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Interaction between *K*-Particles and Nucleons

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Some consequences of the strong interactions between *K*-particles and nucleons are discussed. A connection is noted between the associated production mechanism and spatial exchange characteristics of *K*-nucleon scattering. (The same is true for Λ^0-nucleon scattering.) The *K*-nucleon interactions may possibly lead to bound states of *K*-particles in nuclear matter ("*K*-fragments"). If a θ^0 fragment exists, its decay modes are 2-, 1-, or 0-mesonic. It is estimated that the former two modes would have comparable probabilities, while the last one is less probable by a factor $\sim$0.005 if the spin of the θ^0 is zero, or by a factor $\sim$0.05 if the spin is 1. The results may have bearing on the interpretation of fragments with energy release larger than corresponds to a bound Λ^0.

COSMOTRON experiments[1] indicate an appreciable cross section ($\sim$1 mb) for the reaction

$$\pi^- + p \rightarrow \Lambda^0 + \theta^0$$

for π energies $\sim$1.5 Bev. As the virtual process $\pi^- + p \leftrightarrow n$ goes via the strong Yukawa-interaction, it follows from these experiments that $n \leftrightarrow \Lambda^0 + \theta^0$ also goes via a coupling that is strong. As a result there exists a strong $n-\theta^0$ interaction that may manifest itself in θ^0-n scattering: by means of $n \rightarrow \Lambda^0 + \theta^0$ the incoming neutron goes over into an outgoing θ^0 with virtual emission of a Λ^0; while via $\Lambda^0 + \theta^0 \rightarrow n$ the incoming θ^0 absorbs this Λ^0 and goes over into an outgoing neutron. Thus the $n-\theta^0$ coupling leads to a space-exchange scattering. This character of the interaction is of importance for the slowing down of θ^0's passing through matter, as exchange forces tend to favor large momentum transfers.

There is very preliminary evidence[2] for the reaction $\pi^- + p \rightarrow \Sigma^0 + \theta^0$ where the Σ^0-hyperon is a particle[3] supposed to be short lived for the transition $\Sigma^0 \rightarrow \Lambda^0 + \gamma$. If further evidence substantiates this reaction there will also be $n-\theta^0$ exchange forces via the intermediary of the Σ^0.

Neither the Λ^0 by itself nor the Σ^0 by itself can act as intermediaries in a conceivable θ^0-p interaction. However, the possibility exists that a θ^0-p force is brought about by the Σ^+. Direct evidence for this would, for example, be obtained if the reaction $\pi^+ + n \rightarrow \Sigma^+ + \theta^0$ were established. At any rate it is clear that the mechanisms of θ^0-n and θ^0-p interactions mentioned here lead to a dissymmetry between these two forces. It should be observed that θ^0-nucleon forces of a nonexchange kind may also be envisaged.[4]

Similar arguments lead to *K*-nucleon forces for other *K*-particles whenever it is known that *K*-production takes place in nucleon-nucleon or π-nucleon collisions. And if the production is of the associated type[5]: $\pi + \text{nucleon} \rightarrow Y + K$, then these forces necessarily have the typical exchange character exemplified above for the θ^0. Thus from the reaction[1] $\pi^- + p \rightarrow \Sigma^- + K^+$ one derives $K^+ - n$ exchange forces via the Σ^-. A $K^+ - p$ force can be brought about via Λ^0 or Σ^0. Various events have been found which may be interpreted as $K^+$$-$nucleon scattering.[6]

By the same argument if follows that the strong interactions $n \leftrightarrow \Lambda^0 + \theta^0$, $p \leftrightarrow \Lambda^0 + K^+$, lead to Λ^0-nucleon exchange scattering. The exchange mechanism here favors the substitution of a nucleon by a Λ^0 when the latter hits nuclear matter and thus tends to increase the probability of hyperfragment formation.

In certain instances (specifically for K^--particles) the *K*-nucleon interaction may manifest itself by a rapid *K*-absorption in nuclear matter with the emission of a hyperon. Events of this kind have been observed[7] and are in accordance with somewhat more detailed theoretical considerations on the properties of the new particles.[8] It has been pointed out by Lee[9] that *K*-

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* On leave of absence from the Institute for Advanced Study.

[1] See R. P. Shutt, Proceedings of the Fifth Annual Rochester Conference, 1955 (University of Rochester, Rochester, to be published).

