Angular Correlation in New Unstable Particle Decays*

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Among the cosmic-ray events recorded with a multiplate cloud chamber there are twelve in which two of the new unstable particles (hyperons or heavy mesons) seem to originate in the same nuclear interaction inside the chamber. Seven events show two neutral V particles, four show one neutral and one charged V, and one a neutral V and an S particle. The histogram of the dihedral angle between the production and decay planes of the unstable particles is found to be consistent with a uniform distribution. This result does not necessarily imply small spin for the new unstable particles.

I. INTRODUCTION

ONE of the fundamental properties of a particle is its spin. The determination of this quantity for hyperons and heavy mesons (here called collectively: "new unstable particles") is as yet an unsolved problem. It is of interest, in particular, to ascertain whether some of the "new unstable particles" have spin greater than $\frac{1}{2}$.[1]

A natural approach to the problem[2] is suggested by the fact that in reactions responsible for the production of the new unstable particles such as

$$\pi^- + p \rightarrow \Lambda^0 + \theta^0, \quad \pi^+ + n \rightarrow \Lambda^0 + K^+, \tag{1}$$

the dihedral angle ψ between the planes of production and of decay[3] of the unstable particles is closely analogous to the angle employed to study the polarization of particles in double-scattering experiments. If the measured distribution of ψ, $F(\psi)$, shows a definite asymmetry, then among the hyperons and heavy mesons there are particles with spin greater than $\frac{1}{2}$.[4]

In reactions of the type observed in a multiplate cloud chamber,

$$(\pi \text{ or nucleon}) + (\text{nucleus}) \rightarrow V_a + V_b + (\text{other charged and neutral secondaries}), \tag{2}$$

the heavy nucleus may seriously affect the presumed correlation between production and decay planes, for the following reasons: (a) a considerable amount of angular momentum may be carried away by the residual nucleus, and the secondaries of the reaction other than the unstable particles; (b) the new unstable particles may be produced plurally or indirectly;[5] (c) the new unstable particles may be scattered before they decay because of strong interactions with the nucleons.[6]

Since the energy of the primary particle is very large compared with the binding energy of the nucleons, reactions of type (2) may nevertheless yield information on the correlations. It is easy to see the necessary conditions for the simple reactions (1) to have occurred. Since in (1) the lines of flight of the primary and those of the two unstable particles must be coplanar, we must have

$$\psi = \chi, \tag{3}$$

where ψ is the polarization angle and χ is the dihedral angle between the plane determined by the lines of flight of the two unstable particles, and the plane that contains the lines of flight of one of the unstable particles and either of its decay products.[7]

As a consequence of conservation of energy and momentum, we must also have

$$\left.\begin{array}{l}\phi_{\text{lab}}(\Lambda^0) < 57^\circ \\ \phi_{\text{lab}}(\theta^0) \text{ unrestricted}\end{array}\right\}, \tag{4}$$

where ϕ is the angle that the line of flight of the V^0

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[1] See the discussion by M. Gell-Mann and A. Pais in *Proceedings of the Glasgow Conference* (Pergamon Press, London, 1955). It would be of theoretical interest to find particles with spin $\geqslant 1$ in view of the renormalization difficulties encountered there. It may also be noted that the existence of a spin (and isotopic spin) $\frac{3}{2}$ isobar of the nucleon, which is suggested by the resonances in the π-nucleon scattering and photomesonic cross sections, may be closely related to the existence of the "new unstable particles." See H. Bethe and F. de Hoffmann, *Mesons and Fields* (Row, Peterson and Company, Evanston, 1955), p. 192 ff. Also, a knowledge of spins would shed light on the identity of the θ and τ mesons.

[2] Other methods have been suggested by S. Treiman, and by R. Karplus and M. Ruderman (to be published).

[3] The plane of production is determined by the lines of flight of the bombarding particle and of the unstable one. The plane of decay is determined by the lines of flight of the unstable particle and that of either of its charged secondaries.

