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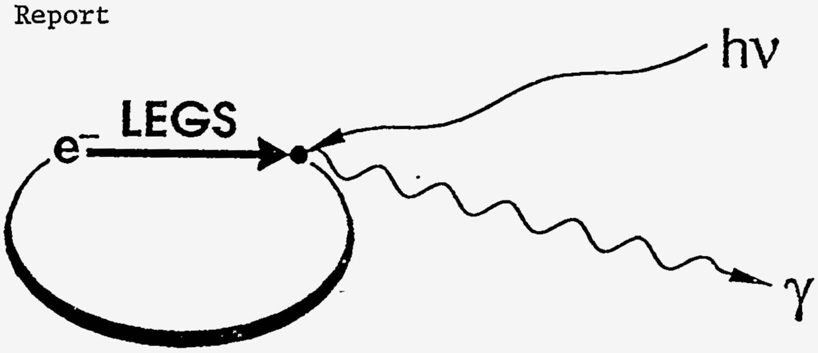

Probing the Strange Nature of the Nucleon with Phi Photoproduction

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Introduction

The presence inside the nucleon of a significant component of strange-antistrange quark pairs has been invoked to explain a number of current puzzles in the low energy realm of QCD. The σ term in πN scattering is a venerable conundrum which can be explained with a 10%-20% admixture[1]. The "spin crisis" brought on by the EMC result[2] and follow on experiments[3] was first interpreted as requiring a large strange content of s quarks whose spin helped cancel the contribution of the u and d quarks to the nucleon spin, again of order 10%. Excess phi meson production in $p\bar{p}$ annihilation at LEAR[4] has also been explained in terms of up to a 19% admixture of $s\bar{s}$ pairs. Charm production in deep-inelastic neutrino scattering[5] would appear to provide evidence for a 3% strange sea. It is clear that a definite probe of the strange quark content would be an invaluable tool in unraveling a number of mysteries. This paper will explore one such tool, originally proposed by Henley, *et al.*[6] and then refined in calculations by A. I. Titov, S. N. Yang and Y. Oh[7].

The Probe

The essential idea is to use photoproduction of the ϕ vector meson to measure the strange quark content of the nucleon. Because the quark nature of the ϕ is nearly pure $s\bar{s}$ (due to ideal mixing with the ω), processes for its creation not involving pre-existing strangeness are OZI suppressed. In fact, OZI suppression was invented to understand its interactions. The standard mechanism for vector meson photoproduction supposes that the incoming photon mixes into a virtual meson and then scatters diffractively off the nucleon and onto the mass shell by the exchange of a Pomeron. The presence of $s\bar{s}$ pairs within the nucleon allows a second contribution to ϕ photoproduction, direct knockout and transmutation of a pre-existing pair into a ϕ (see Figure 1). The calculations of Ref [7] show that, with only a 1-2% admixture, the knockout cross-section is $\approx$ 10% of the normal diffractive process near 2 GeV (see Figure 2). Extension of their calculation to higher energy shows the knockout process to be less competitive (see Figure 2). The problem is that the un-struck quark wavefunctions must be overlapped with those of the recoiling ϕ and proton which becomes increasingly difficult as the energy increases. At large momentum transfers, the core knockout mechanism