[2] R. P. Shutt and W. D. Walker, Proceedings of the Fifth Annual Rochester Conference, 1955 (University of Rochester, Rochester, to be published).

[3] For the designation of the various hyperon states see, e.g., M. Gell-Mann and A. Pais, Proceedings of the Glasgow Conference (Pergamon Press, London, 1955).

[4] Assuming the existence of antibaryons, a θ^0 can virtually give an anti-Λ^0 plus a neutron, for example, where the neutron in this intermediate state can interact with the initial nucleon via the π-meson field. This is the type of interaction presumably referred to by M. W. Friedlander *et al.*, Nuovo cimento **1**, 694 (1955).

[5] For experimental evidence of the associated production of charged *K*'s and hyperons, see, e.g., K. Gottstein, Nuovo cimento **1**, 277 (1955).

[6] See, e.g., R. R. Daniel and D. Lal, Proc. Indian Acad. Sci. **41**, 15 (1955); W. R. Chupp *et al.*, University of California Radiation Laboratory Report UCRL-2963; M. W. Friedlander *et al.*, Nuovo cimento **1**, 694 (1955).

[7] See, e.g., H. de Staebler, Phys. Rev. **95**, 1110 (1954); M. W. Friedlander *et al.*, Phil. Mag. **46**, 144 (1955).

[8] See A. Pais, Proceedings of the Rochester Conference, 1955 (University of Rochester, Rochester, to be published). The *K*-particles discussed there are given the tentative designation B^+, B^-, B^0, $\bar{B}^0$. The charge Q for these particles is given by $Q = I_3 + K_3$, $I_3 = \pm\frac{1}{2}$, $K_3 = \pm\frac{1}{2}$. For strong and electromagnetic interactions ΣI_3 and ΣK_3 are supposed to be conserved. The *K*-particle absorption by nuclei with Λ^0 emission satisfies these conservation rules for those *K*-particles which have $K_3 = -\frac{1}{2}$, ($\bar{B}^0$ and B^-). These same rules prohibit this absorption mechanism for B^+ and B^0. We assume here the θ^0 is of the $\bar{B}^0$-type: $I_3 = -\frac{1}{2}$, $K_3 = \frac{1}{2}$, consistent with their associated production with Λ^0's and with the assignments $I_3 = 0$, $K_3 = -\frac{1}{2}$ for Λ^0. In the same Pro-

absorption experiments on certain specific nuclei are of importance for the verification of isotopic spin assignments to the new particles.

According to the theoretical views just referred to,[8] K-absorption cannot go fast for positive K's (even disregarding the Coulomb repulsion) and for neutral ones of the type θ^0. Apart from the scattering phenomena mentioned previously, there is still another source of information concerning strong K-nucleon interactions of these particles, namely charge-exchange scattering, such as

$$\theta^0+p\rightarrow n+\theta^+, \tag{1a}$$

where θ^+ is a positive K-particle belonging to the same "multiplet" as θ^0. The θ^+ is presumably the experimentally identified particle $K_{\pi 2}{}^+$ (or χ^+). A reaction of the kind (1a) is in accordance with selection rules that have been proposed for strong interactions.[8] This scattering can for instance go via the Λ^0: the proton emits a Λ^0 and goes over into θ^+; the θ^0 absorbs the Λ^0 and goes over into a neutron.

At the time of writing it is far from clear how many distinct K-particles (of given charge, say) there are. However, Dalitz's analysis of τ-decay data[10] strongly suggests that there are at least two distinct kinds of K-particles. Within the framework of theoretical ideas hitherto advanced,[8] these distinct K-particles should be assigned the same quantum numbers of isotopic type that have been specified so far. This leads us to a new problem, first noted by Friedlander *et al.*[6]: is the scattering

$$K+\text{nucleon}\rightarrow K'+\text{nucleon} \tag{1b}$$

possible, where K and K' belong to distinct K-multiplets and where, of course, (1b) is in accordance with charge conservation? Can a τ^+ for example go over into a θ^+ or a θ^0 in this way? The selection rules for strong interactions[8] are not inhibitive here. That such $\theta\leftrightarrow\tau$ transitions could nevertheless be prohibited by more specific assumptions about the dynamics of the interactions concerned is evident from the example discussed by Utiyama and Tobocman.[11] The interactions proposed by these authors actually forbid the conversion of a θ into a τ via strong interactions. Apart from all theoretical speculation the experimental verification of whether or not reactions like (1b) can take place raises a new question: How can one experimentally determine "which K-particle is which" in a situation where this particle cannot be followed till its decay? While such a determination does not seem impossible in principle, it is certainly far from easy and it will be especially difficult the more nearly mass-degenerate distinct K-particles will be.

