Mass Difference of Neutral K Mesons (*)

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Summary. — The mass difference $\Delta M$ between the $K_i^0$ and $K_0^0$ mesons has been investigated by producing $K^0$ mesons and observing the $K^0$ component of the $K^0$-$\bar{K}^0$ admixture as a function of time. The $\bar{K}^0$'s were sampled by using the charge exchange process and detecting the resulting $K^-$ mesons. The best value for the mass difference is $\Delta M = 1.9 \pm 0.3\mu/\tau_1\cdot e^2$ where $\tau_1$ is the mean life of the $K_1^0$. However, selected high mass-differences ($\Delta M > 10$) are also consistent with the data.

1. - Introduction.

We describe here an experiment designed to measure the mass difference $\Delta M$ between the $K_i^0$ and $K_2^0$ mesons in the range of $0 < \Delta M < 10\mu/\tau_1\cdot e^2$, where $\tau_1$ is the mean life of the $K_i^0$ meson ($10^{-10}\text{ s}$). That a mass difference between the $K_1^0$ and $K_2^0$ would, under the proper circumstances, appear as an interference effect in the relative abundance of $K^0$ and $\bar{K}^0$ was first suggested by Serber and discussed in the paper of Pais and Piccioni (1). It is pointed out in this paper that the relative intensity, $I$, of the $K^0$ or $\bar{K}^0$ as a function

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of the elapsed time \( t \) from the moment of production of a \( K^0 \) is given by

\[
I \left( \frac{\overline{K}^0}{K^0} \right) = \frac{1}{4} \left[ 1 + \exp \left( -t/\tau_1 \right) \right] \exp \left( -t/2\tau_1 \right) \cos \Delta \omega t,
\]

where

\[
\Delta \omega = \frac{\Delta M c^2}{\hbar} = \frac{\mu}{\tau_1},
\]

and where the \( K^0_2 \) decay rate has been neglected. It has become customary in the literature to express the mass difference in units of the width of the \( K^0_1 \) mass, \( i.e., \Delta M = \mu \hbar / \tau_1 c^2 \).

A mass difference between the \( K^0_1 \) and \( K^0_2 \) can be expected since the lifetimes of the two particles are different. Indeed, the principal interest in the mass difference stems largely from its being the only known instance where a self-energy due to the weak interactions is susceptible of experimental determination. In addition, a convincing demonstration of a small mass difference would rule out the possibility of transitions involving a strangeness change of 2. Such transitions permit a rapid mixing of \( K^0 \) and \( \overline{K}^0 \) giving rise to a large apparent mass difference between \( K^0_1 \) and \( K^0_2 \).

Good has suggested (3) a different effect sensitive to the mass difference. He has shown that the angular distribution of the \( K^0_1 \) mesons regenerated in material placed in a \( K^0_1 \) beam is sensitive to the mass difference. This method has been employed in the experiment of Muller et al. (4).

Various other ramifications of the mass difference and the determination of its sign have been discussed by several authors (5-7). The initial mass difference measurement (8), of limited statistical accuracy, utilized the interference effects given by eq. (1). In this measurement the \( K^0 \) and \( \overline{K}^0 \) components were sampled as a function of time by observing strangeness conserving interactions. Treiman and Sachs (9) have pointed out that the leptonic decay modes also sample these components. In particular, within the framework of

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the $\Delta I = \frac{1}{2}$ rule, the $K^0$ decays to $e^+(\mu^+)+\pi^-+\nu$ and the $\bar{K}^0$ decays to $e^-(\mu^-)+\pi^++\bar{\nu}$. Since this method was proposed the decay rates for the leptonic modes have been measured and found to be relatively small ($^{10,11}$). In condensed material the interaction rate is substantially higher than the decay rate. For this reason it appears most feasible to measure the $K^0$-$\bar{K}^0$ admixture through the strong interactions and this is the technique employed in the present experiment.

