effects diminish] would indicate that the neutron and proton distributions were not identical. This in the case of mirror nuclei would be quite surprising.

Heavier nuclei are also of great interest because it is for them that the experiments which have suggested distribution differences are most reliable. It is not possible, however, to get complete symmetry between protons and neutrons once one leaves the region of the mirror nuclei. Instead one can choose cases in which neutron and proton shells are completed in the respective residual nuclei. These are advantageous because factors other than distribution differences which might influence the reduced widths are minimized, while at the same time the possibility of separating the ground state level from other levels so that a measurement can be made is enhanced. An example would be $Tl^{205}(d,n)Pb^{206}$ and $Pb^{207}(d,p)Pb^{208}$.

Note added in proof.—Our attention has been called to related experimental and theoretical work on pickup processes by W. N. Hess and B. J. Moyer, Phys. Rev. **96**, 859 (A) (1954); and W. N. Hess, thesis, University of California Radiation Laboratory Report UCRL-2670, 1954 (unpublished).

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Angular Correlation Effects in Unstable Particle Decay*

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One line of approach in the attempt to reconcile the long lifetimes and copious production of the new unstable particles is to suppose that the particles have high spin angular momentum.[1] This view is beset with grave difficulties, but the assumption of large spin does lead to testable consequences. In particular one might expect to find strong angular correlation effects in both the production and decay processes of the high spin particles.

There is some preliminary evidence, from Brookhaven[2] as well as from cosmic-ray experiments,[3] that Λ^0 particles are produced in states of high orbital angular momentum. This is by no means conclusive proof of high spin, but it is suggestive. The purpose of the present note is to discuss an experimental method which can provide a lower-limit estimate of the spins of unstable particles which undergo two-body decay. This consists in searching for angular correlation effects in the decay processes. Quite aside from the question of whether the assumption of large spin will ultimately prove adequate to account for their metastability, it is of course a matter of considerable interest to determine the spins of the new unstable particles. Preliminary evidence reported in the following letter[4] indicates that there may be at least one species of V^0 particle which has spin greater than one-half.

Consider a particle which undergoes two-body decay. The normal to the decay plane, $\mathbf{n}$, must be perpendicular to the line of flight of the unstable particle. Let $\mathbf{N}$ be some reference vector which is normal to the line of flight and which is defined independently of the decay normal $\mathbf{n}$. For example, in the case of single V^0-particle events, one may define $\mathbf{N}$ as the normal to the plane containing the line of flight of the primary particle which produces the nuclear interaction and the line of flight of the emerging V^0 particle. In events where two unstable particles come from a common nuclear interaction, an alternate choice for $\mathbf{N}$ would be the normal to the plane containing the two unstable particles. (It is events of this kind which are discussed in the following letter.)

In either case, if the unstable particle decays isotropically in its rest frame, the angle η between $\mathbf{n}$ and $\mathbf{N}$ should take on all possible values with uniform probability. Now spin zero and spin one-half particles must in fact decay isotropically, for reasons of parity and angular momentum conservation. Thus, any statistically significant departure from a uniform distribution in η for a series of decay events would immediately imply spin greater than one-half. The converse, however, is not necessarily true: a uniform distribution in η does not rule out spin greater than one-half, since the spins may be randomly oriented with respect to the reference vector $\mathbf{N}$.

The most general form of the angular distribution in the case of a particle of spin S which undergoes two-body decay can easily be obtained by the methods of Wolfenstein.[5] In the rest system of the unstable particle, the final state wave function ψ has definite parity and is an eigenfunction of angular momentum corresponding to eigenvalue S. The outgoing intensity $|\psi|^2$ must therefore transform under rotations as a sum of spherical harmonics of even parity. After one sums over final spin states, the spherical harmonic of maximum degree which can appear in the expression for the outgoing intensity is either $2S$ or $2S-1$ (according as S is integer or half-odd integer).[5]

