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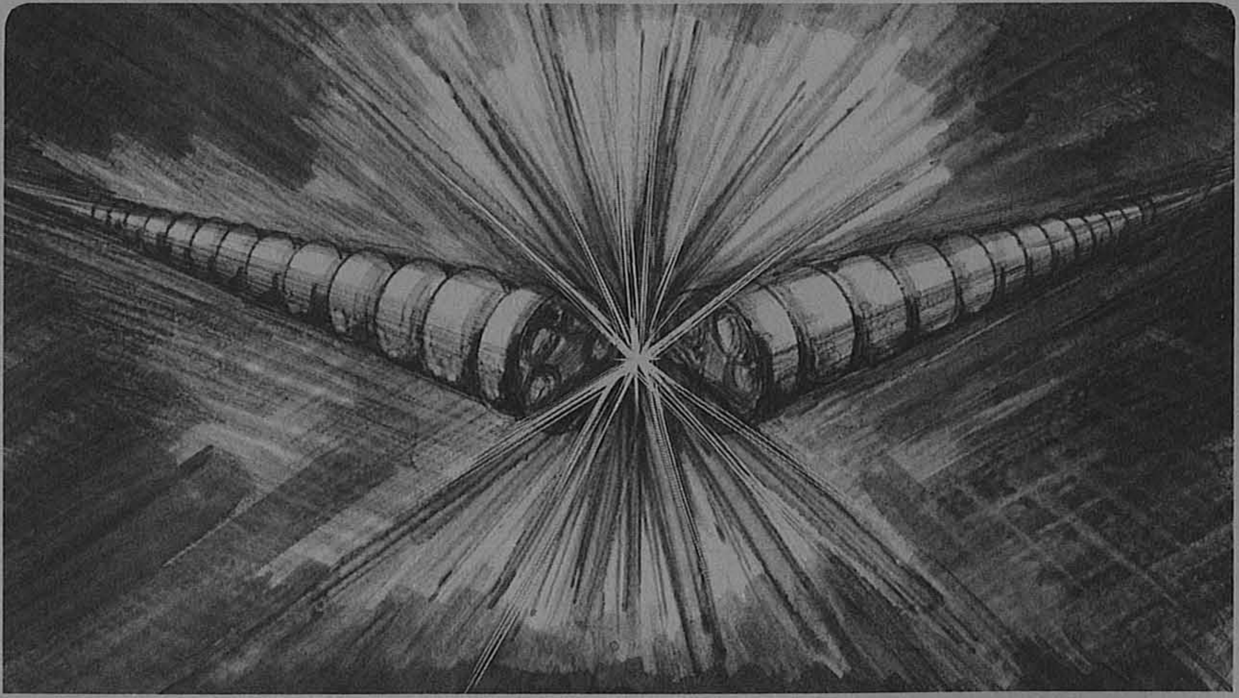

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ASYMMETRIC PHI FACTORIES—A PROPOSED EXPERIMENT AND ITS TECHNICAL FEASIBILITY*

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ABSTRACT

We discuss an experiment and the technical feasibility of the required asymmetric ϕ–factory to test nonlocal quantum mechanics in kaon systems.

1. INTRODUCTION

An asymmetric ϕ-factory has the advantage over a symmetric one that the short-lived neutral kaons that are produced when the ϕ-mesons decay, travel farther. Targets can be located on their path to study their interactions. At symmetric factories, with e^+- and e^--beams of 510 MeV, the K^0 momentum is 110 MeV/c and the average K_S range is 6 mm. For asymmetric factories, we consider the cases of 2, 3, or 9 GeV positrons colliding with 130, 90, or 30 MeV electrons, respectively. Then the average kaon momentum is 0.94, 1.46, or 4.5 GeV/c and the K_S range is 5.4, 8.1, or 24 cm, which is more practical experimentally. The advantage of the asymmetry is similar for ϕ- and for B-factories. Feasibility studies and proposals to construct such accelerators exist ([1, 2]). In the following we first describe in detail a particular experiment designed to test nonlocal quantum mechanics, followed by a discussion of the required collider.

2. THE EXPERIMENT

To give an example of the kind of experiment that can be done at an asymmetric factory, let us mention a test of the non-local effects of quantum theory in kaon physics [3]. The test is based on a study of the regeneration ($K_s \rightarrow K_L$) of these kaons produced by ϕ-decay.

Four different setups are used in the experiment. They are described in Fig. 1. ϕ-mesons are produced at the e^+e^--collision point and decay immediately. We are interested in those ϕ's that decay into two neutral kaons. The experiment consists of measuring the rate of events where two long-lived neutral kaons (K_L) are detected in these four different setups, which differ by the number and the location of regenerators interposed on the kaon paths.