As seen from eq. (1) the interference effects are damped with a time constant of $2\tau$, corresponding to a distance of approximately 2.4 in. for particle momentum of 500 MeV/c. Since it is necessary to make observations close to the point of production, and therefore in a region of high background, it was the design of this experiment to charge exchange the neutral $K^0$ mesons to $K^-$ meson and with their relatively long lifetimes let them carry away the information from the region of high background. The experimental apparatus consisted of a source of $K^0$ mesons (5.3 GeV protons striking a Pt target in the bevatron), a converter variable in distance from the target (1½ in. to 5 in.) for charge exchanging the neutral mesons, and a detector of $K^-$ mesons in a region of relatively low background approximately 18 ft. from the target. The energy of the proton beam and the angle of observation from the target were chosen to be highly unfavorable for the direct production of $K^-$ and $K^0$ mesons.

2. - Apparatus.

The $K$-mesons were produced in a 1½ in. long, ½ in. wide, and ½ in. thick platinum target bombarded by protons with a mean energy of 5.3 GeV. The target was located in the west straight section of the bevatron and the $K$'s were observed on the inside radius at an angle of 84° with respect to the proton beam. Rather than move a single converter back and forth relative to the target, we chose to use different converters at different distances in order that the converters subtend a constant solid angle at the center of the target. Furthermore, to enhance any effect originating in the converter an absorber which shadowed the detector from direct radiation from the target was used. This so-called shadow bar was 2 in. thick in the $K$ beam direction, ½ in. high, and 2½ in. long, and was made of uranium. The target, converter, shadow-bar assembly is shown schematically in Fig. 1.


It was necessary to plunge the target assembly into the beam region of the bevatron with each pulse. The mechanical arrangement was such as to make it possible to place any of the four converters in position by a remote switch. To obtain data at additional positions it was necessary to remove the target assembly and install a new set of converters. In these changes one of the converters was always held at a fixed position to provide a means of checking that no systematic effects occurred. Three sets of converters were used during two runs of the experiment at the bevatron. The first set was of copper, \(\frac{1}{2}\) in. thick, which subtended horizontally a half-angle of \(118.5^\circ\). The vertical half-angle was \(60^\circ\) except for the converter at the largest distance which, for mechanical reasons, was made to subtend a half-angle of \(50^\circ\). The converters were spaced at intervals of \(1\frac{1}{4}\) in. from the center of the target. The second set consisted of four \(\frac{1}{4}\) in. thick tantalum converters also spaced at \(1\frac{1}{2}\) in. intervals from the target. In this case the horizontal and vertical half-angles were \(11\frac{1}{2}^\circ\) and \(50^\circ\). The third set of converters was similar to the second set except that they were located at \(1\frac{1}{4}, 1\frac{7}{8}, 3\frac{1}{8},\) and \(4\frac{3}{8}\) inches from the target. Note that the first converters in the second and third sets are identical.

The \(K\)-mesons were selected by momentum analysis, velocity selection, and range. Fig. 2 shows a plan view of the experimental arrangement within the magnet ring at the bevatron. The \(K\) beams from the target assembly are first
momentum-analysed (~540 MeV/c) in a 18 in. x 36 in. H magnet. They are then focussed at a point approximately 20 ft. from the target by two 6 in. aperture quadrupoles. Additional momentum analysis is provided by a 12 x 24 in. C magnet placed after the focussing magnets for beam cleaning purposes. It is necessary for the detector to cover the image of the largest converter. For this reason the vertical and horizontal magnifications were chosen to be 0.4 and 1 respectively. In addition to the shielding shown in the plan view, the detector was enclosed on all sides by iron loaded concrete.