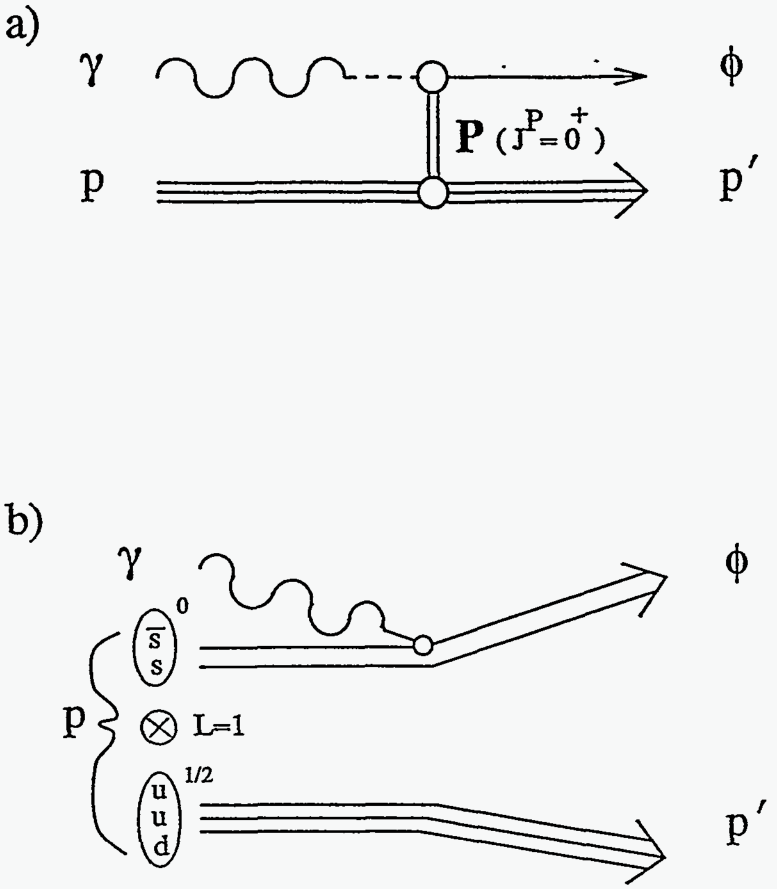

Figure 1: Feynmann graphs of the two principle mechanisms for ϕ photoproduction. a) Diffractive scattering, where the incoming γ mixes into a virtual ϕ that interacts with the nucleon via Pomeron exchange. The Pomeron is a $J^P = 0^+$ object so the ϕ has the γ polarization and the recoil proton has that of the target. b) Knockout of a ${}^1S_0$ $s\bar{s}$ pair to form the ${}^3S_1$ $s\bar{s}$ ϕ. The pair is initially coupled to a ${}^2S_{\frac{1}{2}}$ uud core. The intrinsic parity of the proton requires the coupling to be L=1. The ϕ has the γ polarization and the recoil proton has that of the core.

(leaving a spectator ϕ) is dominant but all the cross-sections are so small that this is not a practical alternative. Thus there is no practical combination of beam energy and detection angle where the knockout mechanism can cleanly be distinguished from the diffractive.

Polarization Observables

The next possibility is to consider polarization observables. Because of the strong forward peaking of the cross-section, single transverse polarization observables (which must go to zero at zero degrees) are not desireable; and, of course, single longitudinal polarization observables are zero from parity. That leads to consideration of double polarization observables.

One can further narrow the choices by noting that one prefers an asymmetry to which the diffractive mechanism does not contribute. The spin characteristics of the diffractive can have a diffractive contribution to both the parallel and the anti-parallel cases so they will cancel in the difference. This means we require either beam or vector meson coupled to either target or recoil polarizations. Given the difficulty of determining the polarization of the recoil proton, one is left with the necessity of a polarized target. Assuming a backward Compton scattered laser beam as the source of the γ, a beam-target asymmetry is the obvious choice.

The choice between a transverse or a longitudinal asymmetry can be made by requiring one in which there is an interference between the diffractive and the $s\bar{s}$ knockout amplitudes. This imposes the constraint that incoming and outgoing quantum numbers should be the same for both amplitudes. The spin structure of the $s\bar{s}$ knockout must now be deduced. An $s\bar{s}$ pair in a relative S-wave can be either a spin singlet or a spin triplet state. The outgoing ϕ is also an S-wave spin triplett. In the $s\bar{s}$ pair, the quarks have equal but opposite charges and magnetic moments so their contributions to the interactaction with the γ cancel each other in the spin symmetric triplet to triplet transition. Only the singlet can participate in the $s\bar{s}$ knockout mechanism. The $\bar{s}$ quark has negative intrinsic parity so to restore the proton's overall positive parity the pair must be coupled to the core with an L=1 orbital angular momentum. Thus we find the interesting proton configuration is a spin 0 $s\bar{s}$ pair coupled in a P-wave to a spin 1/2 *uud* core. This is illustrated in Figure 1b. For interference the spectator core, which becomes the recoil, must have the same spin as the overall proton, implying the L=1 orbital angular momentum has M=0 along the proton spin axis. But a $Y_{1,0}$ spherical harmonic is zero in the XY plane, so there is no transverse $s\bar{s}$ knockout amplitude with the same quantum numbers as the diffractive amplitude and no interference in any transverse asymmetry.

