one arrives at an upper limit for the width of the 665-kev excited state of Mo^{97}, $\Gamma \leq 5\times10^{-4}$ ev, and at a lower limit for the lifetime of this state of 1.5×10^{-12} second. This lifetime is one order of magnitude longer than the one expected from the Weisskopf formula. Thus, the $M1$ transition in Mo^{97} shows the same behavior as the low-energy $M1$'s.

It should be mentioned that the Mo^{97} transition, as well as most of the low-energy transitions measured by the Canadian group, involve a change of two units of orbital angular momentum, whereas the Li^7 gamma ray presumably leads from a $p_{\frac{1}{2}}$ to a $p_{\frac{3}{2}}$ state.

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† Assisted by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.

[1] M. Goldhaber and R. D. Hill, Revs. Modern Phys. **24**, 179 (1952).

[2] W. Kuhn, Phil. Mag. **8**, 625 (1929); P. B. Moon, Proc. Phys. Soc. (London) **63**, 1189 (1950).

[3] V. Weisskopf, Phys. Rev. **83**, 1073 (1951).

[4] L. G. Elliott and R. E. Bell, Phys. Rev. **76**, 168 (1949).

[5] R. L. Graham and R. E. Bell, Can. J. Phys. **31**, 377 (1953).

[6] Obtained from Y-12 Plant, Carbon and Carbide Corporation, Oak Ridge, Tennessee.

Production of V_1^0 Particles by Negative Pions in Hydrogen*

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THE photograph reproduced in Fig. 1 is one of two obtained in a hydrogen-filled diffusion cloud chamber exposed to a beam of 1.5-Bev negative pions (π^-) from the Cosmotron. The hydrogen was at a pressure of 18 atmospheres, and a field of 11 000 gauss was applied. The picture is believed to represent the production of a V_1^0 particle by a π^- interaction with a proton. Track a is the incident π^-, the end point of which is to be called A. Tracks b and c are the decay products of the V_1^0. A single neutral heavy meson also may have been produced at A, which would travel in the direction indicated by d.[1]

Since track a is short, its momentum can only be estimated to lie near the nominal π^- beam momentum of 1.63 Bev/c. This track is parallel to the other beam tracks and thus probably is not due to a secondary particle. The line connecting point A with the vertex of b and c, to be called G, forms an angle of 26° with a. The distance between A and G is 0.65 cm. Tracks a, b, and c are coplanar, while only coplanarity of A, b, and c is necessary for the tracks to be associated. In addition, the components of momentum of b and c perpendicular to line AG balance. Track b forms an angle of 16° with a; b is caused by a positive particle with a measured momentum of 480 ± 80 Mev/c and an estimated ionization density of 3× minimum. Thus b is identified as a proton track. The angle between b and c is 37°. Track c is negative, with a momentum of 210 ± 70 Mev/c and estimated ionization density of less than 1.5× minimum. An upper limit of 410 m_e is inferred for its mass, indicating a π^-. Assuming that b and c represent the decay of a $V_1^0(\rightarrow p+\pi^-+Q)$, one finds a Q-value of 51 Mev from these data.[2] Assuming the generally accepted Q of 37 Mev one would find that, for the given angles, the momenta should be 460 Mev/c for the proton and 180 Mev/c for the π^-. These values fall within the errors given for the measured values and have been used for the further computations. The lifetime of this V_1^0 is 4×10^{-11} sec.