[4] The angular distributions are discussed by E. Eisner and R. G. Sachs, Phys. Rev. **72**, 680 (1947); L. Wolfenstein, Phys. Rev. **75**, 1664 (1949); Treiman, Reynolds, and Hodson, Phys. Rev. **97**, 244 (1955); S. Treiman and H. Wyld, Phys. Rev. **100**, 879 (1955); R. Adair, Phys. Rev. **100**, 1540 (1955); L. P. Puzikov and Ia.A. Smorodinskii, Doklady Akad. Nauk. U.S.S.R. **104**, No. 6, 843 (1955) (translation by M. D. Friedman, 572 California Street, Newtonville 60, Massachusetts).

[5] Besides the possibility of successive production of the unstable particles in the nucleus (plural production), both unstable particles could be produced by particles other than the visible primary (indirect production).

[6] The possible importance of scattering has been noted in connection with the energy spectrum of the hyperons by G. James and R. Salmeron, Phil. Mag. **46**, 377, 571 (1955).

[7] This definition extends to $V^0 - V^{\text{ch}}$ events the angle used by Ballam, Hodson, Martin, Rau, Reynolds, Treiman, Phys. Rev. **97**, 244 (1955).

forms with the line of flight of the primary of the interaction.[8]

In an attempt to determine the possible asymmetry of $F(\psi)$ we have analyzed twelve reactions of the general type (2) produced in the Massachusetts Institute of Technology cloud chamber by energetic cosmic rays.[9] It is seen from Tables I and II that Eq. (3) is satisfied in five of the twelve events presented and that all but one of the events satisfies Eq. (4).

II. SELECTION OF THE EVENTS AND IDENTIFICATION OF THE UNSTABLE PARTICLES

We discarded for one of the following reasons seven of the nineteen M.I.T. events that show more than one unstable particle: (a) the only possible origin of the unstable particles is outside the chamber; (b) none of the nuclear interactions visible inside the chamber can be identified as the origin of the unstable particles without leaving one of the transverse momenta unbalanced; (c) the secondary prongs of each V are too short to permit a determination of the Q value. In the twelve events reported, there is only one possible origin common to the two unstable particles inside the chamber.

TABLE I. Data on double V^0 events. N_s—number of visible charged secondaries produced with the unstable particles. δ—angle of uncoplanarity of the V. ϕ—angle between the primary of the interaction and the unstable particle. ψ—dihedral angle between the production and decay planes of the unstable particle. χ—dihedral angle between the plane formed by the lines of flight of the two V's and the decay plane of the unstable particle.

Serial No.	N_s	δ(deg)	ϕ(deg)	ψ(deg)	χ(deg)	Q(Mev), remarks
26 194	9	1.6	56	9	9	<41, probable Λ^0.
		10	28	70	70	Cannot be identified.
27 429	1	3.5	22	59	11	>81 if θ^0, cannot be Λ^0.
		4.2	81	57	37	Cannot be identified.
32 659	2	1.5	56	67	40	Cannot be identified.
		3.6	35	1	49	31–73Λ^0. Cannot be θ^0.
3872x	2	3	14	74	9	33Λ^0. Cannot be θ^0.
		13	38	44	62	Cannot be Λ^0.
64 844	0	3.7	79	19	19	24–49Λ^0.
		1.0	35	57	51	Cannot be identified.
94 328	6	4	32	1.5	33.5	<51Λ^0. Cannot be θ^0.
		2	145	55	33.5	>199θ^0. Cannot be Λ^0.
103 075	1	2	29	33	61	26–27Λ^0. Cannot be θ^0.
		0	46	34	70	>101θ^0. Cannot be Λ^0.

TABLE II. Data on double V's: V^0+V^{ch}. The symbols are those employed in Table I.