Finally we are left with only the beam-target longitudinal asymmetry to consider. In this case, we do have $s\bar{s}$ knockout amplitude. Further, the effect on the $|uud\rangle \otimes |s\bar{s}\rangle$ wavefunction of flipping the target spin is simply to reverse the m-values of the Clebsch-Gordan coefficient coupling the core and the orbital angular momentum to the proton spin; *i.e.*, $\langle \frac{1}{2}\frac{1}{2}, 10|\frac{1}{2}\frac{1}{2}\rangle$ to $\langle \frac{1}{2}-\frac{1}{2}, 10|\frac{1}{2}-\frac{1}{2}\rangle$. That causes the CG coefficient and thus the wavefunction and the amplitude to flip sign as well. Clearly, the simple diffractive amplitude will not flip sign so we have found an asymmetry with the desired sensitivity to the interference of the diffractive and $s\bar{s}$ knockout amplitudes.

Figure 3 shows the calculation of the Beam-Target longitudinal asymmetry as a function of t, for several different admixtures at 2.1 GeV and 4.0 GeV photon energy. There is a remarkable sensitivity to the $s\bar{s}$ admixture covering the full range of current theoretical speculation.

Phi Properties

Let us now turn to some of the experimental details that must be addressed in order to measure this asymmetry. The ϕ is a neutral vector meson with a mass of 1019.414 ± 0.010 MeV and width of 4.41 ± 0.05 MeV[10]. Its principle decay modes are K^+K^- $(49.5 \pm 1.0)\%$, K_LK_S $(34.4 \pm 0.9)\%$ and $\rho\pi$ $(12.9 \pm 0.7)\%$. Concentrating on the charged kaon (mass = 493.646 MeV) decay mode, we see there is only 32.122 Mev available for the decay in the rest frame of the ϕ. This means the kaons are kinematically constrained to lie within a small opening angle of the ϕ momentum and will share that momentum nearly equally.

Figure 4 show the lab angles and kinetic energies of the ϕ and recoil proton and the maximum lab angle of the kaons all as a function of the Mandelstein invariant t at 2.1 GeV. Figure 4 also gives the integrated ϕ photoproduction rate for 10^7 γ's per second on the SPHIce target (5 cm length of HD ice, see Appendix) as a function of t_{min}. One can see that most of the rate occurs between $t = -0.15$ and $t = -0.6$ GeV^2. This corresponds to ϕ lab angles between 5 and 17 degrees and proton lab angles between 25 and 35 degrees. The lab angles, lab energies and integrated yields at 4 GeV are plotted in Figure 5. Similar but more severe kinematic constraints exist at this energy as well. The proton is at more backward angles, 45 - 55 degrees and the ϕ is more forward, 3 - 11 degrees. The higher energy of the ϕ limits the kaon opening angle even further.

Given these rather tight kinematical constraints, we believe it should be possible to uniquely identify the ϕ photoproduction reaction without the need for a magnet. Monte Carlo studies are underway to verify this. The detection concept for 2.1 GeV is drawn in Figure 6. Silicon strip detectors cover the angles from 5 to 40 degrees for vertex determination of the kaons and trajectory determination of the proton. They are backed beyond 25 degrees by plastic scintillator capable of stopping protons upto 300 MeV (0.5 meters) for particle identification and energy determination of the protons. For rejection of leptons and pions, we plan on a silca aerogel Čerenkov counter. This would be followed by several planes of wire chambers to define the kaon trajectories precisely. At 4.0 GeV, the detection scheme is similar but the much higher β of the kaons will make the Čerenkov veto more difficult. Again, we are investigating the detection scheme with Monte Carlo simulations.

Summary

We have seen that a central question in the study of QCD phenomena is the $s\bar{s}$ content of the nucleon. Further, the longitudinal beam target asymmetry in ϕ photoproduction is a particularly sensitive probe of that content. Monte Carlo studies are underway to define the appropriate detector configuration for γ energies available at Spring8 and at TJNAF.