The foregoing discussion referred to bosonic K-particles (K_B) only. It is our understanding of the present situation that it is not inconceivable that all K-decay modes observed so far could actually be interpreted as heavy-boson disintegrations. Nevertheless it seems proper to ask in which way various arguments would be affected if we would have to envisage also the existence of fermionic K-particles, K_F.

First of all it will be clear from the conservation of angular momentum and of baryons that in a nucleon-nucleon or π-nucleon collision K_F's can only be produced together with another "light fermion" i.e., a fermion that is not a baryon; (the K_F-production may either be direct or indirect via the decay of some "super-K_B"). Suppose this light fermion is itself a K_F. There will then be no special problem in explaining possible long lifetimes[12] for the K_F. In particular, there can be no objection from this point of view to a pair coupling between K_F's and nucleons; such an interaction would give rise to K_F-nucleon scattering. It may be worth while to point out that the arguments[8] for the interpretation of an apparent plus-minus asymmetry of K-particles so far specifically refer to K_B's. The point is that, assuming associated production, the lowest threshold reactions involve the production of a $K_B{}^+$ and a hyperon. If we assume $2K_F$-production, there is no analogous reaction for K_F and the plus-minus ratio should behave differently for K_F than for K_B.

If on the other hand the light fermion accompanying the K_F were of much smaller mass (a muon, electron, or neutrino), then a strong production rate (direct or indirect) for K_F would, with as much stringency as for K_B, require associated production with a hyperon. In this situation it would be indispensable to assign to K_F quantum numbers of the isotopic type if the selection rules for strong interactions[8] are to be upheld. For the moment it does not seem worth while to pursue further consequences of such a situation; we will now return to the exclusive consideration of heavy bosons.

Further information about forces between K^+ or K^0 and nucleons may obtain if these K-particles can form bound states with a nucleon. It is clearly a question of much more detail than can at present be handled theoretically whether such bound states actually exist. On the other hand we can ask: if they exist how would they be detected? An obvious answer is that they then might show up in the existence of "K-fragments," just as the existence of Λ^0-nucleon binding is proved from the existence of hyperfragments. To be specific let us consider the θ^0 (this is, of course, a more plausible case than the K^+ anyway) and inquire what the decay modes are of a hypothetical θ^0 fragment.

The main free θ^0-decay mode is

$$\theta^0\rightarrow\pi^++\pi^-+\sim 214\text{ Mev.} \tag{2}$$

Accordingly, when a θ^0 assumed bound in nuclear matter decays, we may expect the emergence of (a) two pions, or (b) one pion, the other one being virtually emitted in decay and reabsorbed by a nucleon, or (c) no pions, both pions being emitted virtually in decay and reabsorbed by nucleons. We call these modes 2-, 1-, and 0-mesonic decay respectively. We shall indicate below how the relative probabilities of these modes have been estimated, but will first state the results.

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ceedings the equivalence of these assignments with the rules first proposed by M. Gell-Mann is discussed.

[9] T. D. Lee, Phys. Rev. **99**, 337 (1955).

[10] R. H. Dalitz, Phil. Mag. **44**, 1068 (1953); Phys. Rev. **94**, 1046 (1954); Proceedings of the Rochester Conference, 1955 (University of Rochester, Rochester, to be published).

[11] R. Utiyama and W. Tobocman, Phys. Rev. **98**, 780 (1955).

[12] See A. Pais, Phys. Rev. **86**, 663 (1952).