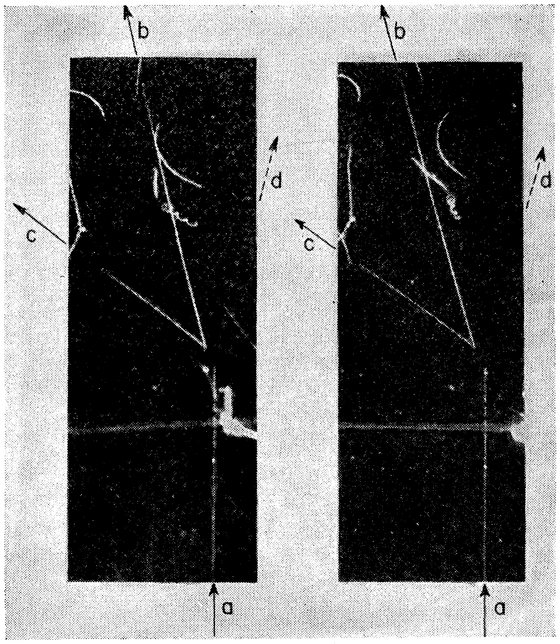

FIG. 1. Stereoscopic photograph of a V_1^0 (tracks b and c) produced in hydrogen by a negative pion (track a) of an energy of 1.5 Bev. If one heavy meson of a mass of about 1350m_e has been produced in addition, its line of flight is indicated by d.

The total energy of the V_1^0 is 1.26 Bev, and its momentum is 610 Mev/c. To conserve energy and momentum at least one other neutral particle must start at A. Assuming a single particle, its total energy would have to be 1.31 Bev and its momentum 1.11 Bev/c, leading to a mass of 1350 ± 70 m_e for a kinetic energy of 1.5 Bev for the incident π^-. For an energy of 1.2 Bev instead of 1.5 Bev one would obtain a value of 1150 m_e. However, such a low value for the incident energy is improbable. In any case, if only one other particle had been produced in addition to the V_1^0, this would have to be a heavy meson. Its direction of flight is indicated by d in Fig. 1, and its lifetime must have been longer than 4×10^{-10} sec since no decay was observed in a path of 23 cm in the chamber. A threshold energy of 870 Mev is necessary for the process discussed, while 1.06 Bev were available for a 1.5-Bev incident π^- (including the rest mass of the π^-).

The other photograph is quite similar to the one described, except that no momentum measurements can be obtained. However, the measured angles and estimated ionization densities are quite consistent with a V_1^0. Its direction of flight forms an angle of 30° with the incident π^-. If it is assumed to be a V_1^0 one calculates that its total energy is 1.33 Bev, its momentum 745 Mev/c, and is lifetime 3×10^{-11} sec. Assuming again that only one other neutral particle leaves the event, its mass would be 1280 ± 80 m_e (for a 1.5-Bev incident π^-) and its lifetime longer than 3×10^{-10} sec.

Of course, instead of one heavy particle several lighter ones (for instance two π^0's, or a π^0 and a V_2^0) could originate from the events in addition to the V_1^0. However, the present results are consistent with the possibility of production of V_1^0 together with one other heavy unstable particle.[3]

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[1] It is not likely that the interaction of the π^- at A involved carbon or oxygen in the alcohol rather than H_2, since (1) there is at most one molecule of alcohol per 800 molecules of H_2 and (2) an interaction with C or O would most probably give rise to charged prongs.

[2] Leighton, Wanlass, and Anderson, Phys. Rev. **89**, 148 (1953).

[3] A. Pais, Phys. Rev. **86**, 663 (1952). References to previous work are cited in this article.

Effect of the Electric Quadrupole Interaction on the $\gamma-\gamma$ Directional Correlation in Cd^{111}. III

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IN previous letters[1,2] we showed the effect of an interaction between the nuclear electric quadrupole moment of the intermediate state and an extranuclear inhomogenous electric field on the angular correlation of the Cd^{111} $\gamma-\gamma$ cascade. Since it is not possible to produce artificial inhomogenous electric fields of sufficient strength we used metallic indium single crystals containing active In^{111} as sources. Our preliminary experiments proved that quadrupole interaction with the crystalline field occurs and we pointed out that the investigation of this interaction can yield the electric quadrupole moment of the first excited state of Cd^{111}.

