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A REVIEW OF KAON FACTORY PROPOSALS

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1. What is a Kaon Factory

Several laboratories are studying the possibilities for kaon factories. Ideas include increasing the energy of an existing high intensity machine (Los Alamos, TRIUMF, and SIN), increasing the intensity of an existing high energy machine (KEK and Brookhaven), and building an entirely new machine (Munich and Kyoto). All agree that what is desired and possible is a machine that produces on the order of 100 times the annual yield of the Brookhaven Alternating Gradient Synchrotron. In Table 1 we show the estimated annual production for several particles for proposed kaon factories compared to the Brookhaven AGS in 1984.

Table 1

Estimated Annual Yield (Brookhaven AGS 1984 = 1)

	Kaons (7 GeV/c)	Antiprotons (7 GeV/c)	Muon Neutrinos
LAMPF II	193	302	112
TRIUMF II	161	176	100
SIN II	81	88	50

1.1 Nuclear Physics Issues For a Kaon Factory

Nuclear physics is based on a shell model with constituents of protons and neutrons. There are a number of problems that persist despite the best efforts of theorists and the best available data. The Coulomb energy difference between states differing by one in the z component of isotopic spin, namely,

$$[M(A; \alpha, T, T_z) - M(A; \alpha, T, T_z - 1)]_{\text{exp}} \quad (1)$$

is larger than calculated even using phenomenological wave functions and charge distributions measured in electron scattering.¹ This 10% discrepancy, which represents many standard deviations, persists over the whole periodic table. The longitudinal response function for nucleon knockout is measured to be only 0.6 of the theoretical value over a wide range of nuclei.² These and other problems indicate that the assumptions of the model may be in error and that a new basis may be required.

The analysis of the EMC effect data at CERN³ indicates that nucleons change size in nuclear matter. These results have been confirmed with deep inelastic scattering measurements on nuclei at SLAC.⁴ Most nuclear physicists agree that we should be developing a model of nuclei based on QCD with quarks and gluons as the basic constituents, which would naturally explain these observations. Further experiments with lepton probes cannot be the only answer for the development of such a model since leptons interact only with quarks and not with gluons. Hadronic probes are necessary to see gluons. The development of a good model will be very difficult since QCD is simple only in the high momentum limit, not in the low momentum region where nuclei exist.

Three areas of new experimentation are suggested that will be particularly valuable to aid in the development of a new model. These are: 1) experiments with nuclei in which one or more quarks have been replaced by strange quarks (hypernuclei or kaon

scattering); 2) the study of Drell-Yan processes in nuclei with a variety of hadronic probes including $p^\pm$, $\pi^\pm$, and $K^\pm$; and 3) experiments on large energy deposition in nuclei by high energy antiproton annihilation, which may achieve the necessary energy density at normal baryon density to form a quark-gluon plasma. In addition, nuclear physicists will need to perform experiments on the spectroscopy of hadrons at low energy, which is the natural testing ground for QCD based models of hadronic matter.

1.2 Particle Physics Issues for a Kaon Factory

The principal advantage of a Kaon Factory for particle physics is that the high intensity beam makes possible the study of extremely small cross sections and the study of extremely rare decays. The "standard model" explains the known interactions. With a Kaon Factory we can search for new physics not now contained in the standard model. We shall discuss a few of the possibilities for physics beyond the standard model which might be discovered at a Kaon Factory.

At present, no transitions are known among the three families of leptons. The class of rare decays that can be used to search for such transitions includes the following:

$$\begin{aligned} \mu &\rightarrow e + \gamma \\ \mu &\rightarrow e + \gamma + \gamma \\ \mu &\rightarrow e + e + e \\ \tau &\rightarrow \mu + e \\ K &\rightarrow \pi + \mu + e \\ K &\rightarrow \mu + e \end{aligned}$$

If there exists a boson that can couple to the electron and muon families, that is the "horizontal gauge boson," then these decays might be observable. A lower limit on the boson mass from the $K \rightarrow \mu + e$ reaction is obtained from the relation⁵

$$M' = 17 \text{ TeV} \frac{10^{-8}}{\text{BR}(K_{L \rightarrow \mu e})^{1/4}} \frac{g'}{g_W} \quad (2)$$

At a Kaon Factory, the possibility exists to see branching ratios much smaller than 10^{-8} , so that we are searching the mass scale well above that which can be reached directly with machines like the SSC. Indeed, in the rare muon decays as shown in Fig. 1, we are at the level of almost 10^{-12} , with the prospect of 10^{-13} at a Kaon Factory (the proposed MEGA experiment at LAMPF II is the last point on the figure). The history of muon decays shows an improvement in sensitivity of 1000 each 10 years, or an increase in the mass scale searched by a factor of 6 each 10 years. A similar conclusion can be reached from Fig. 2, where the history for the decay $K \rightarrow \pi + \text{missing neutrals}$ is shown. For this reaction, there are both upper and lower bounds available from theory. A Kaon Factory is required to get sufficient intensity to see the decay.