(*a*) *2-mesonic decay.*—A preliminary question is whether, along with the scheme (2), also $\theta^0 \rightarrow 2\pi^0$ is possible. This is so only if the spin and parity of the θ^0 are even. If this is the case, the relative probability for the charged and neutral mode depends on specifics of the interaction. Assuming that the interaction brings about a change of a half-unit of isotopic spin between the initial and final state,[3,7] one has

$$w_{\mathrm{ch}}^{(2)} = 2w_0^{(2)}, \qquad (3)$$

where $w_{\mathrm{ch}}^{(2)}$ and $w_0^{(2)}$ are the probabilities for charged or neutral 2π decay respectively. The decay interaction H_g defined by equation (5) below is in accordance with relation (3). The charged 2 mesonic decay of a θ^0-fragment will give rise to two fast charged pions[13] of ~110 Mev. It depends on the fragment size what the chances are for these pions to escape. For a fragment of the size of *C* the probability for escape of both pions are small, and the chances for star formation correspondingly large.

(*b*) *1-mesonic decay.*—Considering the decay process as a two-body (θ^0-nucleon) interaction, one will get a fast nucleon (~75 Mev) plus a fast pion (~260 Mev). Call the probability for this process $w^{(1)}$. We have estimated that $w^{(1)} \sim w^{(2)}$. If $2\pi^0$ decay is dynamically allowed, we must again distinguish between the emission of a single charged or neutral pion. Under the same assumptions as above for the decay interaction, we have

$$w_{\mathrm{ch}}^{(1)} = 2w_0^{(1)}. \qquad (4)$$

(*c*) *0-mesonic decay.*—Now both pions virtually created in θ^0 decay are reabsorbed by nucleons. In this case two fast nucleons (each ~250 Mev) will emerge; it is clear that here as well as in discussing $w^{(1)}$ we may neglect effects of the exclusion principle in the final state. We find that the probability $w^{(0)}$ for this process is $\sim\frac{1}{2}\%$ of $w^{(2)}$ if the spin of θ^0 is zero; and ~5% if this spin is equal to 1.

Such a hypothetical θ^0 fragment, with an expected lifetime comparable to (but shorter than) the free θ^0 lifetime ($\sim 1.5 \times 10^{-10}$ sec) clearly distinguishes itself from a Λ^0 fragment by its much larger energy release. In fact, it was just because they found a fragment with high-energy release that Fry and Swami first suggested[14] the possibility of bound θ^0's. A further event in this high-energy category has meanwhile been found by the Wisconsin group.[15] Of course, these phenomena may be due to altogether different causes.[16]

These higher-energy fragments are of particular interest for those theoretical considerations[8] according to which the only known hyperon that can be semistably bound in nuclear matter is the Λ^0. Alternative explanations of higher-energy fragments as being possibly due to other effects than hyperon binding are therefore of some interest; such explorations may help ascertain whether or not the theoretical assumptions made need modification.

We come now to the estimates of the decay probabilities $w^{(2)}$, $w^{(1)}$, $w^{(0)}$. At this point it should be emphasized that the particle which decays (in free space) into $\pi^+ + \pi^-$ should, in a terminology explained elsewhere, be called the member of the "θ^0-particle mixture" for which 2π decay is allowed.[17] We call ϕ the wave function of the particle that can undergo 2π decay. Consider first zero-spin θ^0's as an instance of the case: even spin and parity. A phenomenological interaction,

$$H_g = gM_0\phi\chi^2 \qquad (5)$$

(where g is the coupling constant with dimensions of charge, M_0 is the θ^0 mass put in for dimensional reasons, and χ is the pion wave function expressed in the usual isotopic components χ_1, χ_2, χ_3), gives[18]

$$w_{\mathrm{ch}}^{(2)} = \frac{g^2}{4\pi}\left(1 - \frac{4\mu^2}{M_0^2}\right)^{\frac{1}{2}} M_0 \qquad (6)$$

(where μ is the pion mass). One easily sees that the structure (5) of H_g leads to the relation (3). The two pions produced in 2-mesonic decay have an initial kinetic energy ~110 Mev. The mean π-nucleon scattering cross section $\langle\sigma_{\mathrm{sc}}\rangle$ at this energy is ~60 mb, corresponding to a scattering mean free path $\lambda_{\mathrm{sc}} \sim 2 \times 10^{-13}$ cm. Comparing this with a nuclear radius of, say, carbon ($\simeq 3.2 \times 10^{-13}$ cm) it follows that there is a fair chance for at least one pion to get absorbed and form a star.