Meanwhile, careful quantitative experiments have been made and the theory of the influence of external fields on the angular correlation of a $\gamma-\gamma$ cascade has been developed and treated in detail for the case of axial symmetric fields.[3] The correlation function depends in a complicated way upon the orientation of the symmetry axis **c** of the field with respect to the two counters. To simplify the formulas we restricted ourselves to the measurement of the anisotropy $\epsilon=W(\pi)/W(\pi/2)-1$, and we chose the arrangement where the **c** axis lay in the plane of the two counters (experiment 1 and arrangement 1 of references 1 and 3, respectively). The orientation of the **c** axis is characterized by the angle ϑ between the vector $\mathbf{k}_1$ and the **c** axis. For this case the anisotropy can be written as

$$\epsilon=\Sigma_n d_n \cos^n\vartheta / \Sigma_n e_n \cos^n\vartheta, \tag{1}$$

if the undisturbed correlation is $W(\theta)=A_{kk}P_k(\cos\theta)$. The coefficients d_n and e_n are of the form

$$d_n=\Sigma_\mu \sigma_{n\mu}{}^{k_1k_2}A_{k_1k_2}G_\mu{}^{k_1k_2}, \tag{2}$$
$$n,\ k_1,\ k_2 \text{ even}; \qquad \mu<k_1,\ k_2.$$

The $A_{k_1k_2}$ describe the correlation function and can be taken from the tables of Rose.[4] The attenuation factors $G_\mu{}^{k_1k_2}$ describe the mechanism and the strength of the interaction. For pure electric interaction they are defined as the sums:

$$G_\mu{}^{k_1k_2}=\sum_m s_{m\mu}{}^{k_1k_2}\frac{1}{1+(mx)^2}. \tag{3}$$

The numerical factors $s_{m\mu}{}^{k_1k_2}$ and $\sigma_{n\mu}{}^{k_1k_2}$ are tabulated in reference 3. x measures the strength of the interaction and is, for half-integer spin values;

$$x=\frac{eQ}{2\hbar}\frac{\partial E_z}{\partial z}\frac{6}{(2I-1)I}\tau. \tag{4}$$

τ is the mean life of the intermediate state, Q the quadrupole moment of the nucleus, and $\partial E_z/\partial z$ the interacting field gradient.

For our experiments we used metallic indium single crystals. The crystals are tetragonal and we assume the symmetry axis to be identical with the crystalline **c** axis. The orientation of the **c** axis was obtained from x-ray rotating crystal diagrams. The anisotropy $\epsilon(\vartheta)$ was measured as a function of the angle ϑ, and the interaction strength x was found by a least-squares fit. This fit had to take into account the finite solid angle of the detectors and the finite resolving time of the coincidence circuit.

Two independent runs with two different single crystals have been made; the results are:

crystal 1, $x=1.57\pm0.03$;
crystal 2, $x=1.60\pm0.02$;
mean value, $x=1.59\pm0.02$.

One of the results is shown in Fig. 1. With the known spin (5/2) and mean life $[\tau=(1.23\pm0.06)\times10^{-7}$ sec$]$ of the 247-kev level of Cd^{111} one gets:

$$(eQ/h)(\partial E_z/\partial z)=(6.86\pm0.4)\text{ Mc/sec},$$
$$Q\partial E_z/\partial z=(2.84\pm0.18)\times10^{-8}\text{ volt}.$$

The sign of $Q\cdot\partial E_z/\partial z$ cannot be obtained by this experiment as can be seen from Eq. (3).

Three additional methods have been used to determine the value of x. Another geometrical arrangement (experiment 2 of reference 1) gave $x=1.85\pm0.2$. Polycrystalline metallic sources gave the result $x=1.4\pm0.2$. In a third experiment we oriented the crystalline **c**-axis perpendicular to the plane of the two counters and applied a magnetic field in the same direction.[5] The result was $x=1.6\pm0.2$. The arrangement 1 is, however, much more sensitive than the others.