Serial No.	N_s	δ(deg)	ϕ(deg)	ψ(deg)	χ(deg)	Q(Mev), remarks
67060	6	V^0 0	38	28	76	30–81Λ^0
		V^{ch}	59	6	36	
87074	3	V^0 1	16	67	67	<45Λ^0
		V^{ch}	27	14	10	
96787	5	V^0 2	141	54	54	18–53Λ^0
		S	136			$K_{\mu 2}$ (72–85 g range, Br)
98163	8	V^0 4	32	27	27	18–71Λ^0
		V^{ch}	19	12	12	
95829	9	V^0 4.7	...	...	38	<50Λ^0
		V^{ch}	...	...	24	(produced by neutral primary)

The V^0 particles have been analyzed assuming the following decay schemes:

$$V^0 \rightarrow p+\pi^-, \quad (5)$$

$$V^0 \rightarrow \pi^+ + \pi^-. \quad (6)$$

A V^0 which, when analyzed according to scheme (5), gives a Q value compatible with 37 Mev is identified as a probable Λ^0. A V^0 which, when analyzed according to scheme (6), gives a Q value compatible with 214 Mev is identified as a probable θ^0. In many events it is possible to say that the V^0 is not a Λ^0 (or a θ^0) from considerations of residual range, ionization, and inferred transverse momentum of the charged secondaries.

It is unfortunate that the identity of the V^{ch} particles cannot be established. In the four events analyzed, the charged secondary forms a large angle ω with the line of flight of the V^{ch} and leaves the chamber without penetrating any plates. From an estimate of the ionization of the V^{ch} and the measured angle ω we can conclude that in three of the four V^0-V^{ch} events (the exception being 95 829), the unstable particle can be neither a π decaying into a μ meson nor a hyperon decaying into a proton. It is not possible to say whether the V^{ch} particles are heavy mesons decaying into π's or μ's or hyperons decaying into π mesons. The S particle in event 96 787 is most probably a $K_{\mu 2}$ since its secondary has a range between 72 and 85 g cm^{-2} of brass.

It is difficult to determine exactly the error involved in angular measurements. Our estimate is that for all the angles discussed the error is between 2 and 4 degrees.[10]

III. SUMMARY OF RESULTS

The number of charged secondaries, the angles, and the Q values are given in Tables I and II.

[8] A detailed analysis of the dynamics of reaction (1) is found in reference 5.

[9] The chamber is described by Bridge, Peyrou, Rossi, and Safford, Phys. Rev. **90**, 921 (1953). The plates in this chamber are brass or lead. Our cases do not indicate that the type of nucleus in Eq. (2) is relevant for the angular distributions discussed.

[10] See the discussion by Bridge, Peyrou, Rossi, and Safford, Phys. Rev. **91**, 362 (1953).

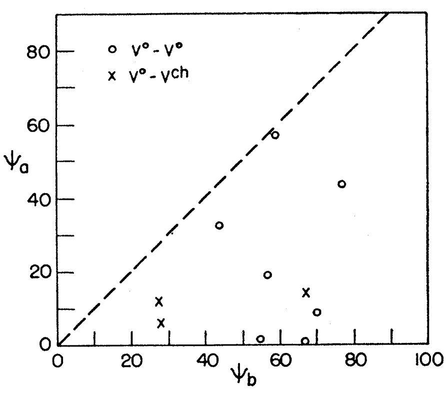

FIG. 1. Distribution of 10 double-V events in the $\psi_a-\psi_b$ plane ($\psi_a<\psi_b$ in degrees).

We note some general features of the events considered.

(i) The number of visible prongs that emerge from the interaction presumably responsible for the production of the unstable particles ranges from 0 to 9. These prongs do not seem to lie preferentially in a plane.

(ii) The V^0 particles that have been identified as probable Λ^0 (with the exception of 96 787) have angles of production in the laboratory frame of reference, ϕ_{lab}, smaller than 60°.[11]

(iii) Event 64 844 is likely to represent a reaction of type (1):

$$(\text{charged primary})+(\text{nucleon})\rightarrow\Lambda^0+\theta^0.$$

Since no charged prong is seen to come from the interaction in spite of the fact that the origin of the V's is in the well-illuminated region of the chamber and about one millimeter above the bottom of a plate. Also $\psi=\chi$ for both V's. It is probably accidental that $\psi=\chi$ in event 26 194 since $N_s=9$ and for one of the V's $\delta=10°$.