To estimate $w^{(1)}$, we need a mechanism describing single π absorption. It seems proper to take for this interaction

$$H_G = G\mu^{-1}\psi^\dagger(\boldsymbol{\sigma}\cdot\boldsymbol{\nabla})(\boldsymbol{\tau}\cdot\boldsymbol{\chi})\psi, \qquad (7)$$

with a G which we take from π-nucleon interaction. For a θ^0 at rest in a nuclear medium with average density $\sim 3\mu^3/4\pi$, we get

$$w_{\mathrm{ch}}^{(1)} = 24\frac{G^2}{4\pi}\frac{g^2}{4\pi}\left(\frac{p}{\omega}\right)^3\left(\frac{\mu}{\omega}\right)\frac{M}{M+\omega}M_0,$$

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[13] In nuclear matter the 2-mesonic decay is stimulated by virtual absorption and emission of the pions by the surrounding nucleons. The same is true for the other decay modes.

[14] W. F. Fry and M. S. Swami, Phys. Rev. **96**, 809 (1954).

[15] Fry, Schneps, and Swami, this issue [Phys. Rev. **99**, 1561 (1955)]. We want to thank these authors for sending us preprints of their work.

[16] For example the event NK_4 observed by J. Hornbostel and E. O. Salant, Phys. Rev. **98**, 218 (1955) looks like a case involving a charged hyperon where more energy is released than corresponds to any known hyperon decay, provided the secondary *L*-particle is assumed to be a pion. Bound θ^0's can have nothing to do with this event. Here μ or β decay of a Σ may perhaps account for the phenomenon.

[17] M. Gell-Mann and A. Pais, Phys. Rev. **97**, 1387 (1955). From the arguments presented there it will be clear that there are still other decay-modes to be considered for a possible θ^0 fragment, namely those corresponding to the disintegration scheme of the other member of the θ^0 mixture. We shall not study these here.

[18] We put $\hbar = c = 1$.

where p and ω are the momentum and total energy of the emerging pion; M is the nucleon mass. From (5) and (7) one sees that (4) holds true. With $\omega \sim 400$ Mev, we get $w_{\mathrm{ch}}^{(1)}/w_{\mathrm{ch}}^{(2)} \sim 8G^2/4\pi$. From π-nucleon scattering, one estimates[19] $G^2/4\pi$ to be ~ 0.1 and hence $w^{(1)}$ and $w^{(2)}$ are of comparable magnitude.

For the pion energy considered here $\langle\sigma_{\mathrm{sc}}\rangle \sim 90$ mb, so $\lambda_{\mathrm{sc}} \sim 1.3 \times 10^{-13}$ cm. Hence the fast pion produced in 1-mesonic decay has a good chance to be captured in a C-nucleus and to produce a star. It follows from the foregoing that the large absorption probability of the real pions involved will make it hard to disentangle 2-, 1-, and 0-mesonic decay for nuclei as heavy as carbon or heavier. Only for the very light nuclei could these various decay modes of our assumed θ^0 fragment be clearly distinguishable.

In estimating the probability that the two decay mesons (either oppositely charged or both neutral) are virtually absorbed by two distinct nucleons (the initial momentum of which we may neglect compared to their final momentum), we use again (5) and (7). Consider first the case that we deal with just two nucleons rather than a bigger nucleus. The matrix element m^0 for the process than is:

$$m^0 = g(M_0/2)^{\frac{1}{2}}\, \omega^2\, (\omega^2 - \tfrac{1}{4}M_0^2)^{-2}\, V(\mathbf{p}), \tag{9}$$

where $\mathbf{p}$ is the momentum of one of the final nucleons, $\omega = (p^2+\mu^2)^{\frac{1}{2}}$, while

$$V(p) = G^2(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)(\boldsymbol{\sigma}_1\cdot\mathbf{p})(\boldsymbol{\sigma}_2\cdot\mathbf{p})\omega^{-2}\mu^{-2} \tag{10}$$

is a Fourier component of the nuclear force $\sim G^2$ brought about by the interaction (7). Actually (9) seems more reliable if we treat $V(p)$ phenomenologically rather than insist on its specific form (10). Thus we proceed as follows: for large p we have approximately

$$V(p) = -p^2\varphi(p)/M\psi(0), \tag{11}$$

where $\psi(0)$ is the value at the origin of the wave function $\psi(r)$ describing the relative motion of the nucleon pair, while $\varphi(\mathbf{p}) = \int d^3x\psi(\mathbf{x}) \exp(-i\mathbf{p}\cdot\mathbf{x})$. For large p the main contributions in (11) come from small distances where, in the specific case of n-p interaction, the S-state part of the wave function predominates over its D-state part, so that we may consider $\psi(r)$ and $\varphi(p)$ to refer to the central part of the nuclear interaction which is of comparable magnitude for each charge state of the nucleon pair.[20] Then we need not specify the nucleon charges in what follows.