Fig. 3 shows the counter arrangement used to detect the K-mesons. Velocity selection was done using both Čerenkov and dE/dx counters. Čerenkov counters C₁ and C₂ are each sensitive to particles with velocities between the Čerenkov threshold and the velocity at which the radiation is totally internally reflected (0.62 < β < 0.78 for the carbon disulphide radiation) (12). Čerenkov counter C₃ (threshold β = 0.75) is operated in anticoincidence to reject those π-mesons which may have been detected in C₁ and C₂. Following the Čerenkov counters, four scintillation counters, denoted by S₁, S₂, S₃ and S₄, imposed a range requirement on the K-mesons in the beam. Counters S₁, S₂, and S₃ were operated in coincidence and S₄, run in anticoincidence, set the maximum range accepted. Counters S₂ and S₃ served as dE/dx counters. The output of S₂ and S₃ was fed to a fast integral discriminator which was set to eliminate about 10% of the minimum ionizing π-mesons. The K-meson stopping in absorber B was signaled by a C₁C₂C₃ S₁S₂S₃S₄ coincidence (prime denotes anticoincidence). Absorber B in the case of run I was 1 in. thick, in run II, ½ in. thick. The thickness of copper absorber A could be varied remotely. That the overall detection system was effective is seen from the differential range curves for

Fig. 4. – Differential range curves of K⁺ and K⁻ mesons.

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both K− and K+-mesons originating in the target, shown in Fig. 4. The small background seen in the K− range curve is due largely to beam particles. This background decreased proportionately when the shadow bar was inserted to attenuate the beam directly from the target. The ratio of the number of K− to K+ mesons coming directly from the target was approximately 0.01. The shadow bar attenuated the K+ beam by a factor of ~10. Taking the number of K0's equal to the number of K+ 's at the target the background level of K− mesons was ~10−3 of the number of K0's at the target. The π-meson rate was given by a S1, S2, S3 coincidence with the S1 and S2 discriminators set to a low value. The π−/K− ratio was approximately 104 at the detector.

It was important to minimize the number of protons which traversed the target, recirculated around the bevatron, and struck the converter structure. To this end a large target was placed 180° around the machine at a smaller radius to absorb the recirculating protons. During the long period in which the protons were allowed to strike the target, there was a substantial energy variation in the proton beam. For this reason data were recorded in three tandem time channels corresponding to mean energies of 5.0, 5.4, and 5.7 GeV. The final data showed no difference within statistics at the various incident proton energies. They were therefore combined.

The circulating beam striking the target was monitored by two separate counter telescopes which viewed the target directly from outside the magnet ring. The π and K rates were normalized to the monitor rate.

3. – Data.

The number of K+, K−, and (for checking purposes) π± was recorded in a large number of relatively short runs for the various converter positions. The sum of all the data is shown in Fig. 5. The ratio of K− to K+ is used not only to aid in removing systematic effects but also because any charge exchange of the K0 component is thereby included. As is seen from eq. (1) the mass difference effects have an opposite phase in the K0 and K0 components. Taking

Fig. 5. – Experimental results. The curve through the K−/K+ points is the best fit as determined from a least-squares analysis. The π−/π± points are fitted visually.
the ratio therefore emphasizes any mass difference effect that may be occurring.

The most striking evidence for the occurrence of the charge exchange process comes when the shadow bar is inserted into the beam. The $K^-/K^+$ ratio increases by about 30% when the shadow bar is in place. One would expect the ratio to decrease due to the greater absorption of the $K^-$ mesons unless conversion was actually taking place in the material placed in the beam.

A possible explanation lies in the production of $K^-$'s by $\Lambda$'s and $\Sigma$'s originating in the target. This, however, requires the production of $\Lambda^0$'s with a momentum of 1.5 GeV/c at 90°, a highly unlikely event. Furthermore, the data point closest to the target is good evidence against this possibility.

For comparison, the $\pi^-/\pi^+$ ratio is shown as a function of converter distance. The essential flatness of this curve indicates that no gross systematic effect was taking place.

Included in Fig. 5 are data (displaced data) obtained by moving the first set of converters 5 in. closer to the target. This changed the solid angle subtended by the various converters and for that reason the data from these displaced converters are treated on a different basis.

