6 Rare Kaon Decays at Brookhaven AGS

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The two projects E-865 and KOPIO discussed below have used or will use the unique low-momentum neutral and charged kaon beams available at Brookhaven National Laboratory's Alternating Gradient Synchrotron (AGS). Although BNL E-865 finished data-taking four years ago a small part of the analysis is still in progress. KOPIO on the other hand is still in its planning phase. The experimental proposal has been reviewed and approved for funding by the U.S. National Science Foundation.

6.1 BNL E-865: a search for lepton flavor violation in K^+ decay

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While the analysis of the data for the lepton flavor violating decay $K^+ \to \pi^+\mu^+e^-$ ($K_{\pi\mu e}$) [1], the primary goal of experiment E-865 at the Brookhaven AGS [2], is still in progress, the analysis of the $K^+ \to \pi^0 e^+\nu_e$ (K^+_{e3}) decay channel has been concluded last year [3; 4]. Furthermore the definitive publication on the $K^+ \to \pi^+\pi^- e^+\nu_e$ (K^+_{e4}) results has been submitted [5].

6.1.1 $K^+ \to \pi^0 e^+\nu_e$ (K^+_{e3})

During the last two weeks of data taking around Christmas 1998 we collected 70,000 events from the decay with the purpose to measure the branching ratio for this decay mode as accurately as possible. This branching ratio and that of the analogous decay of the neutral kaon $K^0_L \to \pi^\pm e^\mp \overline{\nu_e}(\nu_e)$ (K^0_{Le3}) are the primary sources for the determination of the Cabbibo-Kobayashi-Maskawa (CKM) matrix element V_{us}, linking the first and the second quark generation. One of several relations resulting from the unitarity of the CKM-matrix relates the elements of the first row as

$$\sum_i |V_{ui}|^2 = |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

With $V_{ud} = 0.9740 \pm 0.0005$ determined from nuclear superallowed Fermi β-decays or with $V_{ud} = 0.9745 \pm 0.0016$ from neutron β-decay [6], $V_{us} = 0.2196 \pm 0.0023$ and $V_{ub} = 0.0036 \pm 0.0010$ [7] one obtains

$$\begin{aligned} \textstyle\sum_i |V_{ui}|^2 &= 0.9968 \pm 0.0014 \qquad \text{(nuclear)} \\ &= 0.9978 \pm 0.0033 \qquad \text{(neutron)}\ . \end{aligned}$$

The deviation from unitarity at two standard deviation level has been discussed for quite some time, and e.g. lead to considerable experimental activity remeasuring decay asymmetries and correlations in neutron decay, where the data [8] are still somewhat inconsistent.

On the other hand the value for V_{us} quoted above stems from pre-1984 K_{e3} measurements with fairly low statistics. The second source for V_{us}, hyperon decay suffers from larger uncertainties arising from the axial-vector couplings. K_{e3} is a pure Fermi transition

$$\langle \pi^0(p)|V_\mu|K^+(k)\rangle = \frac{1}{\sqrt{2}}\left((k+p)_\mu f_+(q^2) + (k-p)_\mu f_-(q^2)\right) \ , \ q^2 = (k-p)^2 \ ,$$

leading to the transition rate

$$d\Gamma(K^+_{e3}) = \frac{G_F^2 M_K^5}{64\pi^3}|V_{us}|^2|f_+(0)|^2\left(1+\lambda_+\frac{q^2}{m_\pi^2}\right)dq^2 \ .$$

The contribution from $f_-(t)$ has been neglected because it enters multiplied with m_e^2/m_K^2. In order to determine V_{us} one needs to measure the K_{e3} branching ratio and the slope factor λ_+, evaluate the radiative corrections and calculate $f_+(0)$. The latter is done in the frame of chiral perturbation theory pioneered for K_{e3} by Leutwyler and Roos [10], which leads to the value of V_{us} quoted above. In the SU(3)-limit $f_+(0) = 1$ holds (Adamollo-Gatto theorem). The latest $\mathcal{O}(p^4)$ calculation including an estimate of the $\mathcal{O}(p^6)$ corrections yields $f_+(0) = 0.9874 \pm 0.0084$ [9], leading to $V_{us} = 0.2207 \pm 0.0024$. The nuclear value for V_{ud} combined with unitarity would require $V_{us} = 0.2265 \pm 0.0034$ and hence a K^+_{e3} branching ratio 5% larger than the measured one.