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Appendix : SPHIce –

A Strongly Polarized Hydrogen - Deuteride Ice Target

Overview

The optimal polarized target for photonuclear physics experiments on hydrogen or deuterium must provide adequate target thickness, minimal amounts of other nuclear species and maximal polarization. The first two considerations would suggest the use of solid molecular hydrogen or deuterium. Molecular physics, however, make this impossible. The ground state of the molecule places the two nuclei in a relative S state. This means that the coupling between the nuclear spin and the crystal lattice is very weak so that the polarization in an external field will build up extremely slowly. Worse, the anti-symmetrization of the identical protons in H_2 means they must have zero total nuclear spin, and thus orbital angular momentum zero H_2 (para-H_2) cannot be polarized at all.

The solution is to employ hetero-nuclear molecules such as ammonia (NH_3) or butanol (C_4H_9OH) or, best in terms of free protons by weight, hydrogen-deuteride (HD) as the target material. The first two molecules have been utilized in other targets but they sacrifice the characteristic of weak coupling of nuclear spins to the lattice and thus can never be removed from the bulky apparatus, with its high field and ultra-cold temperature, needed to produce polarization. We still have the opposite problem for HD, the coupling is weak and so it will not polarize. That this can be temporarily overcome is one of the important advantages of this target material exploited by the SPHIce target system. The SPHIce target uses a relaxation switch, fast relaxation to obtain a high degree of hydrogen polarization (80%), and then slow relaxation to freeze the polarization and allow removal from the polarization apparatus, storage for long periods, and eventual usage in a much simpler dewar. This provides unprecedented visibility of the nuclear reaction products.

Hydrogen Polarization

The symmetry restriction imposed on the total wave function of H_2 divides its molecules into two species on the basis of their nuclear spin. The equilibrium species at low temperature is the para-hydrogen state with nuclear spin I=0 and molecular orbital angular momentum L=0. With no net spin, p-H_2 cannot be polarized. The most abundant species at room temperature, the ortho state, is I=1 and L=odd. Since the state has a net nuclear spin and its L=1 molecular rotation at low temperatures provides a strong coupling to the crystal lattice, o-H_2 can be readily polarized. In contrast, the orbital and spin angular momenta of the heteronuclear molecule HD are not limited by symmetry requirements and are thus independent. At low temperatures, its L=0 configuration is poorly coupled to the lattice, making direct polarization practically impossible. However, all hydrogen nuclei share the same Larmor frequency so that a rapid spin exchange can occur between o-H_2 and HD. Thus, as suggested by Honig [1] in 1967, the relaxation (polarization) time of the H in HD can be drastically reduced by introducing small ($\sim 10^{-4}$) concentrations of o-H_2.

The choice of o-H_2 impurities as a magnetically active intermediary for the HD carries another advantage. The o-H_2 is meta-stable at low temperatures, decaying with a mean life of 6.25 days, independent of temperature and applied magnetic field, to the magnetically inert p-H_2. This provides a so-called "relaxation switch"; by simply holding the target at low temperature and high field, the relaxation time will increase as the impurity concentration declines. Under the conditions in the SPHIce polarization apparatus, 15 mK and 17 Tesla, and with an initial mole fraction doping of 0.0003 o-H_2, we can reach an equilibrium H polarization of 80% in a few days and freeze in that value after about 6 weeks of aging time.

The drawback to the use of o-H_2 is that its decay to the para species releases heat. If not removed, the heat would warm the HD and lower the equilibrium polarization. In the SPHIce target, aluminum cooling wires of 25 micron diameter at an areal density of 650/cm^2 are used to carry off this heat (these constitute 5% of the target by weight).

Deuteron Polarization

As for the H_2 molecule, symmetry constraints give the D_2 molecule two forms, the L=0 ortho with I=0,2 which is poorly coupled to the lattice and the L=1 para with I=1 which is well coupled. Thus, a similar relaxation switch procedure could be used to polarize the D component of the HD. There are two disadvantages to the technique in this case. The smaller magnetic moment of the deuteron means that, at the 15 mK and 17 Tesla available, the deuteron equilibrium polarization is only 20%. Secondly, the 18.2 day decay constant for the magnetically active p-D2 would require aging periods of months.