The angular distribution in the rest frame of the unstable particle is therefore

$$I(\theta,\varphi)=\sum_{L=0}^{L_{\max}}\sum_{M=-L}^{L}C_L^M Y_L^M(\theta,\varphi),$$

$$L_{\max}=\begin{cases}2S \text{ (integral } S)\\ 2S-1 \text{ (half-odd integral } S),\end{cases}$$

where L can take on only even values. Suppose that the unstable particle travels along the z axis in the laboratory system; and suppose the y axis is chosen along the direction of the reference vector $\mathbf{N}$. Then the azimuthal angle φ is just equal to the angle η between $\mathbf{N}$ and the normal to the decay plane, $\mathbf{n}$. The most general form of the probability distribution in η is therefore given by

$$p(\eta)=\int I(\theta,\eta)\sin\theta d\theta$$

$$=\sum_{M=0,2,\ldots}^{L_{\max}}(A_M\cos M\eta+B_M\sin M\eta).$$

A lower limit on S can thus be obtained by determining the largest value of M required to fit the decay data for a series of events. (This is only a lower limit because some of the coefficients in the above expression may vanish; for randomly oriented spins, for example, only A_0 will be nonzero.)

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Orientation of Planes in Double V^0 Decay Events*

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In a set of 30 000 photographs taken of a Wilson cloud chamber operated in a magnetic field,[1] seven events have been found in which a pair of V^0 particles appear to come from a common origin.[2] These have been analyzed for possible angular correlations between the decay planes, as discussed in the preceding letter.[3]

The illuminated region of the chamber has average dimensions 16 in.×16 in. ×5 in. A stereo camera with lens separation of 17° takes two photographs of each event. The spatial geometry of each event is reconstructed by projecting the two views onto a screen through an optical system identical with that used to photograph the chamber. The space coordinates of a particular point on a track are determined by moving the projector parallel to the optic axis of the lenses, until the point appears stationary on the screen when the two views are projected in rapid succession. The screen-projector distance measures the z coordinate of the point (a correction is made for chamber expansion); and the location on the screen determines the x and y coordinates. This procedure is repeated for many points along each relevant track, so that a spatial reconstruction of the entire event is obtained. An alternate procedure, which determines directly the orientation of the decay planes, consists in tilting the screen until the images of both decay tracks of a particular V^0 event appear stationary when the two stereo views are projected in rapid succession. This procedure is less accurate than the one described above, but in every case the two methods agreed to within a few degrees.

In each event a search was made for all possible origins of the two V^0 particles. We assume that the V^0 particles undergo two-body decay, so that the origin for a given V^0 must lie in its decay plane and the line connecting the origin with the decay point must pass

Table I. Summary of geometrical data for ten V^0-particle pairs. δ is angle of noncoplanarity with assumed origin. θ_1 is angle between lines of flight of V_a^0 and V_b^0. θ_2 is angle between decay planes of V_a^0 and V_b^0. η is angle between decay plane and plane containing lines of flight of V_a^0 and V_b^0. The last column gives the identification.

Event	V^0	δ	θ_1	θ_2	η	Ident.
26–5946	a	1.4°	36.6°	76.6°	14.8± 4°	···
	b	2.1			88.5± 5	···
56–240	a	2.7	31.8	78.5	16.0±11	···
	b	3.7			62.6±10	···
69–210	a	0.6	43.8	45.2	29.0± 3	···
	b	2.1			63.7± 3	θ^0
73–29	a	0.5	20.6	62.2	25.3± 5	Λ^0
	b	0.8			85.8± 5	θ^0
95–622	a	1.3	41.4	72.5	39.8± 3	θ^0
	b	0.4			78.3± 4	θ^0
126B–30034	a	0.7	3.1	44.8	4.4± 3	···
	b	0.2			40.0± 3	···
146B–40761	a	0.1	14.5	88.0	17.0± 3	···
	b	0.4			72.4± 4	···
Brookhaven	a				27 ±10	Λ^0
	b				70 ± 5	θ^0
Brookhaven	a				18 ± 7	Λ^0
	b				60 ± 6	θ^0
Thompson *et al.*	a				10.6	θ^0
	b				26.5	Λ^0