The neutrino mass is zero in the standard model. Reasonable extensions to the model in an attempt to reach another level of unification of the theory lead to the possibility of massive neutrinos. The search for neutrino oscillations, in which one kind of massive neutrino can transform into another, can be pushed to sensitivity levels more than 100 times below those available today at Brookhaven. An accurate study of

RARE MUON DECAY EXPERIMENTAL HISTORY

Fig. 1 History of rare muon decay branching ratio limits. The three open circles are proposed results from the Los Alamos group. The 1995 point will be obtained with LAMPF II.

Fig. 2 History of branching ratio limit in $K^+ \rightarrow \pi^+ \nu_l \bar{\nu}_l$ decay.

$\nu_l \bar{\nu}_l$ scattering can also search for terms not included in the V-A interaction of the standard model.

In assessing the possible physics to come out of a Kaon Factory, we note that if only one of the rare decays is found to have a measurable rate, it will mean that new physics has been found. In this sense, such a discovery would be comparable to the discovery of charm. And even if we get only more accurate measurements and tighter limits on rare decays, the situation would be like that of constraining the

structure of the standard model by the missing decays and predicting the mass of the W and Z from the knowledge of the muon decay spectrum.

2. A Brief Review of Kaon Factory Accelerator Proposals

I will discuss in detail only the proposals from the three meson factories, SIN,⁶ TRIUMF,⁷ and LAMPF⁸ because only for these is sufficient information available.

The two cyclotron-based meson factories have the problem of matching the continuous beam of a cyclotron into a synchrotron, which is most efficiently injected with a short pulse. At TRIUMF the cyclotron will be modified to store a few hundred turns, a total of 4.3×10^5 turns will be accumulated in an accumulator ring, the energy will be raised to 3 GeV in a 50 Hz booster synchrotron, 5 booster batches will be accumulated in a collector ring, these will be accelerated to 30 GeV in a 10 Hz driver ring, and the duty factor will be increased to 100% in an extender ring. A layout of the 5 rings and experimental areas of the TRIUMF proposal is shown in Fig. 3. The TRIUMF group expects to achieve 100 microamperes at 30 GeV and 100% duty factor with this design.

Fig. 3 Proposed TRIUMF Kaon Factory layout.

The SIN proposal calls for a special second stage cyclotron with pulsed output at 1.3 GeV, ASTOR. The 2000 Hz output of ASTOR will be shared between a 1.3 GeV experimental program and a four ring collector, similar to the four ring CERN PS Booster. The collector output will be accelerated to 30 GeV in a 25 Hz synchrotron, with a stretcher added to obtain 100% duty factor. The SIN group expects to obtain 50 microamperes average current. A schematic layout of the SIN proposal is shown in Fig. 4.

The Los Alamos group proposes to make use of the existing 800 MeV R-beam from the LAMPF II linac, which is the best existing injector for a high energy synchro-

Fig. 4 Proposed SIN II Kaon factory.

tron. A two stage synchrotron is proposed, the first stage is to achieve 7.3 GeV and 144 μ A, with the second stage delivering 45 GeV and 34 μ A with 507 flattop for slow extraction. One hundred and ten (110) microamperes of beam at 7.3 GeV (13 booster batches of 17) will be delivered to the neutrino area and pulsed muon area. The use of the majority of the booster beam for neutrino and pulsed muon physics makes unnecessary the collector ring(s) which are included in the TRIUMF and

Fig. 5 Proposed LAMPE II Facility layout.

SIN proposals. The LAMPE II proposal, whose layout is shown in Fig. 5, is the simplest of the three accelerators, and is the only one that proposes re-utilization of existing meson factory experimental areas. (Note: the LAMPE II proposal is being revised. New booster parameters are shown in Table 2. Main ring parameters are from the proposal. Figure 5 shows the old booster and main ring.)