Inserting (11) into (9), we get an expression for m^0 in which it has not yet been taken into account that the nucleon pair considered is itself imbedded in nuclear matter. A nucleon pair model of the actual nucleus seems a reasonable description for processes involving large final momenta.[21] On this pair model, the transition to the actual nucleus is made by replacing $(m^0)^2$ by

$$(m^0)^2 \cdot \frac{1}{2}\left(\frac{3\mu^3}{4\pi}\right)^2 f,$$

where the factor f indicates the deviation of the pair correlation from its value for uniform density. The probability $w^{(0)}$ is then given by

$$w^{(0)} = \frac{9f}{128\pi^2}\frac{g^2}{4\pi}\mu^6\omega^4p^5M^{-1}\left(\omega^2 - \frac{M_0^2}{4}\right)^{-4}\frac{|\varphi(p)|^2}{|\psi(0)|^2}M_0.$$

$\varphi(p)$ may be considered as a high Fourier component of the ${}^3S$-state deuteron wave function about which we certainly have not much direct information. However, we can compare $\varphi(p)$ and $\psi(0)$ with the same quantities used by Levinger[21] to fit the high-energy nuclear photoeffect. Doing this, we get

$$|\varphi(p)|^2/|\psi(0)|^2 = 16\pi^2\alpha^2(1+\beta)^2p^{-8},$$

where $\alpha = (M|\epsilon|)^{\frac{1}{2}}$ and $\epsilon =$ binding energy of the deuteron. The numerical constant β is equal[21] to 6.7. Hence, finally,

$$w^{(0)} = \frac{9}{8}(1+\beta)^2 f\frac{g^2}{4\pi}\frac{\alpha^2\mu^6\omega^4}{Mp^3}\left(\omega^2 - \frac{M_0^2}{4}\right)^{-4}M_0.$$

According to Brueckner, Serber and Watson,[22] $f \simeq 35$ for a carbon nucleus. For f-values of this order of magnitude we find on comparison with (6) that $w^{(0)}/w_{\mathrm{ch}}^{(2)} \sim 0.005$, so that 0-mesonic emission is a relatively unimportant decay mode of the assumed θ^0-fragment.

The above estimate of $w^{(0)}$ is incomplete without the consideration of the case where the two pions are virtually absorbed by the same nucleon which then recoils with another nucleon to carry off momentum. However, it can be shown that this contribution is very nearly proportional to the scalar product of the initial and final two-nucleon state, which is zero due to orthogonality. Hence this effect is small compared to the one we have calculated in the foregoing.[23]

Finally it remains to consider to what extent the foregoing results are sensitive to the assumption of zero spin for the θ^0. To explore this we have also considered the spin-1 case where there is no $2\pi^0$-decay. Instead of (5) we now take $H_\theta = ig\phi_\mu[\chi^*(\partial\chi/\partial x_\mu) - (\partial\chi^*/\partial x_\mu)\chi]$. Here ϕ_μ is the vector-θ^0 wave function, χ the charged

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[19] See M. H. Friedman and T. D. Lee, Bull. Am. Phys. Soc. **30**, No. 3, 18 (1955). The same value was also found by R. Serber and T. D. Lee (unpublished), using an improved version of the Chew-Low plot for π-nucleon scattering [see Proceedings of the Fifth Annual Rochester Conference, 1955 (University of Rochester, Rochester, to be published)].

[20] See R. L. Pease and H. Feshbach, Phys. Rev. **81**, 142 (1951).

[21] See, e.g., J. S. Levinger, Phys. Rev. **84**, 43 (1951).

[22] See Brueckner, Serber, and Watson, Phys. Rev. **84**, 258 (1951).