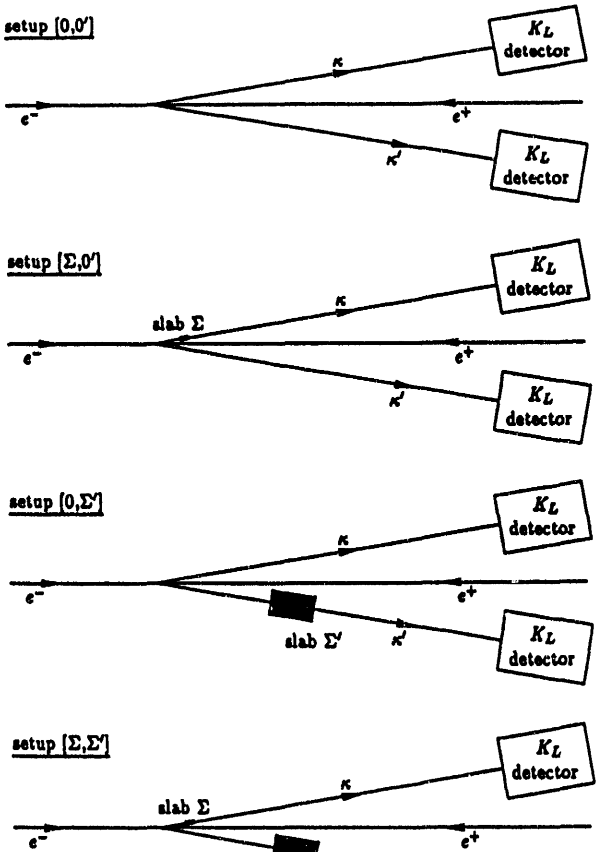

Figure 1. The four experimental setups

Two K_L-detectors, D and D′, are set up downstream, in "conjugate" directions, i.e. such that if a kaon κ is emitted toward D, the other, κ', is emitted in the direction of D'. D and D' are disposed far from the rest of the setup, practically out of reach of the K_S produced anywhere else in the experiment. For an e^+-energy of (2, 3, 9 GeV), the distances between K_L-detectors and collision point is (0.9, 1.35, 4.2 m). Therefore the detection efficiency for the K_L

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is about 97%, but the probability to detect a K_S only ~10^{-7}. The regenerators in each setup are disposed as shown in Fig. 1, i.e. for e^+ energies of (2, 3, 9 GeV):

[0,0′]: no material between the e^+e^--collision point and the neutral kaon detectors; [Σ,0′]: a slab, Σ, interposed on the path of particle κ, near the collision point; material (copper, copper, graphite); thickness (4, 4, 10 mm); no material on κ′; [0,Σ′]: a (5, 5, 15 cm) slab, Σ′, made of (copper, copper, graphite), on the path of κ′, occupying a space between (25, 37, 125 cm) and (30, 42, 140 cm) downstream from the collision point; nothing on the path of κ; [Σ,Σ′]: both slabs in place together.

The four possible two-particle states κκ′ are $K_LK'_L$, $K_LK'_S$ $K_SK'_L$, or $K_SK'_S$. Quantum theory, e^+e^--coupling, and charge conjugation invariance predict that, in setup [0,0′], all events are of the type $K_LK'_S$ or $K_SK'_L$. However, in setup [Σ,0′], or [0,Σ′], $K_LK'_L$ events are expected to be present, because some kaons are regenerated from the K_S-state to the K_L-state in the slabs Σ or Σ′. The number of $K_LK'_L$ in setup [Σ,0′] is predicted to be exactly equal to the number of kaons κ born K_S and regenerated into the K_L-state in slab Σ. Similarly, in setup [0,Σ′], the number of $K_LK'_L$ events is equal to the number of K_S regenerated into K_L in slab Σ′. For an e^+-energy of (2, 3, 9 GeV) and an integrated luminosity of ($1.5\text{x}10^{38}$, $4\text{x}10^{38}$, $6\text{x}10^{38}$ cm^{-2}) in each experimental setup, the numbers of $K_LK'_L$ events are predicted to be [4]

$$n_{\Sigma 0'} = (1840, 1750, 1600)\ \text{in setup}[\Sigma, 0'] \qquad (1)$$

$$n_{0\Sigma'} = (1100, 1290, 910)\ \text{in setup}[0, \Sigma'] \qquad (2)$$

In setup [Σ,Σ′], the two regeneration-processes are at work. Suppose the regeneration processes in slab Σ and Σ′ are local processes. Since only $K_LK'_S$ and $K_SK'_L$ events are seen in setup [0,0′] without regenerators, a $K_LK'_L$ event in setup [Σ,Σ′] must involve either a kaon κ regenerated from the K_S-state into the K_L-state in slab Σ, as in setup [Σ,0′], and the associated kaon κ′ surviving as a K_L after traversing the slab Σ′; or, similarly, a κ′ regenerated by Σ′ and κ surviving its traversal of Σ. Because of K_L absorption in the material, one may expect fewer $K_LK'_L$ events in setup [Σ,Σ′] than the sum of the number of K_S regenerated in Σ (i.e. the number of $K_LK'_L$ events in setup [Σ,0′]) plus the number of K_S regenerated in Σ′ (i.e. the number of $K_LK'_L$ events in setup [0,Σ′]). However theory predicts more $K_LK'_L$ events than that sum [4],

