Simulation study of $K_L$-beam: $K_L$ rates and background

I. LARIN
• $K_L$ beamline
• Simulation of $K_L$ production
• Beam momentum resolution
• Expected $K_L$ and background rates
Hall D

5.5 passes to Hall D

add 5 cryomodules

20 existing cryomodules

add arc

20 existing cryomodules

add 5 cryomodules

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**$K_L$-beam line**

- **Be** and **Pb** collimators
- Sweeping magnet
- Hall D:
  - Collimator area
  - Wall
  - Liquid hydrogen target
  - Spectrometer

Dimensions:
- **L 15cm**
- **L 40cm**
- **16...20m to target**
$K_L$-production and propagation: simulation details

- $K_L$ production mechanisms
- $K_L$ absorption
- $K_L$ beam momentum spectrum
- Comparison with Pythia
- Expected rates
$K_L$ production:

- One of the main $K_L$ production mechanisms at our momentum range is $\phi$ photoproduction. It gives same number of $K^0$ and $\bar{K}^0$ in the beam. This mechanism was studied in our simulations in details.
- For thick production target $K_L$ yield in first approximation is proportional to material rad. length and density, i.e. r.l. expressed in $[g/cm^2]$. It determines beryllium, boron and carbon as most preferable $K_L$ production targets. We performed detailed simulation studies for beryllium, which is “traditional” $K_L$ production target.
- We compared our simulation results with what Pythia is giving us.
**\( \phi \) photoproduction: cross section**

Total photoproduction cross section as a function of beam energy

Differential cross section \((\frac{d\sigma}{dt})\) as a function of \(t_{\perp}\)

**FIG. 3.** (a) The total cross section of \(\gamma p \rightarrow \phi p\) reaction as a function of the photon energy \(E_{\gamma}\) for models I–III indicated by dashed, long-dashed, and dot-dashed curves, respectively. Data are taken from Refs. [57,58]. (b) The total cross section for the hybrid model.


**K_L production via φ decay: angular distributions**

**Gottfried – Jackson frame**

\[ \frac{d\sigma}{d\cos\theta^*} \]

FIG. 7. The angular distribution of the φ-meson decay in the reaction $\gamma p \rightarrow \phi p$ with unpolarized photon beam at $E_\gamma = 2.2$ GeV and $|t| = 0.2$, 0.5, and 1.8 GeV\(^2\). (a) The dependence on $\cos\theta$ (integrated over the azimuthal angle $\Phi$); (b) the dependence on $\Phi$ (integrated over $\cos\theta$).

**helicity frame**

FIG. 13. Angular distribution $W(\cos\theta)$ for the $\gamma D \rightarrow \phi D \rightarrow K^+K^-D$ reaction in the helicity frame at $E_\gamma = 3.1$ GeV and $-t_0 = 0.3$ GeV\(^2\). Experimental data for two energy intervals and $|t| = 0.35$–0.8 GeV\(^2\) are taken from Ref. [16].


$K_L$ absorption on the way:
in beryllium (primary target) and lead (beam shutter)

- ~80% of Kaons will be absorbed in Be and lead
- Elastic Kaon scattering does not decrease $K_L$ flux on target

Data from “Production of $K_L$ mesons and neutrons from Electrons on Beryllium Above 10GeV”, G.W. Brandenburg, Phys. Rev. D 7 (1973)
\( K_L \) from \( \phi \) decays simulations

- \( K_L \) yield via \( \phi \) photoproduction was simulated in GEANT program
- Roughly, only over billion photons gives \( K_L \) at target face – simulation of 1M statistics at target would require generation of \( \sim 10^{15} \) events

- Possible solution:
  - generate \( \phi \) photoproduction on each tiny photon track segment
  - Assign weight which equals to photoproduction probability in case if product \( K_L \) reaches the target
Growing part of kaon spectrum: 
$\phi$ decay cone angle in lab frame decreases, which requires smaller $\phi$ production $t$ values ($\phi$ production angle should be close to $\phi$ decay cone angle for our geometry)