Rather, in the standard cycle that will be used to prepare SPHIce targets, o-H_2 doping will be used to polarize the hydrogen at high field/low temperature, but no p-D_2 will be introduced. Instead, the deuterium will be polarized by successively transfering the hydrogen polarization to the deuterons with an RF technique commonly known as 'Adiabatic Fast Passage'[2]. This method takes advantage of the dipolar coupling of H and D nuclei in different HD molecules to induce nominally forbidden RF transitions. A maximum of 66% of the polarization of the protons can be transfered to unpolarized deuterons in this manner. Presently, the efficiency for this process is about 50%, reducing the polarization transfer to 33% of the hydrogen value. The protons can be repolarized and, since the time needed to achieve maximum proton polarization is relatively short compared with the 6.25 day o-H_2 decay time, the deuteron polarization may be built up to a higher level by repeating the adiabatic fast passage and proton repolarization procedure. The sample is then held at high field and low temperature until the o-H_2 impurity has decayed and the relaxation time increased.

SPHIce will thus provide frozen-spin HD ice targets with 80% free-proton polarization and at least 50% deuteron vector polarization. (The corresponding deuteron tensor polarization is 20%.)

SPHIce Operation

At 1.5 K and 10 Tesla, the relaxation time of a fully aged SPHIce target is over 250 days for H and in excess of a year for D. This makes possible storage and transport of the target between production and usage. During the experimental running periods, the targets will be transfered, one at a time from the storage vessel to the in-beam dewar. At the 0.45 K and greater than 1 Tesla present in the in-beam dewar, the relaxation times are over 3 weeks and over 6 weeks for H and D, respectively. Although this will allow useful data taking with only a single target being produced per cycle, it is planned to prepare 3 targets simultaneously. In the in-beam position, the polarizations of the H and the D may be oriented independently. (Rotating the holding field will flip the HD pair and Rf-induced transitions can be used to separately orient the H.)

The key technical development that makes these manipulations of the target possible is the cold transfer dewar[3]. This is a LHe/LN2 dewar that one can insert into the dilution refrigerator (or other cryostat), connect to the polarized target, extract the target, place it in a second cryostat and disconnect. All this while maintaining 4 K and 300 Gauss in order to prevent polarization loss during the period of transfer. This capability is also exploited during the initial solidification of the HD from room temperature gas. This is done in a specialized variable-temperature cryostat and then the solid but unpolarized target is transferred into the dilution refrigerator for the start of the polarization cycle.

SPHIce Status

All the major steps in the polarization cycle have been carried out separately on less than full size samples. Two full size targets have been frozen and studied and a successful first trial of polarization and cold transfer with a full size target has been carried out. What remains is to deal with the minor problems in equipment design and process technique that arise in combining and performing all the necessary steps on single full size targets. All the various dewars exist and are in various stages of being brought into operation. The one exception is the in-beam cryostat which is currently under construction at Orsay and scheduled for delivery at the end of June. We anticipate that first use of a SPHIce target will occur at LEGS in mid-August, 1997.