$$n_{\Sigma\Sigma'} = (3750, 3820, 3330)\,. \qquad (3)$$

There is a surplus

$$\Delta n = n_{\Sigma\Sigma'} - n_{\Sigma 0'} - n_{0\Sigma'} = (810, 780, 820) \qquad (4)$$

of $K_LK'_L$ events. This is because, in addition to the regeneration in slabs Σ and Σ′, there is an interference effect between the two regeneration processes. This surplus exists only if both regenerators are in place. A possible picture of that phenomenon is one where the regeneration process in one regenerator is enhanced by the presence of the other regenerator. However, there is no known particle or wave to carry any influence from any point on the path of κ to any point on the path of κ′; or vice versa. For that reason, the effect is called a non-local effect. It is a very basic effect having its roots in the foundation of quantum mechanics. A more elaborate analysis of this question is made in Ref. [4], where also the relation to the EPR paradox and Bell's inequalities is further discussed.

3. THE COLLIDER

The integrated luminosities obtained above assumes a cross-section of 4 μb for $e^+e^- \rightarrow \phi$ and a branching ratio of 34% for ϕ decay into two neutral kaons. Demanding that all the events for the four setups be collected in four operating years ($4\text{x}10^7$ seconds) of the collider, we require an average luminosity of $1.5\text{x}10^{31}\text{cm}^{-2}\text{s}^{-1}$ for a 2 GeV (e^+) x 130 MeV (e^-) collider, increasing to $6\text{x}10^{31}\text{cm}^{-2}\text{s}^{-1}$ for a 9 GeV (e^+) x 30 MeV (e^-) collider, due to rapid fall of the kaon regeneration cross-section. If we envision colliding low energy (30 MeV–130 MeV) electrons from a relatively small linac against a high energy (9 GeV–2 GeV) positron beam from a storage ring, attaining such luminosities is made quite feasible by today's technology of superconducting radio-frequency (SCRF) CW linacs. Since production, accumulation and acceleration of intense low energy positron beams is cumbersome and relatively more difficult, a low energy beam of electrons is the configuration of choice, being simple and straightforward in its implementation.

The luminosity for such collisions, assuming Gaussian beams colliding head-on and completely overlapping, is given by:

$$L = f\frac{N_+N_-}{4\pi\sigma_x\sigma_y}H \qquad (5)$$

where f is the collision frequency, N_+ and N_- are the numbers of positrons and electrons per colliding bunches respectively, σ_x and σ_y the rms transverse beam sizes at the collision point and H the luminosity enhancement factor due to beam-beam focusing. We assume, conservatively, that H is close to unity, although strong beam-beam pinch is expected to lead to enhanced luminosity. We will comment later, however, on the complex beam dynamics at the collision point due to beam-beam pinching.

In Table I, we summarize the collider parameters for a 130, 90 and 30 MeV CW electron beam colliding against a 2, 3 and 9 GeV positron beam, respectively, producing the required luminosities. The 3 GeV positron scenario (column B in Table I) is the most straightforward, the positrons being obtained from the low energy ring of a 9 GeV (e^-) x 3.1 GeV (e^+) asymmetric collider for a B-factory [2], say. If injection strategies and ion accumulation in storing electrons in the low energy ring do not pose problems, one can also envision colliding 9 GeV positrons from the high energy ring of the B-factory colliding against 30 MeV electrons from a short linac (column C in Table I). Alternatively, one could consider the 8 GeV hard x-ray rings being constructed worldwide. The 2 GeV (e^+) x 130 MeV (e^-) scenario (column A in Table I) is predicated upon availability of a third generation low emittance, high brightness positron synchrotron radiation (SR) ring. To date, however, most of the SR rings, with the exception of Super ACO (which has much lower energy of 800 MeV), are based on electrons, although some have positron upgrade capability. In our estimates, we have used the positron beam parameters from existing designs of B-factories [2] and synchrotron radiation rings [5].