In our experiment [3] the π^0 is detected via its Dalitz decay $\pi^0 \to e^+e^-\gamma$ and the K^+_{e3} branching ratio (B) is measured relative to the sum of all other decays involving π^0: $K^+ \to \pi^0\mu^+\nu_e$ $(K^+_{\mu3})$, $K^+ \to \pi^0\pi^+$ $(K^+_{\pi2})$ and $K^+ \to \pi^0\pi^0\pi^+$ $(K^+_{\pi3})$. We measured

$$\frac{\mathrm{B}(K^+_{e3})}{0.990\ \mathrm{B}(K^+_{\mu3}) + 0.990\ \mathrm{B}(K^+_{\pi2}) + 0.995\ \mathrm{B}(K^+_{\pi3})} = 0.1998 \pm 0.0008 \text{ stat. } \pm 0.0036 \text{ syst.} \ ,$$

which using the Particle Data Group values [7] in the denominator leads to

$$\mathrm{B}(K^+_{e3}) = (5.16 \pm 0.02 \text{ stat. } \pm 0.09 \text{ syst.} \pm 0.04 \text{ norm.})\%$$

This value is higher than the Particle Data Group value $\mathrm{B}(K^+_{e3}) = (4.82 \pm 0.06)\%$ [7] by $(7.1 \pm 2.5)\%$ and would hence solve the unitarity problem.

The data were taken at a beam intensity reduced by a factor of ten compared to the $K_{\pi\mu e}$ runs to reduce the chamber occupancy in the charged particle spectrometer, which followed a magnet separating the K decay products by charge. The K_{e3} trigger required the identification of a low mass e^+e^- pair ($M_{ee} <$ 50 MeV, characteristic of π^0 Dalitz-decay) through a signal from the two CH_4 filled threshold Čerenkov counters located inside the spectrometer on both sides. A prescaled version of the same trigger requiring only three out of the four Čerenkov counters was used to measure their efficiency. For the second e^+ the information of the electromagnetic calorimeter was used in those cases, where one of the Čerenkov counters did not deliver a signal. In one third of the event sample the photon from the π^0 Dalitz-decay was detected too. This allowed checks of the reconstruction methods, but in the final sample the photon was not required. The 1.8% relative systematic error quoted above was determined from the stability under the variation of the reconstruction procedure, selection criteria, detector efficiencies applied to the Monte Carlo simulation and subdivision of data and monitor samples. It includes uncertainties in the magnetic field (0.3%), vertex finding and quality cut (0.6%), Čerenkov counter efficiency and ambiguity cut (0.4%), proportional chamber and trigger counter efficiencies (0.25%), background contamination from $\pi^0 \to e^+e^-e^+e^-$ and misidentified π^+/μ^+ (0.3%) and small, but significant discrepancies between the observed and Monte Carlo simulated e^+/e^- momentum (1.3%) and vertical decay angle (0.8 %) distributions, adding quadratically

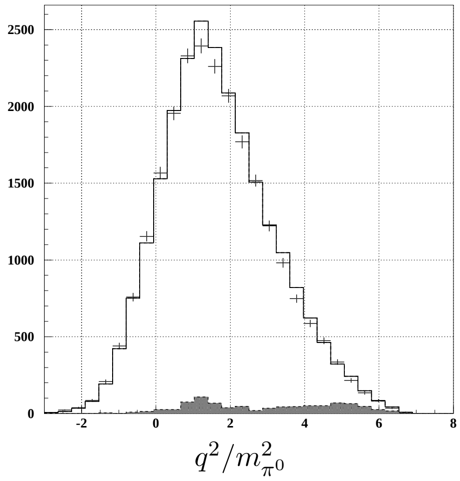

Figure 6.1: *Momentum transfer $q^2/m^2_{\pi^0}$ distribution in K^+_{e3} decay. The open (shaded) histogram shows the Monte Carlo simulated signal (background) distributions. The points with error bars are measured data.*

to 1.8%. The Monte Carlo simulation includes radiative corrections [9]. The detector efficiencies were all determined from data. Figure 6.1 demonstrates the good agreement between simulation and data using the momentum transfer q^2 distribution as an example. From this distribution the slope parameter λ_+ could be extracted with the result $\lambda_+ = 0.0324 \pm 0.0044$, which is in good agreement with the PDG value $\lambda_+ = 0.0282 \pm 0.0027$ [7]. As a further check the $K^+ \rightarrow \pi^+\pi^-\pi^+$ (K_τ) branching ratio was determined relative to the same normalisation channels used for K^+_{e3}, and found to agree with the PDG value within a factor 1.01 ± 0.02.