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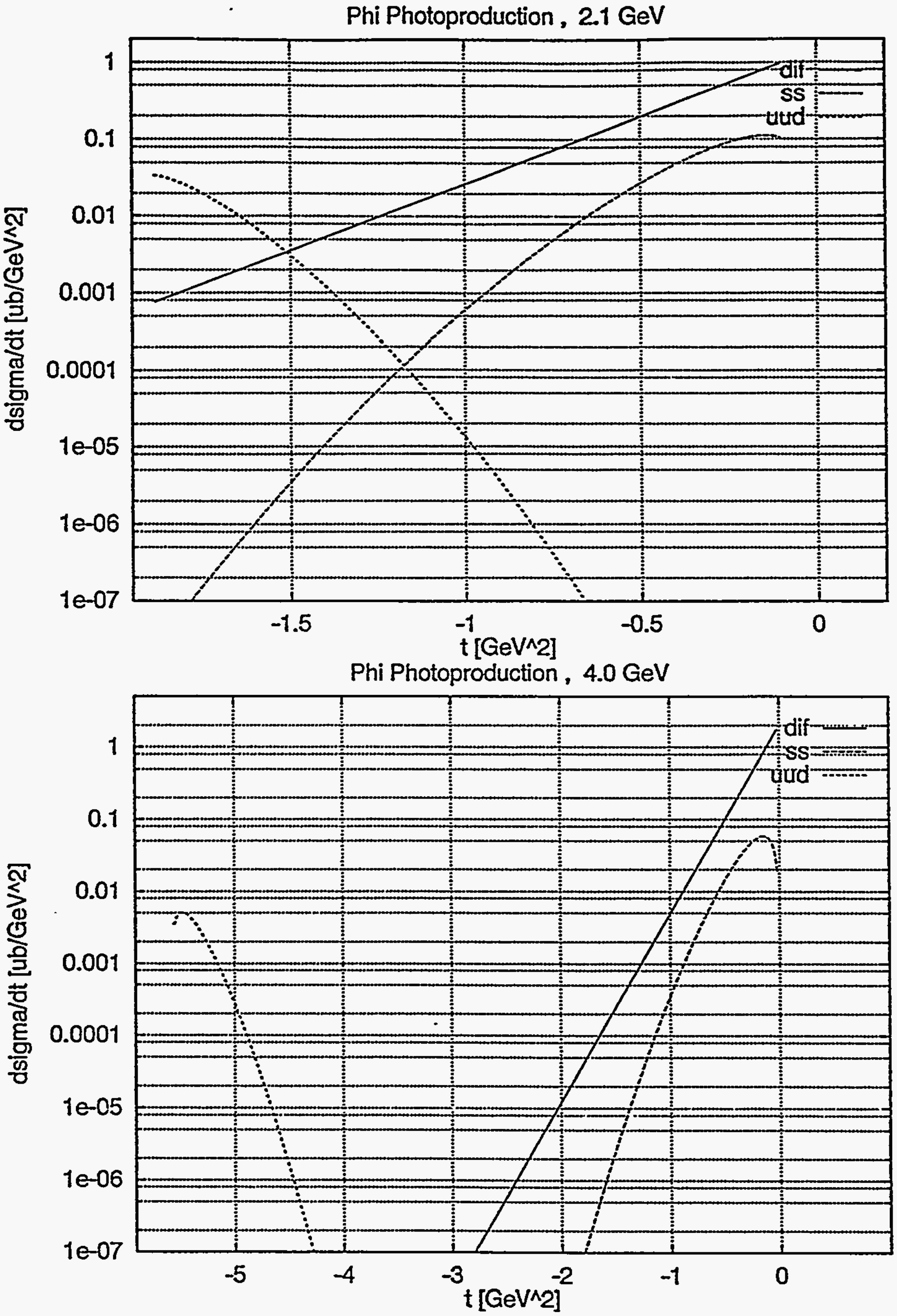

Figure 2: Cross-sections for ϕ production at 2.1 and 4.0 GeV. Contributions from 3 mechanisms are shown: diffractive, $s\bar{s}$ knockout, and uud knockout. The knockout is from the theory and calculations of Ref. [7]. The diffractive is based on the experimental cross-sections of H. J. Besch, *et al.*[8] at 2.1 GeV, and of H. -J. Behrend, *et al.*[9], at 4.0 GeV.