Two corrections have been made before computing the ratio. The first one is for multiple scattering around the shadow bar. The correction is negligible in the copper converter data except for that converter closest to the shadow bar. The corrections in the case of the tantalum converters closest to the shadow bar are quite substantial. However, the ratio $K^-/K^+$ is quite insensitive to this correction—a correction made with fair accuracy. The velocity difference between the $\pi$ and $K$ mesons leads to a difference in the multiple scattering which makes it easy to pinpoint and check the magnitude of this effect. The second correction is made only to the data from the displaced copper converter nearest the target. This correction, which raised the plotted point about one-half the length of the error bar, comes from the beam which goes through the target, recirculates around the bevatron and strikes the converter. A radial profile of this recirculating beam was obtained by leaving the converters in place and moving the target about 10 ft. downstream in the same straight section of the machine. The number of $K$'s was then recorded as a function of the converter as in the normal course of the experiment. The number of recirculating protons falls off very rapidly as one goes to radii smaller than the target radius and it was necessary to correct only the data from the converter closest to the target.

To interpret the structure seen in Fig. 5 in terms of a mass difference it is necessary to know the velocity of the pertinent $K^0$'s. The velocity spectrum of $K^0$ mesons which give rise to the charged mesons detected depends on the details of the charge exchange process in the copper and tantalum converters. Since little is known of these details we have estimated the average velocity
(and its rms deviation) from the following considerations. The detector selects charged K-mesons of approximately 540 MeV/c. The neutral K-mesons which cast, by charge exchange, K⁺'s into this momentum channel must possess momenta between approximately 540 MeV/c and the maximum momentum of the production spectrum. Assuming the charge exchange cross-section to be independent of energy lost in the process the number of K⁰-mesons effective in the experiment is given by the production spectrum above approximately 540 MeV/c. In the design of the experiment a production spectrum given by phase space was used. As a check the number of K⁺-mesons at 540, 635, and 730 MeV/c was measured. The measurements at 635 and 730 MeV/c were made by raising the magnet currents appropriately and degrading the energy of the K-mesons with carbon and aluminum absorbers before they entered the velocity and range-sensitive detector. The results have therefore been corrected for absorption and multiple scattering in the degrader and for the fact that a given momentum interval corresponds to a larger range interval.

Fig. 6. - Production spectrum measurements compared with the results of various phase space calculations. The relative number is proportional to the differential cross section for the production of K⁺ at 90° in the laboratory. The solid line refers to the reaction p + n → Λ⁰ + K⁺ + n for a proton energy of 5.8 GeV. The broken line refers to the reaction p + n → Σ⁰ + K⁺ + n for a proton energy of 4.8 GeV. A Gaussian distributed Fermi momentum with a mean energy of 19.3 MeV was used along with a matrix element |H| which expresses various angular and momentum dependences, viz. (a) |H|² = 1, (b) |H|² = cos² θ, (c) |H|² = γ² - 1, and (d) |H|² = cos² γ(γ² - 1). The angle θ and relativistic factor γ are c.m. values for the K meson. The measurements were made at a mean energy of 5.3 GeV and at an angle of 84°.
at higher momentum. Confidence in the correction was established by checking with \( \pi \)-mesons which have a somewhat higher absorption cross-section and show nearly the same multiple scattering at these momenta. The results are shown in Fig. 6 along with the results of the phase space calculations for a variety of matrix elements (*) (13).

It is observed that the measured K\(^+\) flux extends to a higher momentum than the phase space calculations suggest. Presumably, the extra contribution is due to secondary scattering processes in the producing nucleus. Using the measured spectrum we obtain for the average momentum over 540 MeV/c, \( p/M = \gamma \beta = 1.30 \pm 0.20 \). We consider this to give an upper limit to the velocity spread.