To determine the value of Q from these measurements one must know the magnitude of $\partial E_z/\partial z$. Calculations are very difficult, but crude estimations give $\partial E_z/\partial z=5.85\times10^{16}$ v cm^{-2} and $Q\sim5\times10^{-25}$ cm^2. It is planned to measure $\partial E_z/\partial_z$ by nuclear induction experiments in which the known quadrupole moment of In^{115} would serve as a reference standard.[6] This experiment would yield $Q(In^{115})$ $\partial E_z/\partial z$. An angular correlation experiment with the same crystal containing In^{111} atoms gave $Q(Cd^{111})$ $\partial E_z/\partial z$. One could in this way measure the quadrupole moment of Cd^{111} (247 kev) in units of the quadrupole moment of In^{115}, assuming the field gradients in both cases to be equal. One difficulty remains for all methods of determination of $\partial E_z/\partial z$: one does not know to what extent the K- capture of the In^{111} and the following γ-decay (recoil) changes the field at the nucleus.

We also hope to study the quadrupole interaction in other single crystals. This would give other values for x and provide a better basis for obtaining the quadrupole moment.

We thank Prof. P. Scherrer for his continued interest and help, Dr. W. Känzig and R. Kern for their help with the growing and orientation of the single crystals, the cyclotron group for the many irradiations carried out for these experiments, and R. Leidenix for the calculation of the field gradient.

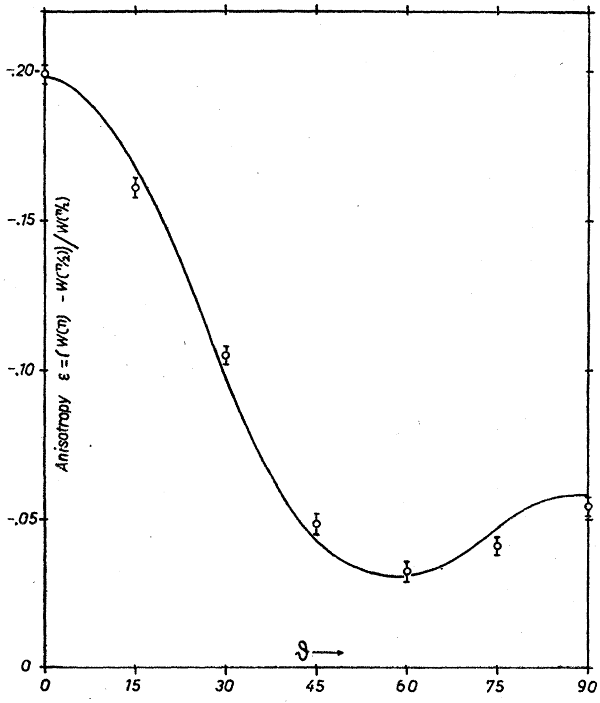

FIG. 1. Result for single crystal 2. $\epsilon=W(\pi)/W(\pi/2)-1$ is plotted against the angle ϑ between the direction of the fixed counter and the **c** axis. The curve shows $\epsilon(\vartheta)$ for $x=1.60$ obtained by a least-squares fit.

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[†] National Science Foundation Postdoctoral Fellow, on leave from Argonne National Laboratory.

[1] Albers-Schönberg, Hänni, Heer, Novey, and Scherrer, Phys. Rev. **90**, 322 (1953).

[2] Albers-Schönberg, Heer, Novey, and Rüetschi, Phys. Rev. **91**, 199 (1953).

[3] Alder, Albers-Schönberg, Heer, and Novey, Helv. Phys. Acta (to be published).

[4] L. C. Biedenharn and M. E. Rose, Revs. Modern Phys. (to be published).

[5] Albers-Schönberg, Alder, Heer, Novey, and Scherrer, Proc. Phys. Soc. (London) (to be published).

[6] A. K. Mann and P. Kusch, Phys. Rev. **77**, 427, 435 (1950).