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NUCLEAR INTERACTIONS OF NEUTRAL K-MESONS OF LONG LIFETIME[*]-II

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SUMMARY.- This work follows a previous study of the interactions of long lived neutral K-mesons, already published. The increased statistics allows us to check the results previously obtained and to determine the cross section for charge exchange of the θ_2^0 particles in the eigenstate of strangeness -1.

1. Introduction.

In a previous work (paper I) [1], we studied the interactions of θ_2^0 in the modes θ^0 and $\bar{\theta}^0$. In that work a volume of 8.5 cm^3 was scanned and sufficient statistics were obtained to evaluate at least as an order of magnitude, the flux of θ_2^0 particles inci-

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dent on the stack, and their probability of interacting in the modes θ^0 and $\bar{\theta}^0$. This was done starting from the number of K^+ and hyperfragments produced.

The rather low number of K^- found, on the contrary, did not permit evaluation of the magnitude of the cross-section for the reaction:

(1) $$\bar{\theta}^0 + n \rightarrow K^- + p.$$

As very little is known [2-4] about the cross-section for charge exchange of K^-, we decided to study this problem by means of the inverse reaction (1). To this purpose we made a more rapid scanning than the previous one, looking only for capture stars. In the additional scanned volume of 14.5 cm^3 we found:

2 τ and 1 τ' ,
7 K^-,
7 Σ^- captured at rest,
1 Σ^+ decaying at rest and 1 Σ^+ decaying in flight,
2 hyperfragments and 6 GOKS,

all emitted from stars in emulsion.

Adding these results to those of paper I it is possible, not only to calculate the magnitude of the charge exchange cross section of $\bar{\theta}^0$, but also to check the previous result on the ratio θ^0 mode/$\bar{\theta}^0$ mode.

Details on the exposure and methods for the particles' identification are described in paper I which deals also with the problem of the possible neutron contamination.

2. - Experimental results.

The data of θ_2^o interaction events found in the total scanned volume of 23 cm^3 are given in Tables I, II-A, II-B, II-C.

The features of the stars from which K^- and K^+ are emitted are in agreement with the assumption that these stars are produced respectively in the two interactions:

$$(1) \qquad \theta^o + p \rightarrow K^+ + n,$$

$$(2) \qquad \bar{\theta}^o + n \rightarrow K^- + p,$$

In fact in Table I there are 6 cases (1, 2, 3, 4, 11, 12) that are readily interpreted according to reaction (1) while the remaining stars, characterized by the presence of an energetic proton, can be due, as already pointed out in paper I, to a double interaction of the θ^o inside the nucleus.

In the stars emitting K^- (Table II-A) an energetic proton, in agreement with reaction (2) is always found among the prongs.

In Table II-B the interactions leading to $\Sigma^{\pm}$ are listed. The events 1... 10 are certainly Σ^- captured at rest: in two cases a relativistic track is present in the parent star, which can very likely be interpreted as a π^+.

3. - θ^o flux [a] as deduced from charge exchange processes.

In paper I an estimate of the θ^o flux was obtained starting from the number of K^+ decaying at rest in the scanned volume. The result was depending on the estimate of the scanning efficiency. This was deduced studying the dip angle distribution of

TABLE I

Event nº.	Strange particle produced	Parent Star		Strange particle		Calculated kinetic energy of θ^0 from $\theta^0 + p \rightarrow K^+ + n$ MeV	REMARKS
		no. of prongs	Total visible kinetic energy Mev	Angle in the L.S. with the θ^0 beam	Kinetic energy Mev		
1	K^+	1	85	43°	85	130	
2	τ^+	4	65	46°	41	95	
3	K^+	1	74	163°	74	300	
4	K^+	1	28	70°	28	70	
5	K^+	5	130	142°	48		One fast proton of kinetic energy of 72 MeV is emitted from the parent star
6	τ'^+	4	324	179°	48		One fast proton of kinetic energy of 254 Mev is emitted from the parent star
7	K^+	8	323	65°	6		One fast proton of kinetic energy of 195 MeV is emitted from the parent star
8	K^+	6	547	139°	58		One fast proton of kinetic energy of 440 MeV is emitted from the parent star
9	K^+	9	180	7°	41		One stopping π^- of 34 MeV and a proton of 71 MeV are emitted from the parent star
10	τ^+	3	> 250	112°	55		One minimum ionization track, not identified, is emitted from the parent star.
11	τ'^+	1	86	26°	86	99	
12	τ^+	1	68	38°	68	157	