Table I

	A	A′	B	C	C′
Positrons from	Standard SR ring	SR ring with Low-β and modified bunch train	Asymmetric B-factory LER	Asymmetric B-Factory HER	Asymmetric B-Factory HER with Low-β
Positron Energy (E^+)	2 (GeV)	2 (GeV)	3 (GeV)	9 (GeV)	9 (GeV)
Required Electron Energy (E^-)	130 (MeV)	130 (MeV)	90 (MeV)	30 (MeV)	30 (MeV)
Required Luminosity	1.5×10^{31} ($cm^{-2}s^{-1}$)	1.5×10^{31} ($cm^{-2}s^{-1}$)	4×10^{31} ($cm^{-2}s^{-1}$)	6×10^{31} ($cm^{-2}s^{-1}$)	6×10^{31} ($cm^{-2}s^{-1}$)
Collision Spot size ($\sigma_y\times\sigma_x$)	30×200 (μm^2)	30×40 (μm^2)	7×185 (μm^2)	7×185 (μm^2)	7×41 (μm^2)
Collision Frequency	500 (MHz)	100 (MHz)	250 (MHz)	250 (MHz)	250 (MHz)
Positrons/ bunch (N_+)	6×10^{9}	3×10^{10}	6×10^{10}	4×10^{10}	4×10^{10}
Required no. of Electrons/ bunch (N_-)	3.6×10^{9}	7.2×10^{8}	4×10^{8}	9×10^{8}	2.5×10^{8}
Electron Current from Linac	288 (mA)	11.5 (mA)	16 (mA)	36 (mA)	9 (mA)
P_{linac} (MW)	37.4	1.5	1.4	1.1	.275
No. of linac cavities	16	16	12	4	4
P_{cavity} (kW)	2300	< 100	117	275	70
Linac Feasibility	No	Yes	Yes	No (?)	Yes

One clearly sees from Table I that while scenario B is quite feasible, scenarios A and C are not, mainly due to the large amount of rf power required for the electron linac. This latter is given by:

$$P_{linac} = 1.6\times10^{-19} N_- f E_- (1/\eta) \qquad (6)$$

where the rf power efficiency η of a superconducting linac is close to unity. Reducing the power would require reducing the intensity and collision frequency of the linac bunches. Note that for linac-on-ring configuration, the combination $(N_+ f)$ in Eq. (5) can be written as $(N_+ N_b) f_0$ where N_b is the number of bunches in the ring and f_0 is the revolution frequency in the ring. For the same circulating positron current in the ring and same intensity N_- per electron bunch, one can reduce the collision frequency by storing more positrons per bunch, keeping $N_+ N_b$, N_- and hence luminosity constant. Moreover, a special low-β insert in the ring will allow tighter collision spots, thus reducing the requirement on electron bunch intensities. In column C′, we have used a low-β in the horizontal plane to reduce the spot area by a factor of four in the 9 GeV e^+ ring. Since bunch intensities are quite high, there is no room for decreasing the bunch collision frequency any further. In column A′, we have reduced the collision frequency by a factor of five by storing five times as much charge per bunch and further employing a low-β insert to reduce the spot area by a factor of 5. Clearly, SR rings being low emittance devices, the necessary beta values required to squeeze the beam horizontally by this amount is achievable. The modification of multi-bunch instabilities due to this altered bunch train pattern is not expected to be significant, although beam lifetime is an important issue. The modified columns A′ and C′ lead to very feasible linac parameters. The linacs required in columns A′, B and C′ are entirely feasible with state-of-the-art SCRF technology and are routinely envisioned for use in high power Free Electron Laser applications [6]. The 500 MHz niobium cavities, as used for CERN, DESY and other colliders, can achieve accelerating gradients of 5 MV/m and have input power capabilities in excess of 100 kW per cavity. They would be perfectly adequate. The damping of higher order modes already achieved in these cavities predict a threshold electron current in excess of 100 mA in the linac against any beam break-up instability [6].

The tune-shift ΔQ induced in the positron beam by the electron beam is given by [7]:

$$\Delta Q = \left(2\cdot 3\times10^{-9}\right)\frac{N_-\beta_y[cm]}{E^-[GeV]\sigma_y\left(\sigma_x+\sigma_y\right)\left[\mu m^2\right]} \qquad (7)$$

and is too small ($\lesssim$ .001) to affect the positron beams significantly. The disruption of the electron beam by the positron beam is, however, severe and the transverse motion of the electrons in the potential well of the positrons could be quite complicated. This needs further detailed study.

4. CONCLUSION

One can carefully configure these colliders in such a way that the linac beam can collide parasitically with the high energy beam at a separate specially designed Interaction Point, without disrupting the primary beam being used for other purposes. Such transparent use of these high intensity electron/positron rings as highly asymmetric ϕ^0-factories offer a rather attractive and potentially cost-effective program of fundamental research. With many synchrotron radiation rings and meson factories either being contemplated or being built worldwide, we have merely pointed out their potential in this very specific use.

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