6.1.2 $K^+ \rightarrow \pi^+\mu^\pm e^\mp$

The analysis of the final $K_{\pi\mu e}$ run dating from 1998, which is the thesis project of Aleksey Sher, is almost completed. In order to quote a limit on the branching ratio the Monte Carlo simulation had to be retuned for the running conditions of 1998, i.e. measured efficiencies had to be implemented. The acceptance for $K_{\pi\mu e}$ events and the two monitor samples $K_{\pi 2}$, K_τ was calculated, with consistent results. In view of the *blind* analysis philosophy, which is followed here, the possible signal region has been excluded from the analysis so far. The statistical analysis tools, the ingredients of the maximum likelihood analysis and the cuts, which reduce the backgrounds in the signal region have been all been optimized and prepared, such that the final answer can be expected in the immediate future.

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[6] For a review see I.S. Towner and J.C. Hardy, J. Phys. G: Nucl. Part. Phys. **29** (2003), 197.

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[8] H. Abele *et al.* Phys.Rev.Lett.**88** (2002), 211801, and references therein.

[9] V. Cirigliano, M. Knecht, H. Neufeld, H. Rupertsberger, and P. Talavera, Eur.Phys.J.**C23** (2002), 121.

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6.2 KOPIO: a study of the CP-violating rare decay $K_L^0 \rightarrow \pi^0\nu\overline{\nu}$

in collaboration with:
Brookhaven National Laboratory, University of Cincinatti, INR Moscow, KEK, Kyoto University of Education, Kyoto University, University of New Mexico, INFN University of Perugia, Stony Brook University, Thomas Jefferson National Accelerator Facility, TRIUMF/UBC, University of Virginia, Virginia Polytechnic Institute & State University, and Yale University.

Enormous efforts are made to study CP violation in the B meson sector. One of the most important measurements is, however, still to be done in the K meson sector, where CP violation was originally discovered, namely that of the $K_L^0 \rightarrow \pi^0\nu\overline{\nu}$ branching ratio, which has a Standard Model (SM) prediction in the range $(3.1 \pm 1.3) \times 10^{-11}$. The KOPIO experiment plans to measure the branching ratio with a single-event sensitivity around 6×10^{-13} corresponding to $\approx 50 \pm 20$ observed events for the SM value.

The combined MECO/KOPIO proposal[2] was submitted to the US National Science Foundations (NSF) Major Research Equipment (MRE) program in 1999. Meanwhile the project has been approved and is part of the budget proposal to the US Congress for the fiscal year 2004. The plan includes funding of pre-construction r&d as well as substantial operating funds required for AGS operation.

The KOPIO experiment plans to use an intense low momentum, time structured K_L^0 beam available only at the AGS. The planned detection system will allow a fully constrained reconstruction of the π^0 mass, momentum and energy in the K_L^0 center-of-mass system. Kinematical cuts and an elaborate veto counter system are designed to nearly eliminate all background contributions from K_L^0 decays with more than one π^0 or from other photon sources. The goal of KOPIO is to obtain the ≈ 50 events with a signal to background ratio of 2:1, yielding a 10% uncertainty for the height of the CKM triangle.

The University of Zürich group has taken on the responsibility for the design and test of the charged particle veto counters, which are of crucial importance for a variety of background sources, e.g. from the radiative decay $K_L^0 \rightarrow \pi^- e^+ \gamma \nu_e$. The energy of the PSI $\pi^\pm$ beams is ideally suited for such measurements, which have started in 2000/1.