[23] The argument is not quite clean, because the probability for the absorption of the two pions by a single nucleon is divergent. However, if one, for lack of better methods, estimates the contribution up to the nucleon Compton wavelength it turns out that the effective interaction constant $G^2\mu^{-2}$ has to be replaced by $G^2\mu^{-2}(1+\log 2M/\mu)$, which gives an additional factor that is at any rate not too big.

pion field, χ^* its Hermitian conjugate. One obtains

$$\left(\frac{w_{\mathrm{ch}}^{(1)}}{w_{\mathrm{ch}}^{(2)}}\right)_{\mathrm{vector}}=\left(\frac{w_{\mathrm{ch}}^{(1)}}{w_{\mathrm{ch}}^{(2)}}\right)_{\mathrm{scalar}}\cdot\frac{4p^2}{M_0^2}\left(1-\frac{4\mu^2}{M_0^2}\right)^{-1},$$

where p is the momentum ($\sim$380 Mev/c) of the pion emerging in 1-mesonic decay. Thus the relative factor of vector to scalar ratio is $\simeq$2.7 which does not materially change the situation. In the vector case, the ratio of 0- to 2-mesonic decay is increased by a factor $(4M/M_0)(1-4\mu^2/M_0^2)^{-1}\sim 10$. Thus, like the 1-mesonic decay, the 0-mesonic mode gains in relative importance due to the stronger momentum dependence of H_g in the vector case. Also in this case, $w^{(0)}$ is still small compared to $w^{(2)}$. We have not considered cases of higher spin.

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Analysis of Properties of Secondary Particles in Nucleon-Nucleon Collisions at Very High Energy*

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Momentum measurements were made on the individual secondary particles emitted in the "outer" cone of the S-star. A lower limit to the momentum of the particles in the "inner" cone was obtained. The transformation from the laboratory system to the center-of-mass system can be made, using suitable approximations, on the assumption that all charged secondaries are pions. This leads to a symmetrical angular and energy distribution with all particles included in a forward or backward cone of half-angle 20°. The results are compared with various multiple production theories. It is possible to infer that there is no more than one pair of particles of protonic mass among the secondaries and that even the presence of one pair would violate symmetry. The number of K-mesons must also be small. The methods of analysis should be useful on other events in this energy range.

I. INTRODUCTION

THE problem of analyzing stars caused by high-energy cosmic-ray particles in nuclear emulsions is, in general, quite complicated. However, if the incident particle is a nucleon and the target is a nucleon also, the analysis is considerably simplified since it is then possible to postulate bilateral symmetry in the center-of-mass system.[1] Even in cases where the target nucleus is more complicated but where there is some evidence that the principal interaction was with a peripheral nucleon, it is possible to analyze the star on the basis of a nucleon-nucleon interaction since the energy transferred to the rest of the target nucleus may be negligibly small. It is possible to make a real distinction here between low and high energies. At low energies it is possible to have an appreciable fraction of the energy emitted from the "first nucleon-nucleon collision" in the form of secondary particles at relatively large angles. It is then quite probable that these secondaries will strike another nucleon inside the nucleus and that a nuclear cascade may develop. In the case of the very high energies ($E_p > 10^{13}$ ev), the secondaries from a given nucleon-nucleon collision are known to be very strongly collimated in the direction of motion of the incident nucleon, and hence it is quite possible that a collision with a peripheral nucleon will result in almost all the energy being transferred into a cone so narrow that it intersects no other nucleons. This is the same phenomenon which takes place in central collisions and produces the so-called "tunnel effect."[2] A simple computation shows that peripheral collisions are rather probable if the target nucleus is a light nucleus of the emulsion (C, N, O).

A number of authors have presented stars of varying degrees of complexity with primary energies of the order of 10^{13} ev or greater, generally with no possibility of analyzing the energy of the secondaries.[3]

In the present paper a careful analysis of the S star[1] is reported which illustrates the advantages of being able to measure the multiple scattering on several of the shower tracks. The S star is shown in Fig. 1. It occurred in a 200μ Ilford G-5 emulsion flown at above 90 000 feet for over 16 hours from Chicago, Illinois.

The fact that the only two secondary tracks (B and C) which are not closely collimated (within 5° in space) with the original direction of the primary track are gray tracks indicates that only an insignificant propor-

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[1] Lord, Fainberg, and Schein, Phys. Rev. **80**, 970 (1950).

[2] F. C. Roesler and C. B. A. McCusker, Nuovo cimento **10**, 127 (1953).

[3] Engler, Haber-Scheim, and Winkler, Nuovo cimento **12**, 930 (1954), contains references to earlier work.