equations so obtained can then be solved by standard methods.

Unfortunately, the method runs into a serious difficulty connected with the vacuum self-energy. When Eq. (1) is iterated once, we obtain

$$(E-E_N)a(N)=\left\{\Sigma_M\frac{H'(MN)H'(NM)}{E-E_M}\right\}a(N)+\text{other terms}. \tag{2}$$

The sum on the right of (2) is very badly divergent, since H' has matrix elements for creating 3 particles with only one relation between the 3 momenta. This divergence cannot be eliminated by renormalization. It shows a real inadequacy in the Tamm-Dancoff method. Physically, every state of the interacting fields contains very many particles which are continually created and annihilated in the vacuum. Restricting the total wave function to a fixed number of particles imposes an artificial correlation between the vacuum fluctuations at points far distant in space. This artificial correlation makes itself felt in Eq. (2) as a spurious effect of the vacuum fluctuations upon the behavior of real particles.

A simple modification of the Tamm-Dancoff method will avoid this difficulty entirely. Let Ψ be the actual state of the system with energy E, and let Ψ_0 be the vacuum state of the interacting fields with energy E_0. Both E and E_0 are infinite, but the observable difference $\epsilon=E-E_0$ is finite. We write $A(N)$ for the product of free particle annihilation operators which annihilates the particles specified by N, and $C(N)$ for the product of the corresponding creation operators. Instead of the Tamm-Dancoff amplitude $a(N)$, we define

$$a(N', N)=(\Psi_0{}^*C(N')A(N)\Psi). \tag{3}$$

This describes the amplitude for finding in the actual state Ψ the set N of free particles *minus* the set N'. The minus particles are, loosely speaking, those which are absent in Ψ but present in the physical vacuum state Ψ_0.

The Schrödinger equations for Ψ and Ψ_0 now give

$$(\epsilon-E_N+E_{N'})a(N', N)=(\Psi_0{}^*[C(N')A(N), H']\Psi). \tag{4}$$

The commutator on the right of Eq. (4) can be expanded into a sum of products of creation and annihilation operators with the creation operators standing on the left[3] as in Eq. (3). Then (4) becomes a set of homogeneous linear equations for the amplitudes $a(N', N)$. These equations can be handled by the standard Tamm-Dancoff technique.

Equations (4) differ from (1) in three respects. (a) The physically observable energy ϵ appears instead of the meaningless quantity E. (b) The commutator on the right of Eq. (4) does not have matrix elements involving 3 particles with 2 arbitrary momenta. Instead one of the particles created or annihilated by H' has to belong to the discrete set specified by N or N', and hence only one degree of freedom is left for the momenta of the 2 remaining particles. This means that divergences of the unpleasant vacuum self-energy type can bo longer appear in the theory. (c) The appearance of "minus" particles in the amplitude $a(N', N)$ restores the symmetry between emission and absorption which is lacking in the Tamm-Dancoff method, and so brings the Tamm-Dancoff method into closer correspondence with formally covariant four-dimensional methods.

[1] This letter was stimulated by an unpublished paper by Marcello Cini, to whom the author is indebted for sending him a preprint.
[2] I. Tamm, J. Phys. (U.S.S.R.) **9**, 449 (1945); S. M. Dancoff, Phys Rev. **78**, 382 (1950).
[3] G. C. Wick, Phys. Rev. **80**, 268 (1950).

The Sign of the Phase Shifts in Meson-Nucleon Scattering

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FERMI and collaborators[1] have made extensive experiments on the scattering of mesons by nucleons and have analyzed their results in terms of phase shifts. As is well known, the sign of *all* phase shifts can be simultaneously reversed without changing the differential cross section. The relative signs are of course determined uniquely; in particular, the phase shifts of the two most important waves, S and $P_{3/2}$ for $I=3/2$, have opposite signs.

Fermi *et al.* have chosen the S wave phase-shift positive which conventionally denotes an attractive interaction. The $P_{3/2}$ shift is then automatically negative, i.e., repulsive.

On the other hand all theoretical papers on this subject make the opposite choice of sign. Indications are that the $P_{3/2}$ state has either an actual resonance or very nearly so which, of course, is only possible for an attractive interaction. The S state interaction, on the other hand, is mainly the strong repulsive "core" which has been discussed especially by Drell and Henley.[2]

The purpose of this note is to point out that there is actually some *experimental* evidence in favor of the choice of the theorists. Such evidence can, of course, only come from the interference of the nuclear scattering of mesons with some other scattering of known sign, and this means with Coulomb scattering. The only conclusive experiment of this type would be the observation of the interference with Coulomb scattering in meson-proton scattering, and Van Hove[3] has pointed out that such interference would be observable at quite reasonable angles (about 20°). However, until now no such experiments have been carried out.

The interference with Coulomb scattering has been observed, however, in the scattering of mesons by carbon nuclei. Byfield, Kessler, and Lederman[4] have shown that at 60-Mev meson energy the interference is constructive for negative, destructive for positive mesons, thus indicating an attractive nuclear interaction with the meson.