6.2.1 CP violation in the quark sector: Standard Model and beyond

Within the Standard Model CP violation in the quark sector arises from a single complex phase in the CKM mixing matrix [1]. In the Wolfenstein parametrisation (see last year's annual report) the violation results from a non-zero value of the parameter η which manifests itself in two CKM elements:

$$\begin{array}{lllll} V_{ub} & = & |V_{ub}|e^{-i\beta} & = & A\lambda^3(\rho - i\eta) \\ V_{td} & = & |V_{td}|e^{-i\gamma} & = & A\lambda^3(1-(1-\lambda^2/2)(\rho+i\eta)) \;\approx\; A\lambda^3(1-\rho-i\eta) \end{array}$$

The decay $K_L^0 \rightarrow \pi^0\nu\overline{\nu}$ has major contributions from penguin and box diagrams with up-type quarks in the intermediate state. Since the transition amplitude scales with the quark mass the top contribution dominates by far and $A(K_L^0 \rightarrow \pi^0\nu\overline{\nu}) \propto V_{td}^* V_{ts} - V_{ts}^* V_{td} \propto i\eta$. As a result $B(K_L^0 \rightarrow \pi^0\nu\overline{\nu}) \propto \eta^2$. The branching ratio is thus a direct measure of η, i.e. the area (or height) of

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[2] http://pubweb.bnl.gov/people/rsvp/proposal.ps

the CKM unitarity triangles.

The corresponding charged decay mode does not require CP violation but gives a circular constraint around $\rho = 1.3, \eta = 0$: $B(K^+ \rightarrow \pi^+\nu\overline{\nu}) \propto (\rho - 1.3)^2 + \eta^2$. Until recently BNL E-787 found two event candidates [2]. An upgraded version of this experiment (E-949 [3]) which has started to take data last year hopes to increase the sensitivity by a next order of magnitude. Another experiment (Fermilab E921 [4]) which is still in the stage of preparation should observe some 95 events at the prefered SM branching ratio. Ultimately these two decay modes together will give a complete picture of CP violation in the K system with negligible theoretical uncertainties.

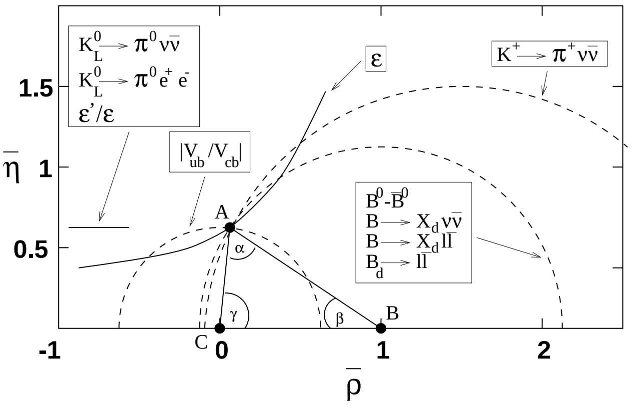

Figure 6.2: *The unitarity triangle and the constraints from various K and B decays.*

Figure 6.2 shows how various observables in K and B decays contribute to our knowledge of $\overline{\eta} \equiv (1 - \lambda^2)\eta$ and $\overline{\rho} \equiv (1 - \lambda^2)\rho$ which define point A in the figure.

Physics beyond the Standard Model generally allows additional CP-violating phases [5] and as a result the SM description with a universal set of Wolfenstein parameters for K and B would break down. It is very fortunate that we may expect significant improvements in the experimental constraints in both areas during the next decade so that meaningful tests can be made.

6.2.2 The charged particle veto system

In last years annual report the complete KOPIO detection system has been presented. The decay $K^0_L \rightarrow \pi^0\nu\overline{\nu}$ will be distinguished from other more likely decay modes on the basis of the following signature:

- Two photons are observed with a common vertex inside the decay region and an invariant mass equal to m_{π^0}.
- No simultaneous charged particles or additional photons are observed.
- The energy $E^*_{\pi^0}$ of the reconstructed π^0 in the K^0_L rest frame (using the K^0 time of flight through the beam line) and the photon energy sharing do not coincide with the regions populated by the background of the decay $K^0 \rightarrow 2\pi^0$ remaining after test 2.

The Zürich group took over the responsibility for the main charged-particle veto system situated directly around the decay region. In the following we discuss the requirements to this system and some other considerations that should lead to a specific design.