A separate estimate of the velocity spectrum was made by assuming the charge exchange process to be completely elastic involving individual nucleons in the nucleus with 20 MeV Fermi energy. Isotropic charge exchange over the angular interval subtended by the converter gives \( \gamma \beta = 1.18 \pm 0.08 \). In the analysis of the data the latter mean momentum was used since that model is probably closer to reality but with a more generous error as indicated by the first estimate, \( \text{viz.} \): 1.18 \pm 0.15.

4. – Results and conclusions.

The K\(^+\) rate, after multiple scattering correction, proved to be nearly constant. For this reason we have fitted the K\(^-\)/K\(^+\) data to the function,

\[
\frac{a + b}{2 \Delta x} \int_{x-\Delta x}^{x+\Delta x} (\exp[-x] - 2 \exp[-x/2] \cos \mu x) dx \simeq
\]

\[
\simeq a + b \left( \exp[-x] - 2 \frac{\sin \mu \Delta x}{\mu \Delta x} \exp[-x/2] \cos \mu x \right),
\]

where \( x \) is the distance between the converters and the target measured in units of the mean decay length of K\(^0\) meson in the laboratory, \( \mu \) the mass difference in units of \( \hbar/c^2 \), \( \Delta x \) the uncertainty in the distance due to the

(*) A number of experiments have relied on the phase space calculations in the interpretation of the data, e.g. PANOSKY et al.: Phys. Rev., 109, 1353 (1958), and BARDON et al. (10). To our knowledge this is the first time these have been even roughly checked in this energy region. Applied to the results of BARDON et al., on the lifetime of the K\(^0\), it suggests that their value should be reduced somewhat because of the higher average velocity of the K mesons than is given by phase space.

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finite thickness of the target and converters and the velocity spread of the K particles, \( a \) and \( b \) two constants to take into account the unknown background and magnitude of the effect. A least squares fit was performed separately for run I and II. There was essentially no difference in the results. Therefore, the data from the two runs were combined. Fig. 7 shows the \( \chi^2 \) probability of the fit as a function of the mass difference. The best fits are for \( \mu = 1.9 \) as well as for discrete values between 10 and \( \infty \). The displaced data points of Fig. 5 run I were not used since they were taken under somewhat different conditions, as discussed before. The point closest to the target however, constitutes a strong argument against a high mass-difference, \( i.e., \mu \geq 30 \). Isolated values of \( \mu \) between 10 and 30 where the wavelength of the interference effect is a multiple of the spacing between the data points are acceptable. The best fit in the interval \( 0 < \mu < 10 \) is for \( \mu = 1.9 \pm 0.3 \) where most of the error arises from the uncertainty in the velocity.

These results are to be compared with those of Camerini et al. \((14)\) \( \mu = 1.5^{+0.2}_{-0.2} \) and with those of Muller et al. \((4)\) using the method suggested by Good, \( \mu = 0.85^{+0.4}_{-0.25} \).

At this mass difference, \( \mu = 1.9 \), the least squares analysis yields \( b/a = 0.11 \pm .03 \). Using this result one can estimate the cross-section for the charge exchange process, \( K^0 + n \rightarrow K^- + p \) in the converter nuclei, assuming isotropy in the c.m. system and an equal number of \( K^0 \) and \( K^+ \) mesons at production. This yields a cross-section per nucleus of \( 0.05 \times \sigma_{\text{geometric}} \).

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RIASSUNTO (*)

Si sono studiate le differenze di massa $\Delta M$ fra i mesoni $K_1^0$ e $K_2^0$, producendo mesoni $K^0$ ed osservando la componente $K^0$ della miscela $K^0-K^0$ in funzione del tempo. Si campionarono i $K^0$ servendosi del processo di scambio di carica e individuando i mesoni $K^-$ risultanti. Il miglior valore della differenza di massa è $\Delta M = (1.9 \pm 0.3) \frac{h}{\tau_1 c^2}$ in cui $\tau_1$ è la vita media del $K^0$. Tuttavia, alcune opportune elevate differenze di massa ($\Delta M > 10$) concordano con i dati.

(*) Traduzione a cura della Redazione.