tical reasoning as the same complex that was obtained by adding donors, except for complete charge sign reversal. It is an electron bound to a negative acceptor ion by a hole pair bond.

The existence of this complex was pointed out by Lampert[4] who estimated its dissociation energy for equal masses of electrons and holes from Ore's calculation[5] of the minimum dissociation energy of a positron bound to a negative hydrogen ion. However, since Ore's calculated value is more than an order of magnitude too low,[6] Lampert's estimate of E_D is correspondingly in error. This is shown by a simple argument by Kohn[7] who is able to place E_D between $0.055E_i$ and $0.35E_i$ in satisfactory agreement with experiment.

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[1]J. R. Haynes, Methods of Experimental Physics, edited by K. Lark-Horovitz and V. A. Johnson (Academic Press, Inc., New York, 1959), Vol. 6, Part B, p. 322.

[2]The equation used is $R_1/R_2=(T_2^{3/2}/T_1^{3/2})\exp(E_D/kT_1-E_D/kT_2)$, where R is the ratio of the area under the sharp lines to that under the exciton line at temperature T. A factor N_1/N_2 should be included if the neutral donor population changes significantly between T_1 and T_2.

[3]G. G. Macfarlane, T. P. McLean, J. E. Quarrington, and V. Roberts, Phys. Rev. 111, 1245 (1958).

[4]M. A. Lampert, Phys. Rev. Letters 1, 450 (1958).

[5]A. Ore, Phys. Rev. 83, 665 (1951).

[6]Using the experimentally determined value of $E_D=0.1E_i$ and reversing Lampert's argument, we obtain a value for the dissociation energy of a positron bound to a negative hydrogen ion (or an electron bound to an antiproton by two positrons) of $0.1(13.6)=1.4$ ev. This is 20 times as large as Ore's calculated value.

[7]Walter Kohn (personal communication). His reasoning follows: For donor impurities the minimum energy of the complex will occur when the effective mass of the hole, $m_h \ll m_e$, the effective mass of the electron. For this condition the "Bohr radius" of the hole is so much larger than that of the two electrons that the system can be considered as consisting of a hole bound to a single negative electronic charge of relatively infinite mass. The dissociation energy $E_D=E_1+E_2-E_X$, where E_1 is the energy required to remove the hole, E_2 is the energy required to remove one of the electrons, and E_X is the energy gained in forming an exciton out of the freed electron and hole. But $E_1=E_X$ so that $E_D/E_i=E_2/E_i$, where E_2 is the energy required to remove an electron from a negative hydrogen ion (0.75 ev) and E_i is the ionization energy of hydrogen (13.6 ev). Thus, the minimum energy of $E_D/E_i=0.055$. The value of E_D/E_i will increase monotonically with m_h/m_e, reaching (when $m_h \gg m_e$) the asymptotic value $E_D/E_i=$(dissociation energy of a hydrogen molecule)$/E_i=4.5/13.6=0.33$.

SEARCH FOR DOUBLE-QUANTUM EMISSION IN THE DECAY OF Xe^{131m}

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As a competing process to the single-quantum decay of an excited nuclear state there is a double-quantum transition in which two gamma rays or conversion electrons are emitted simultaneously.[1,2,3] This second order process gives rise to a continuous distribution of the emitted gamma rays. The structure of this distribution depends mainly on the multipolarity of the two transitions. To date no experimental evidence has been found for the existence of two-quantum emission.

The possibility for detecting two-quantum emission should be largest when the single quantum transition is suppressed. This is, for example, the case in the 0+→0+ transition in Zr^{90}, where a single gamma transition is forbidden. The intense bremsstrahlung from the decay of Y^{90} seems, however, to make the observation of the double-quantum emission difficult. Another possibility for studying the double-quantum emission is in connection with a transition of high multipolarity. In this case the de-excitation can occur also by the emission of two quanta of lower multipolarities. This should be the situation in the decay of the isomeric $h_{11/2}$ level in Xe^{131} to the ground state by the 164-kev $M4$ transition. The relative intensity of any other gamma ray in this decay is estimated to be very low. Using an harmonic oscillator potential, Eichler and Jacob[3] have calculated the ratio between the transition probabilities for double- and single-quantum emission in the decay of Xe^{131m}. They obtained the ratio 5×10^{-5}. The weak, two-quantum distribution is very difficult to observe di-

rectly as it is usually masked by other processes giving similar distributions (i.e., Compton processes and bremsstrahlung). However, it would be possible to investigate the double-quantum emission by studying coincidences with the x rays from the internal conversion. Transitions of all energies are then detected in a narrow region (as x rays), which makes the observation more favorable compared with a distribution measurement.