(iv) In two of the three V^0-V^{ch} events for which comparison is possible, $\psi=\chi$ within the experimental uncertainty. In the V^0-S event, we also find $\psi=\chi$.

(v) To understand the behavior of ψ and χ, we have plotted in Fig. 1 the ψ_a *versus* the ψ_b corresponding to the two unstable particles contained in each event and in Fig. 2 χ_a *versus* χ_b. The conventions $\psi_a<\psi_b$, $\chi_a<\chi_b$ are used with the consequence that the experimental points lie all on the same side of the 45° line. Only Fig. 2 includes events reported by other groups[12] since usually χ but not ψ is given. No tendency towards a clustering of the points is found. Figure 3 is a histogram

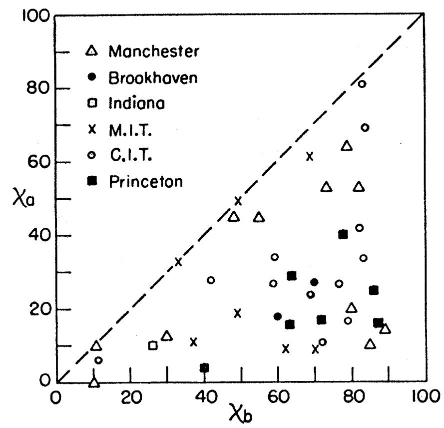

FIG. 2. Distribution of events in $\chi_a-\chi_b$ plane for 40 double-V^0 events reported by various groups ($\chi_a<\chi_b$ in degrees).

of the ψ for 32 events (including our "single V's)."[11] Fitting to the theoretical curves gives no evidence for spin greater than $\frac{1}{2}$.

IV. CONCLUDING REMARKS

Our results may be summarized as follows: the presence of prongs indicates the complexity of the reactions discussed; a number of the events considered satisfy the conditions for an elementary reaction [Eqs. (3) and (4)]; within the statistics the observed distributions of ψ and χ are uniform.

Clearly one cannot combine the statements above to infer that all the "new unstable particles" have spin less than 1 mainly because a heavy nucleus rather than a nucleon is the target of the reactions analyzed. Inelastic collisions of π mesons with hydrogen nuclei, recently studied at Brookhaven, obviate this difficulty.[13]

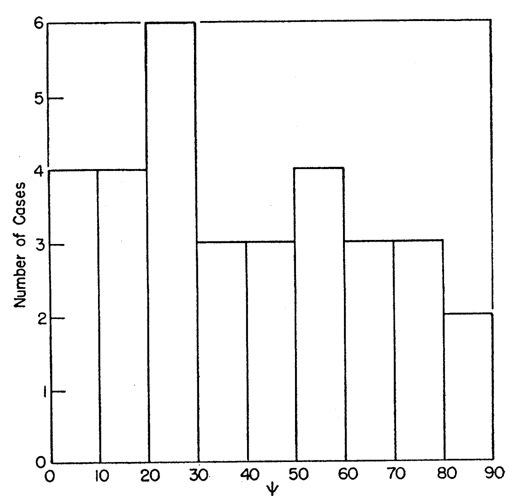

FIG. 3. Dihedral angle (degrees) between production and decay planes of 32 V^0 events.

[11] The histogram of ϕ_{lab} for all identified V^0 [including the single V's previously reported by us, Phys. Rev. **99**, 642(A) (1955)] indicates a peak at about 30°. For a further discussion of this distribution, see R. Jastrow, Phys. Rev. **97**, 181 (1954).

[12] J. Ballam *et al.*, reference 7; G. James and R. Salmeron, reference 6; J. D. Sorrells, private communication; Thompson, Burwell, Huggett, and Karzmark, Phys. Rev. **95**, 1576 (1954). See also forthcoming papers by N. Deutschmann, M. Cresti, W. Greening, L. Guerriero, A. Loria, G. Zago, W. D. Walker, and W. D. Sheperd.

[13] Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **91**, 1287 (1953); **93**, 861 (1954); **98**, 121 (1955).

The results obtained by this latter method seem to favor the existence of spins greater than $\frac{1}{2}$. We hope that improved statistics may soon settle this important question.