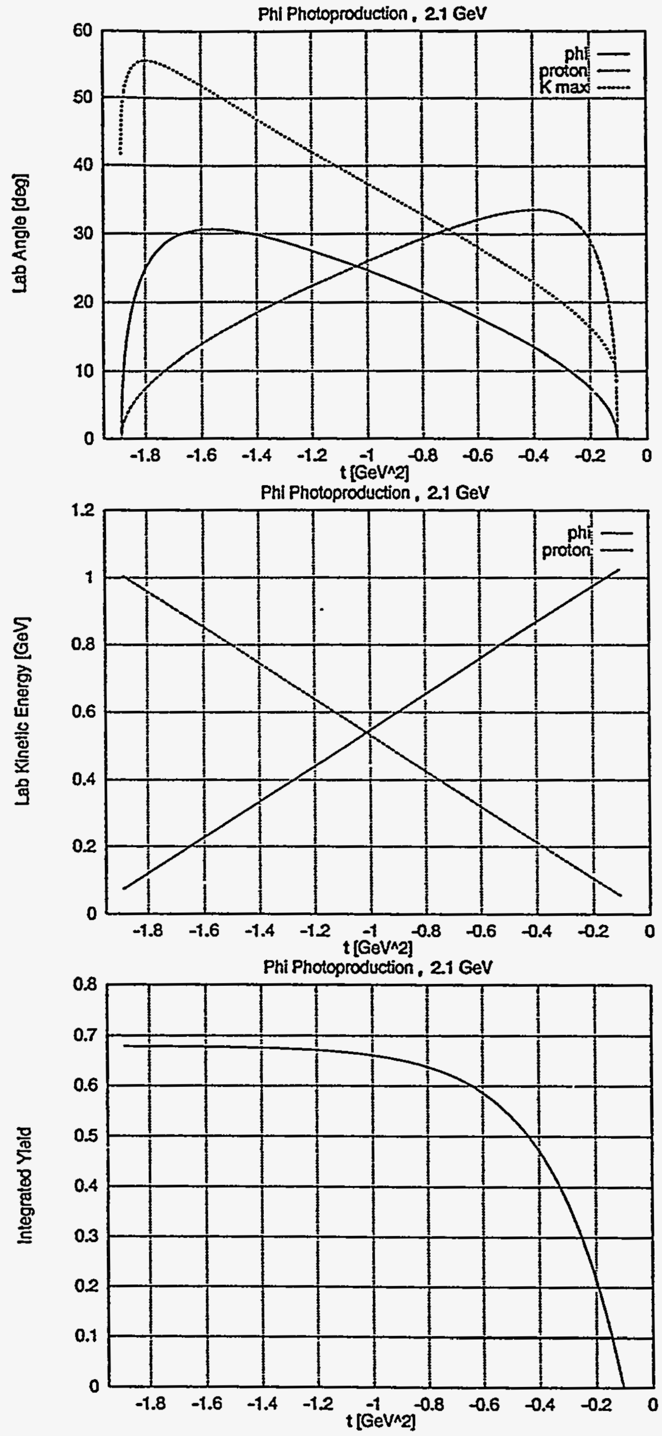

Figure 4: Kinematic variables for ϕ photoproduction at 2.1 GeV. Integrated yield is based on a 5 cm long HD ice target, 10^7 γ's, and the cross-sections of Ref. [8].