TABLE II A

Event no.	Strange particle produced	Parent star		Strange particle					REMARKS	
		no. of prongs	Total visible kinetic energy (MeV)	kinetic energy (MeV)	Track length (μ m)	Angle in L.S. with the beam θ°	Capture star		On the capture star	On the parent star
							no. of prongs	Visible energy (MeV)		
1	K^- (at rest)	8	118	41	10500	127°	2	23	One π^{0} of 22 MeV of kinetic energy is emitted	
2	K^- (at rest)	3	>270	65	24300	88°	3	48		One grey track is probably due to an energetic proton
3	K^- (at rest)	10	198	8	545	40°	{ 2+ recoil	52	One π^- of 52 MeV of kinetic energy is emitted	
4	K^- (at rest)	8	>250	2	62	129°	3	31	One π^- of 26 MeV of kinetic energy is emitted	One relativistic prong, not identified, is emitted.
5	K^- (at rest)	3	255	32	7000	123°	3	211		One proton of 148 MeV of kinetic energy, is emitted
6	K^- (at rest)	4	104	18	2600	44°	3	30		One proton of 72 MeV of kinetic energy, is emitted
7	K^- (in flight)	3	351	35*	6100	107°	2	11	One π^- of 10 MeV of kinetic energy is emitted	One proton of 230 MeV of kinetic energy is emitted
8	K^- (at rest)	11	189	3	140	99°	2	36	One π_{ρ}^{-} of 53 MeV of kinetic energy is emitted	One proton of 76 MeV of kinetic energy, is emitted

* From gap measurements.

TABLE II B

Event no.	Strange particle produced	Parent star			Strange particle						REMARKS
		no. of prongs	Total visible kinetic energy (Mev)	Emission of a π	Kinetic energy (MeV)	Track lenght (μm)	Angle in L.S. with the θ^{o} beam	Capture star or decay mode			
								no. of prongs	Visible energy (MeV)	Mode of decay	
1	Σ^-(at rest)	5	102	no	65	12400	53°	2			
2	Σ^-(at rest)	10	246	no	4	110	158°	4	6		Auger electron visible in the capture star
3	Σ^-(at rest)	7	73	no	5	135	83°	1	10		
4	Σ^-(at rest)	7	50	no	4	90	25°	2	108		
5	Σ^-(at rest)	11	150	no	10	430	85°	2	30		
6	Σ^-(at rest)	5	>530	one relativistic track	27	1560	131°	1	46		
7	Σ^-(at rest)	3	214	no	36	4200	45°	2	2		
8	Σ^-(at rest)	5	68	no	33	$\begin{cases}1410+\\+875\end{cases}$	53°	2	2		The Σ^- suffers an inelastic scattering before being captured at rest
9	Σ^-(at rest)	6	105	no	8	390	112°	4	16		
10	Σ^-(at rest(	3	>440	one relativistic track	36	4200	69°	2	72		
1	Σ^+(decaying in flight)	1	134	no	134	29200	75°			$\Sigma^+ \rightarrow p + \pi^0$	
2	Σ^+(decaying in flight)	1	72	no	72	1880	32°			$\Sigma^+ \rightarrow p + \pi^0$	
3	Σ^+(decaying in flight)	2	155	no	137	19900	160°			$\Sigma^+ \rightarrow p + \pi^0$	
4	Σ^+(decaying in flight)	3	18	no	~8	140	139°			$\Sigma^+ \rightarrow p + \pi^0$	
5	Σ^+(decaying at rest)	5	152	no	85	19400	45°			$\Sigma^+ \rightarrow p + \pi^0$	Range of the proton: 1690μm
								Interaction Star			
								no. of prongs		Visible energy (Mev)	
6	Σ^+(interacting in flight)	3	132	no	69	2200	154°	1		90	$\pi^\pm$ emitted from the interaction star

TABLE II-C

Event no.	Strange particle produced	Parent Star			Strange particle					Remarks
		no. of prongs	Total visible kinetic energy (MeV)	Emission of a π	Track length (μm)	Angle in L S with the θ° beam	Secondary star			
							no. of prongs	Visible energy (MeV)	Mode of decay	
1	H.F.	4	30	no	280	61°	2	2.2	non mesonic	-
2	H.F.	9	94	no	136	62°	$2\begin{cases}p\\p\end{cases}$	$88\begin{cases}84\\4\end{cases}$	non mesonic	Kinematics in agreement with: $^4He_{\Lambda} \rightarrow 2p+2n$
3	H.F.	7	> 172	π^-	40	61°	3	18	non mesonic	-
4	H.F.	4	18	no	160	26°	6	11	non mesonic	-
5	H.F.	9	415	no	5	38°	2	69	non mesonic	-
6	H.F.	6	70	no	24	94	2	12	non mesonic	-

the light secondaries and should be taken as an upper limit since we assumed that all light secondaries with dip angle $\leqslant 45°$ were detected.