The purpose of the charged-particle veto system is the efficient identification of background processes in which an apparent $\pi^0 \rightarrow 2\gamma$ decay inside the decay volume is accompanied by charged particle emission. Examples of such background processes are, (i) $K^0_L \rightarrow \pi^+\pi^-\pi^0$, (ii) $K^0_L \rightarrow e^+\pi^-\nu\gamma$ in which the positron creates a second photon through Bremsstrahlung or annihilation in flight, (iii)

$K_L^0 \to e^+\pi^-\nu$ again followed by $e^+ \to \gamma$ whereas the π^- creates a photon through $\pi^- p \to \pi^0 n$. In all cases two particles with opposite electrical charge emerge. The events may also produce signals in other detector elements, like the barrel veto system. Detection efficiencies of 99.99% or better are required to keep these backgrounds below a few events in the final sample.

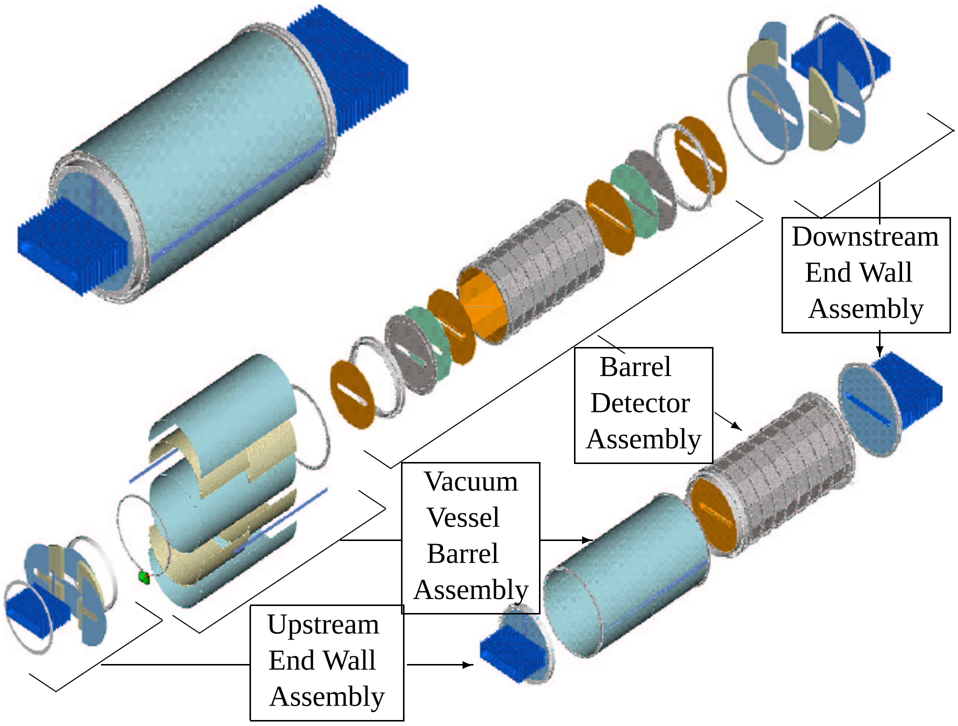

Figure 6.3: *The present concept of the charged particle veto system and surrounding vacuum tank. The latter has a length of 4 m and a diameter of 2.5 m.*

The charged-particle veto system will consist of one or two layers of plastic scintillator mounted inside the vacuum tank surrounding the decay volume. About 100 m^2 of plastic scintillator will be distributed over some 500 independent elements. Figure 6.3 shows an exploded view of the system. As discussed in last year's report the requirement of a veto efficiency for e$^\pm$, $\pi^\pm$ and $\mu^\pm$ of 99.99% or better can be met if the dead layer in front of the veto system (which may include a window separating the detector from the high-vacuum decay region) could be kept below 20 mg/cm^2 if a detection threshold of $\approx$ 75 keV (corresponding to $\approx$ 0.3 mm scintillator thickness) could be reached. Minimising dead material mainly helps to reduce the inefficiency for π^- caused by nuclear reactions.Tests by the PSI vacuum group indicate that it may be possible to leave out the vacuum window in which case only the scintillator wrapping would contribute. A low detection threshold translatesinto a high yield for the number of photo electrons per energy deposit which in turn demands a high efficiency for the collection of the scintillation light. The optimisation of the light yield is the central issue of our present r&d program. In the past year we compared the performance of various wrapping materials. Table 6.1 sum-

Table 6.1: *Mean amplitude of the signals produced by cosmic muons in the scintillator prototype with w.l.s. fibre readout for various wrapping materials.*

wrapping material	ADC peak position
black paper	860
nothing	900
aluminum	1350
white paper (Tyvek[a])	1580
teflon	1610