Table 2
Comparison of Synchrotron Parameters

		LAMPE II BOOSTER	LAMPE II MAIN RING	TRIUMF II BOOSTER	TRIUMF II MAIN RING	SIN II MAIN RING
ENERGY	GeV	7.3	45	3	30	30
RADIUS	m	55.8	222.4	36.1	170.5	115.8
REPETITION RATE	Hz	60	3.53	50	10	25
CHARGE/PULSE		1.5×10^{11}	6×10^{11}	1.2×10^{11}	6×10^{11}	1.2×10^{11}
CURRENT	μ A	145	34	100	100	50
SUPERPERIODS		8	2	6	12	4
CELLS		12	12	24	48	50
Max Q_{ext}	m	11.3×11.1	59.2×66.3	15.5×14.3	18.1×17.5	18.50
Max DISPERSION	m	5.9	8.15	6.26	9.09	4.4
TRANSITION γ		16.441	6.06	9.12	-	19.11
TUNES ν_x, ν_y		$6.18 \pi / 7.26$	$7.35 \pi / 6.45$	$5.22 \pi / 6.18$	$11.22 \pi / 12.18$	$18.45 \pi / 17.25$
SPACE CHARGE Δv		-0.08	-0.05	-0.15	-0.08	-
EMITTANCES	mm mrad	20×20	5×5	119×62	17×16	6×4.6
AT INJECTION	eV m	0.06	0.12	0.064	0.192	0.1
HARMONIC		20	229	45	225	255
RADIOFREQUENCY	MHz	50.3 59.4	59.3 59.7	46.1 61.1	61.1 62.9	50.6 55.7
FREQUENCY SWING		1.18	1.005	1.33	1.03	1.10
DE/dn Max	kV	895	3850	210	2000	6200
RF VOLTS/TURN Max	kV	1440	4620	576	2400	9000
VOLTS/CAVITY Max	kV	90	100	68	44	100
POWER/CAVITY Max	kW	110	173	42	100	96
CAVITIES		16	2823	384	986	30

Two extremely different philosophies are represented by the LAMPF and TRIUMF proposals. The TRIUMF group has optimized the intensity available from a cyclotron, with minimal experimental facilities to be included in the initial proposal. The Los Alamos group simplified the machine design in order to minimize initial cost, with upgrades possible later. The LAMPF II proposal emphasizes a complete set of initial experimental facilities, which should maximize the physics output in the early years.

The parameters of the synchrotrons proposed by the three meson factory groups are shown in Table 2. The similarities of the designs are apparent. All three use essentially the same rf frequency, and all have a similar microstructure. All three proposals include the largest available longitudinal phase space in order to achieve stability. Both the TRIUMF and LAMPF proposals include blowing up the longitudinal phase space between synchrotron stages in order to increase stability. All three proposals include lattice designs that have tunes differing by one between the horizontal and vertical planes.

Some differences among the designs are also apparent. The TRIUMF design relies on extrapolation of the rf system from the Fermilab booster experience. The LAMPF II design is based on the development of perpendicular biased ferrite cavities, to be discussed later, which will deliver more voltage and power to the beam than the Fermilab design. The LAMPF II main ring operates above an intentionally low transition energy, whereas all the others operate with large or imaginary transition energy. The LAMPF II design has a harmonic number of one less than four times the booster harmonic number in order that a vernier is possible to align the incoming booster batch with the empty buckets of the main ring. This should help to minimize beam transfer problems between rings. The effect of the injection

Fig. 6 Calculated yield of K^+ per unit power on target as a function of incident proton energy.

energy is also apparent. The SIN II design with 1.3 GeV injection achieves the smallest invariant phase space, whereas the TRIUMF group will have to handle the largest phase space, which will lead to higher costs.

The choice of energy and current deserves some attention. The physics needs are for high-current beams of neutrinos, kaons, and perhaps antiprotons. The nuclear physics community is particularly interested in high energy secondary beams for Drell-Yan experiments on nuclei. These high energy beams should be at least 30 GeV, and higher energies are desirable. The LAMPF proposal was based on the observation that low energy kaon beam fluxes are essentially independent of proton energy at constant beam power once the proton energy is above a minimum value (see Fig. 6). The main ring energy was set at the highest reasonable energy and our 45 GeV choice will make LAMPF II the world's highest intensity source for secondary beams up to 30 GeV.

Fig. 7 Calculated yield for neutrino-electron scattering as a function of incident proton momentum. The smooth curve is a guide to the eye.

Neutrino experiments do not require high energy protons. Our analysis of a neutrino facility optimized for 30 GeV protons indicates that the neutrino-electron scattering rate in a fixed detector and for fixed tunnel and shield geometry depends only on beam power for protons above 6 GeV (see Fig. 7). For neutrino oscillations, the lower proton energies are advantageous, since lower neutrino energies are important. This observation allowed us to consider using the booster as a source of neutrinos and eliminated the need for a collector stage, such as the TRIUMF C ring. Of course, the TRIUMF machine is more flexible in its choice of beam fraction that can be scheduled for neutrinos. The LAMPF II solution is cheaper, and 45 GeV neutrino facilities can be added at a later date. The LAMPF II neutrino spectrum is shown in Fig. 8, in which the Brookhaven AGS neutrino spectrum is also shown. Note that the TRIUMF neutrino spectrum will have the same shape as the Brookhaven spectrum but will be 100 times more intense.