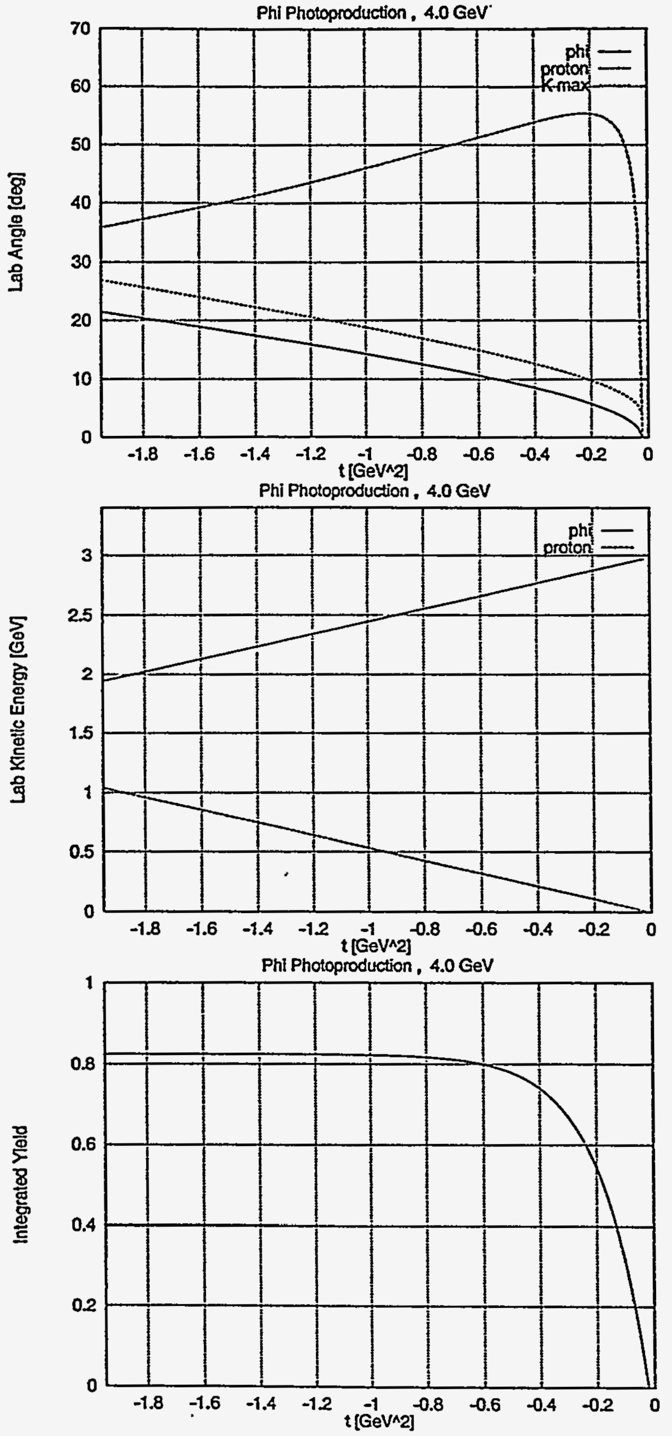

Figure 5: Kinematic variables for ϕ photoproduction at 4.0 GeV. Integrated yield is based on a 5 cm long HD ice target, 10^7 γ's, and the cross-sections of Ref. [9].

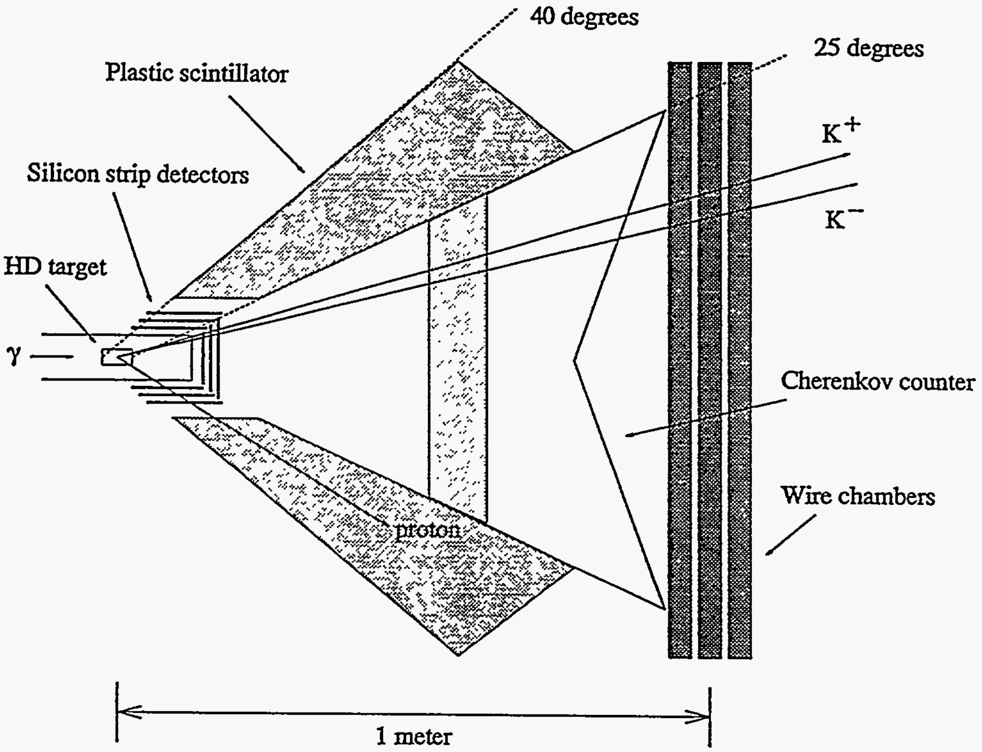

Figure 6: Conceptual design of detector.