[a] Du Pont trademark

marises our findings for a prototype detector with w.l.s. fibre readout. Best results were obtained with teflon and Tyvek which both almost double the light yield. During a two weeks beam period at PSI in September 2002 various prototypes were studied. These tests were made with 550 MeV/c π^-. Two xy MWPC's were used to determine the impact position on the scintillator. Four alternative readout schemes were under investigation:

- Light extraction through wave-length-shifting fibres put in grooves inside the scintillator. The photon detectors would be situated at a few meters distance outside the vacuum tank. As reported last year $\approx$ 10 p.e./mm were observed in a first prototype using Kuraray Y-11(200)MS w.l.s. fibres coupled to Burle S83062E photo multipliers which have enhanced quantum efficiency for the green light emitted by the fibres. Meanwhile we achieved somewhat larger yields with Kuraray SCSF-81Y-11(200)MS fibres.
- Light extraction through wave-length-shifting bars. This scheme gives results which are similar to the fibre readout. It needs more photo cathode area but would be significantly cheaper otherwise.
- Photo-multipliers coupled directly to the scintillator slabs.

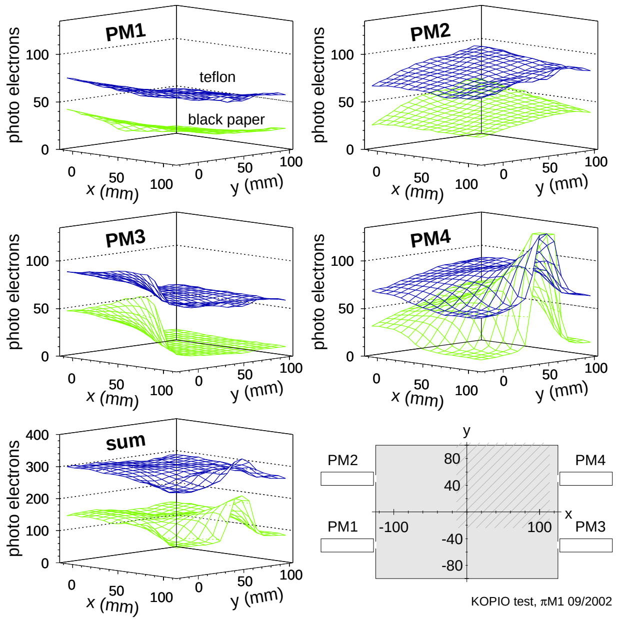

Figure 6.4: *Position dependence of the light yield with and without teflon wrapping. The* $250 \times 200 \times 6$ *mm*^{3} *scintillator was viewed by photo-multipliers through four 10 mm wide holes on opposite sides. The hatched area corresponds to the region studied.*

As a first result of these measurements Fig. 6.4 shows the position dependence of the light extracted through four windows on two opposite sides of a slab of scintillator with and without teflon wrapping. The mean yields for all geometries that were studied with and without reflective wrapping are compared in Fig. 6.5. As in Table 6.1 wrapping tends to double the light yield. In addition the reflecting material improves the uniformity of the detector response over the detector surface. From these results we conclude that scintillator elements of $\approx$ 500 $\times$ 500 mm^2 viewed from one side by a series of small photo-multipliers should give a yield of $\approx$ 50 photo electrons per millimetre which would result in inefficiencies below 3×10^{-5} for the various particles.

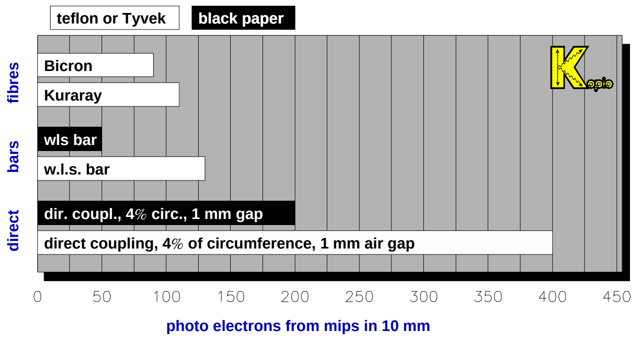

Figure 6.5: *Comparison of the photoelectron yield observed with various light-collection schemes with and without reflective wrapping.*

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