Note added in proof.—W. D. Walker and W. D. Shepard have recently reported some new evidence for angular correlations in the Λ^0 decay [Phys. Rev. **101**, 1810 (1956)].

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Z Dependence of Bremsstrahlung for the Case of Complete Screening*

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The relative yield of 235-Mev photons from the elements Cu, Ta, and U for incident electrons of energy 500 Mev has been measured by using the photoproduction of positive pions from liquid hydrogen as an essentially monoenergetic photon detector. The observed photon yield per radiation length of uranium relative to copper is 0.878 ± 0.02, and of tantalum relative to copper is 0.937 ± 0.015. These results are consistent with the predictions of a theorem of Olsen which evaluates the integral bremsstrahlung cross section in terms of the integral pair-production cross section of Bethe, Maximon, and Davies.

I. INTRODUCTION

THE Bethe-Heitler theory[1] of bremsstrahlung and pair production as developed in 1934 has been superseded recently by the calculations of Bethe, Maximon, and Davies,[2–5] with some important contributions by Bethe, Maximon, and Low,[6] and by Olsen.[7] The essential difference between the present theories of Bethe, Maximon, and Davies and the Bethe-Heitler theory is that the current calculations are based on the use of Furry-type wave functions; whereas the original Bethe-Heitler calculations are based on the Born approximation which represents the electron wave functions in the initial and final states as plane waves and hence ignores the Coulomb distortion effect.

In the first calculations for bremsstrahlung made by Bethe, Maximon, and Davies,[2,3] both the initial and final electron wave functions were represented by a plane wave plus an outgoing spherical wave. In a later article Bethe, Maximon, and Low[6] pointed out that the final electron wave function should be represented instead by a plane wave plus an ingoing spherical wave. This was the basis for the later papers of Bethe, Maximon, and Davies[4,5] in which they concluded (in contradiction to their previous result[2,3]) that, in the limit of complete screening, their formulation for bremsstrahlung went over into the old Bethe-Heitler result. Since then, Olsen[7] has shown that the particular choice of the final state wave function of the electron is important if the differential bremsstrahlung cross section for a given direction of the scattered particle is to be calculated. However, if only the cross section integrated over all possible directions of the scattered particle is desired, then one can equally well use the plane wave plus outgoing spherical wave-type function for the final state. This permits the integral bremsstrahlung cross section to be deduced from the corresponding pair cross section by a detailed balancing transformation. Conversely, by the inverse transformation, the integral pair cross section may be derived from a knowledge of the corresponding bremsstrahlung cross section. This conclusion holds whether the screening is absent, partial, or complete. Using the Davies, Bethe, and Maximon result for pair production (which has had numerous experimental checks at high energies[5]), Olsen gives the following expression for the bremsstrahlung spectrum at high energies:

$$(d\sigma/dk)=(d\sigma/dk)_{\mathrm{BH}}-\frac{4\bar{\phi}}{k}\frac{1}{E_0^2}\left(E_0^2+E^2-\tfrac{2}{3}E_0E\right)f(Z),\quad(1)$$

where $(d\sigma/dk)_{\mathrm{BH}}$ is the Bethe-Heitler bremsstrahlung spectrum including the effect of atomic screening[1]; E_0 and E are the initial and final total electron energies; k is the photon energy; $\bar{\phi}=(Z^2/137)(e^2/mc^2)^2$; and $f(Z)$

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[1] H. A. Bethe and W. Heitler, Proc. Roy. Soc. (London) **A146**, 83 (1934).
[2] L. C. Maximon and H. A. Bethe, Phys. Rev. **87**, 156 (1952).
[3] Handel, Davies, and Bethe, Phys. Rev. **87**, 156 (1952).
[4] H. A. Bethe and L. C. Maximon, Phys. Rev. **93**, 768 (1954).
[5] Davies, Bethe, and Maximon, Phys. Rev. **93**, 788 (1954).
[6] Bethe, Maximon, and Low, Phys. Rev. **91**, 417 (1954).
[7] H. Olsen, Phys. Rev. **99**, 1335 (1955).