The scanning efficiency can also be derived from the known ratio $\frac{K^+}{\tau}$ with the reasonable assumption that all τ and τ' decays have been detected. The increased statistics make this calculation meaningful.

On the total scanned volume (previous work: 8,5 cm^3, present work: 14,5 cm^3) 3 τ and 2 τ' were found. Taking for the $\frac{K^+}{\tau}$ ratio the value [5] 11,5 we estimated the number of K^+ decaying at rest in the scanned volume to be 62, that is $2,7 \pm 0,9$ K^+/cm^3. This has to be compared with the value $N_{K^+}/cm^3 = 1{,}4 \pm 0{,}4$ found in paper I and shows that the scanning efficiency has been previously over estimated.

Since the additional scanned volume lies in the same region of the stack as the volume scanned in the previous research, the geometrical loss due to the finite size of the stack is that evaluated in paper I (89%)[b].

The θ° incident flux integrated over the time of exposure turns out to be:

$$\varphi\theta^\circ = \frac{N_{K^+}}{cm^3}\,\lambda_{c.e.} = 25 \times 170 = (4200 \pm 1400)/cm^2$$

where $\lambda_{c.e.}$ is the effective mean free path for charge exchange as calculated in paper I and the quoted error is the statistical one.

4) $\bar{\theta}^\circ$ flux [a] as deduced from the number of Σ^- hyperons.

An estimate of the $\bar{\theta}^\circ$ flux is done starting from the number of Σ^- captured at rest in the scanned volume. This calculation is now possible owing to the increased statistics.

In the total volume 10 Σ^- captured at rest were found. This number must be corrected for scanning losses. These are mainly due to the fact that scanning by area for capture stars, Σ_ρ events and capture stars with one low energy prong were not detected. Events of this type were estimated by other authors [6] to occur in ~70% of all captures. Assuming 100% efficiency for detection of other kinds of capture stars, the number of Σ^- captured at rest in the scanned volume should have been 33.

In order to deduce the primary flux from this number, we must estimate the percentage of interacting $\bar{\theta}^\circ$ giving rise to a Σ^-

which will be captured at rest in the scanned volume. This could be done by the following considerations.

As in paper I we assume the $\bar{\theta}^o$ to be the charge symmetric particle of the K^- [c], so that information on the cross sections and on the branching ratios in the strong interactions of the $\bar{\theta}^o$ can be obtained from the results on K^- interactions.

The elementary interactions of the $\bar{\theta}^o$ in emulsion are:

1) $\bar{\theta}^o + P \rightarrow \Sigma^+ + \pi^o$

2) $\rightarrow \Sigma^o + \pi^+$

3) $\rightarrow \Lambda^o + \pi^+$

4) $\bar{\theta}^o + N \rightarrow \Sigma^+ + \pi^-$

5) $\rightarrow \Sigma^- + \pi^+$

6) $\rightarrow \Sigma^o + \pi^o$

7) $\rightarrow \Lambda^o + \pi^o$

To these, inelastic $\bar{\theta}^o$ reemission and charge exchange processes must be added; these can be estimated to be of the order of 10% of all $\bar{\theta}^o$ interactions [d].

If we consider the bubble chamber data of Alvarez et al.[8], and make use of charge independence, we expect the fraction of interacting $\bar{\theta}^o$ giving as a product of the reaction inside the nucleus a Σ^- hyperon to be 24%.[e]

From the results on K^- interactions in complex nuclei [3] it is known that only 42% of charged hyperons are not converted in Λ^o in nuclear matter by the reaction: $\Sigma + \mathcal{N} = \Lambda^o + \mathcal{N}$.

The energy spectrum of the Σ^- emitted from nucleus has been then calculated under the following assumptions:

1) the center of mass distribution of the produced Σ^- particles is isotropic.
2) the θ_2^0 primary spectrum is that calculated in paper I (fig.I,b').

To the total spectrum we have to subtract all the particles which did not come to rest before decaying, because they were not detected according to our scanning criteria.

If we calculate the probability of a Σ^- to decay in flight as a function of the energy, it turns out that practically all hyperons having an energy greater than 100 MeV decay in flight and that the number of Σ^- captured at rest is 9,5% of the total spectrum, that is, 9,5% × 24% × 42% = 1% of all $\bar{\theta}^0$ interactions.