3. Secondary Beam Considerations

All of the proposals suggest that a large number of kaon beams are necessary. Unlike pion beams, kaon beams must be designed for a small range of momenta both because the length must be kept short to minimize decay losses, and because the phase space acceptance of the necessary particle separators drops rapidly with

Fig. 8 Neutrino yield from LAMPF II Booster compared with existing BNL wide-band neutrino facility.

increasing momentum. The LAMPF II proposal includes five kaon beams below 6 GeV/c. All the low-momentum kaon beams in the LAMPF II proposal include two stages of separation, with sufficient separation in each stage to clearly separate pions and kaons. Each stage has a separate mass slit, and the second mass slit is isolated from experimental apparatus by at least one additional bending magnet. It is known from experience with bubble chamber beams that purity exceeding one kaon per pion can be achieved by this technique. In Fig. 9 we show the rate of K^- expected at LAMPF II. Included in the calculations are appropriate allowances for beam sharing among the many targets, solid-angle and momentum acceptance that matches separation and momentum resolution requirements, and an estimated channel length to meet the two-stage separation requirements.

For kaons above 6 GeV/c, separation by de electric and magnetic fields becomes impractical. It appears that the only reasonable choice is rf separation. Because of the high duty factor of the proposed Kaon Factories, superconducting rf separators will be required to keep the power consumption to reasonable levels. The high energy accelerator community has had a great deal of success with superconducting cavities lately, and the new technology may be applicable to rf separators.

All the kaon beam lines can readily be adjusted to separate antiprotons from the negative backgrounds. Thus antiproton beams with purity on the order of 1:1 and yield above 10^6 antiprotons per second can be obtained over much of the energy range.

LOW ENERGY K^- BEAM RATES

Fig. 9 Yields of proposed LAMPF II kaon beams compared with existing beams at Brookhaven.

LAMPF II will also be a better source of stopped muons than is LAMPF. We estimate that fluxes will be 10-100 times larger, and the duty factor almost 10 times larger than at LAMPF. Thus a Kaon Factory is also a superb muon factory.

4. Hardware Development for a Kaon Factory

At Los Alamos, we have started two hardware development projects. The first concerns the tuneable rf system for the booster. We have discovered that the losses in a ferrite tuner can be vastly reduced if the bias field is perpendicular to the rf magnetic field, rather than parallel as in previous proton synchrotrons.⁹ A schematic perpendicular-biased cavity is shown in Fig. 10. In Fig. 11 we show the results obtained for quality factor ("Q") in a special cavity in which the bias direction could be changed externally. We see a very large improvement in Q for a frequency range similar to that required for a Kaon Factory booster. This high Q should make possible more energy efficient rf systems than have previously been used, which will be important at a Kaon Factory.

The vacuum chamber is another problem. We have scaled the results obtained with the new thin vacuum chambers for the DESY II synchrotron. Because of the higher repetition rate, larger magnetic field, and larger aperture of the LAMPF II booster, the power losses per unit length of beam pipe will be 100 times larger than at DESY II, and the sextupole distortion 10 times larger. We believe that a better solution is to break up the conductor into small strips to minimize eddy currents, and that the capacity between multiple layers can be used to make the rf impedance small and assure beam stability. A sketch of such a beam pipe is shown in Fig. 12. We are setting out to measure the longitudinal and transverse coupling impedances of this type of vacuum chamber for LAMPF II.

Fig. 10 Proposed LAMPF II Booster rf cavity with perpendicular bias field.

Fig. 11 Measured quality factor for Ni-Zn ferrite in a special test cavity with variable direction external bias field.

Fig. 12 Proposed beam pipe for LAMPF II booster.

5. Costs

The Los Alamos group is the only group that has published a Kaon Factory cost estimate. The construction cost of the LAMPF II booster and experimental area is \$149 million in 1984 dollars. The cost of the main ring and experimental areas is \$103

million. These cost estimates were arrived at jointly by the Los Alamos staff and Science Applications International Corporation, and include EDIA, project management, and contingency. The experimental area costs were nearly half of the total. No detectors were included in these estimates.

6. Prospects for Construction

We believe that the many physics possibilities justify the cost of a Kaon Factory. In the next three to five years, it is likely that a decision to build one Kaon Factory will be taken somewhere in the western world. Because of the large cost of such a facility, it is likely that only one will be built and that physicists from many nations will use it. There are a number of special situations that could influence this decision. A Kaon Factory is the right size project for Canada, but perhaps there are not enough Canadian physicists to fully utilize such a facility. The Swiss and German groups have a tradition of excellence in medium energy physics and accelerator construction, but Europe may be overcommitted to accelerator construction. The Japanese groups may have the best financial situation, but lack users and a site to construct a high intensity facility. At Los Alamos we have the best injector and an active user community, but our field is tied up trying to fund a 4 GeV electron machine. Discussions about international collaborations have already begun in Europe. These will get more realistic as one of the proposals approaches funding. Who knows today which one will be built? Certainly not I.

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