The source, used in this investigation of the decay of Xe^{131m}, was prepared by an electromagnetic isotope separation of Xe, which was previously isolated as the daughter product of I^{131}. The strength of the Xe source was about 0.1 μC. The sample was placed between two NaI(Tl) crystals with 180° geometry. The backscattering from one crystal to the other was hindered by a lead and copper shield between the crystals. The source was surrounded by a thin Al foil stopping the conversion electrons. The pulses from one crystal were fed to a multichannel pulse-height analyzer, while the pulses from the other one were introduced into a single-channel analyzer. The position of this was varied in steps over the whole energy region up to 165 kev, while the multichannel analyzer in all cases recorded pulses corresponding to the x-ray region. Figure 1 shows the coincidence counting rate for the x-ray peak for different positions of the single channel. The points are corrected for the decay of the sample ($T_{1/2} = 12$ days), and also for the change in coincidence efficiency when both channels accept pulses due to x rays.

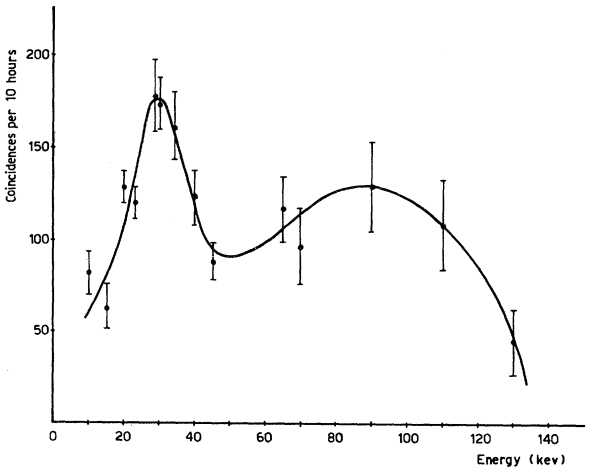

FIG. 1. Coincidence measurements between γ and x rays in the decay of Xe^{131m}.

For each position of the single channel, the pulses obtained which are in coincidence with the x-ray pulses detected in the multichannel analyzer can be due to different processes. No genuine coincidences with x rays occur to a first approximation with the Xe^{131m} sample, but a small I^{131} impurity gives rise to real coincidences. The correction due to the admixture of I^{131} is, however, very small. The rate of accidental coincidences is measured to be less than 2% of the observed counting rate. Other events that may contribute to the observed effect are:

(1) Scattering from one crystal to the other, especially of iodine x-ray escape photons. These effects are suppressed to a negligible value by the lead shield between the crystals.

(2) Internal Compton effect, which should be small for this transition energy.

(3) External bremsstrahlung from the conversion electrons, which is measured to be negligible.

(4) Compton scattering by K electrons (negligible).

(5) K-electron ionization of Xe (about 1 μg carrier in the sample), by the emitted K conversion electrons. This has been checked to be negligible.

(6) An intermediate level.

(7) Double-quantum emission.

Among these effects, only the last three are able to give rise to the observed peak in Fig. 1. As No. 5 is negligible and No. 6 is very improbable, the two-quantum emission is the most probable possibility. This is also supported by the measured distribution in Fig. 1.

From the peak in Fig. 1 it is possible to estimate the ratio between the double- and single-quantum emission. Assuming transitions of $E2M2$ type, a ratio of about 2×10^{-3} is obtained after correction for internal K conversion. This ratio, however, contains a large uncertainty, mainly due to the fact that the conversion coefficients used are those calculated for emission of only one electron, while in the present case there is an emission of two K conversion electrons simultaneously.

[1]M. Göppert-Mayer, Ann. Physik 9, 273 (1931).
[2]R. G. Sachs, Phys. Rev. 57, 194 (1940).
[3]J. Eichler and G. Jacob, Z. Physik 157, 286 (1959).