Taking for the $\bar{\theta}^0$ interaction mean free path the value obtained for low energy K^-[3,9], $\lambda = 27$ cm, we obtained the $\bar{\theta}^0$ flux value:

$$\varphi_{\bar{\theta}^0} = \frac{N_{\Sigma^-}}{\mathrm{cm}^3}\ \lambda\ \frac{1}{1\%} = \frac{33}{23} \times 27 \times 100 = 3900 \pm 950/\mathrm{cm}^2$$

where the quoted error is the statistical one.

The flux value obtained is in amazingly good agreement with the θ^0 flux and this supports the Gell Mann and Pais scheme.

5. $\bar{\theta}^0$ charge exchange cross section.

In the total scanned volume 16 K^- captured at rest were observed. 8 of these, followed back through the stack, were found to originate in emulsion from stars with a neutral primary. If we assume these events to be due to the charge exchange of a $\bar{\theta}^0$[b] an estimate of the cross section for this process can be obtained.

This calculation requires a rather accurate estimate of the losses in detecting K^- captures. These are due both to scanning losses and to the geometrical limitation arising from the finite size of the stack.

The first effect was accounted for with the following considerations.

1) All K_ρ events (18% of all K^- captures) [10] were missed;
2) K^- captures occurring in the upper and lower layer of the plates are very difficult to observe. These layers have been estimated to be ∼10% of the total volume.
3) The scanning efficiency of other types of capture stars depends mainly on the dip of the primary K^- track. The dip angle distribution of the last 50 μm of the K^- tracks observed (16 including the ones coming from outside the stack) was analysed.

The scanning efficiency can be estimated comparing the observed distribution with the true one supposed to be isotropic. The same analysis has also been made for 100 π^- tracks whose captures at rest were observed by area scanning carried on by the same observers (50 π^- in the same stack and 50 π^- in a stack exposed to the cosmic radiation). In all cases the efficiency has been found to be ∼65%. The total scanning losses amount then to 58%.

The evaluation of the losses due to the finite size of the stack has been carried out as in paper I (sec. 6) assuming an average energy loss $\frac{\Delta T}{T} = 50\%$ [3] and gives a geometrical efficiency of detection of 9%.

The total number of K^- produced by charge exchange of $\bar{\theta}^0$

in the scanned volume is then estimated to be $N_{K^-} = 210$, that is $N_{K^-}/cm^3 = 9$.

This leads to a $\bar{\theta}^0$ charge exchange mean free path in the energy interval $(0 \div 400)$ MeV of :

$$\lambda_{c.e.} = \frac{\varphi_{\bar{\theta}^0}}{N_{K^-}/cm^3} = (460 \pm 180)\,cm$$

where for the incident flux we have taken the value averaged over the results of sec. 3 and 4 and where the error is the statistical one.

6. Conclusions.

From a study of the interactions of long lived $\bar{\theta}^0_2$ in emulsion we have derived the following conclusions:

1) the probabilities that θ^0_2 particles interact in the modes θ^0 and $\bar{\theta}^0$ are equal within the experimental errors:

2) the cross section for charge exchange of the $\bar{\theta}^0$ mode is of the order of 5 - 6% of the total $\bar{\theta}^0$ inelastic cross section.

These conclusions are correct if charge independence in the conventional sense holds true.

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[3] F.H. Webb, E.L. Iloff, F.H. Featherston , W.W. Chupp, G. Goldhaber and S. Goldhaber: Nuovo Cim., 8 , 899, (1958).

[4] Report of the 1958 Annual International Conference on High Energy Physics at Cern, page 177.

[a] The expressions Θ^0 and $\bar{\Theta}^0$ flux are used for brevity and stand in place of cm^2 of Θ_2^0 times the probability to be in the eigenstate of strangeness +1 and -1 respectively.

[5] Proceedings of the seventh annual Rochester Conference, VIII - 24.

[b] For the discussion on the contamination due to strange particles produced by high energy neutrons, see Paper I, sec. 3.

[6] W.F. Fry, J. Schneps, G.A. Snow, M.S. Swami and D.C. Wold: Phys. Rev., 107, 257, (1957).

[c] Recently Pais [7] has proposed a scheme in which Θ^0 and K^- (or Θ^0 and K^+) do not belong anymore to the same charge doublet. If this scheme is proved to hold, our calculations must be revised.

[7] A. Pais: "Relative parity of charged and neutral K-particles". Preprint.

[d] From the results of K^- interacting in flight [3], the inelastic reemissions are estimated to occur in 4% of the cases. An estimate of the charge exchange cross section of Θ^0 is given in sec. 5 of the present work and is found to be of the order of (5÷6% of the total cross section.

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[e] If the decrease of the Σ^-/Σ^+ ratio with increasing energy, as indicated by the Berne group [9], is confirmed, this percentage will have to be reduced and our calculations revised.

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