Second part of spectrum is dropping down: 
Due to limited $\gamma$-beam energies (effect of bremsstrahlung spectrum edge)
$K_L$ momentum spectrum ($\phi$ decay only): comparing with Pythia

Simulation result for $K_L$ momenta at 16m downstream primary target

1) Shapes of $K_L$ momentum spectra are close and have maximum at $\sim 4$ GeV

2) Number of $K_L$ produced only via $\phi$ production mechanism in Pythia 30% smaller than in our Monte-Carlo

3) Total number of $K_L$ given by Pythia was $\sim 2.5$ times higher than our Monte-Carlo
$K_L$ momentum spectrum (total): Pythia

1) $K_L$ momentum spectrum has maximum at 4 GeV (same as we see for $\phi$ production mechanism)

2) Number of produced $K^0$ exceeds number of $\bar{K}^0$ by $\sim 30\%$ (due to hyperon photoproduction)

3) $\phi$ photoproduction mechanism in Pythia gives $\sim 30\%$ of total number of $K_L$. 

Simulation result for $K_L$ momenta at 16m downstream primary target
$K_L$-beam rates and run conditions

Calculated rates are given for

- Electron beam current $I_{\text{beam}} = 3.2 \mu\text{A}$
- Tagger radiator thickness $X_{\text{rad}} = 1\% (\text{rad. len.})$
- Beryllium target: thickness $L_{\text{be}} = 40\text{cm}$, radius $R_{\text{Be}} = 2\text{cm}$
- Distance from primary target (Be) to production target (liquid $\text{H}_2$) $z = 16\text{m}$
- Production target (liquid $\text{H}_2$) radius $R_{\text{tgt}} = 2\text{cm}$
- The part of the whole beam integrated over solid angle of production target
**Kₐ-beam rates and run conditions**

Calculated rates for given beam parameters, for survived $K_L$ (no decay or absorption) observed at forward production target plane:

- $K_L$ via $\phi$ photoproduction (50% $K^0$ and 50% $\bar{K}^0$, our simulations) $\sim 100$ per sec
- $K_L$ via all production mechanisms ($\sim 55% K^0$ and $\sim 45% \bar{K}^0$, Pythia) $\sim 240$ per sec

Possible ways to increase $K_L$ beam rate:
- Increase production (liquid H₂) target radius (wider solid angle) from 2cm to 3...4cm
- Increase Be target thickness to 50...55cm
- Increase beam current and tagger radiator thickness

For production target radius $R = 4$cm, 5µA beam current, 5% rad. len. radiator thickness, Be target radius $R_{Be} = 4$cm and thickness $L_{Be} = 50$cm we estimate:

- $K_L$ via all production mechanisms $7k$ per sec (at liquid H₂ target face)
- $K_L$ production rate in Be target at this conditions $\sim 10M$ per sec
Yields vs radiator thickness and Be target size

\( \gamma \)-beam yield on Be-target face vs radiator thickness for different Be radii

\( K_L \) yield vs Be-target thickness
$K_L$-beam resolution

- Time resolution
- Momentum resolution
- $W$ resolution
- Angular resolution
beam time, momentum and $\sqrt{s}$ resolutions

**Input parameters:**
- $K_L$ path from production point to target: 20m
- $K_L$ production primary Be target length: 40cm
- Start counter vs RF time resolution: 0.25ns
- Beam RF structure is essential for TOF analysis: $> 30\text{ns}$

**Simulation results:**
- SC time resolution defines TOF resolution starting at 1 GeV/c
- Beam momentum and $W$ ($K_L+p$ system) resolutions defined by TOF resolution
time and momentum resolution

Time resolution is flat from 1GeV $K_L$ momenta and defined by start counter time

Momentum resolution $\sim 1.7\%$ at 1GeV/c and $\sim 6\%$ at 2GeV/c $K_L$ momentum
W and angle resolution

- W resolution better than 1% up to 1.4 GeV/c and within 2% up to 1.9 GeV/c \( K_L \) momentum
- Angular resolution defined by setup geometry and within 3 mrad
Multilayers shield with magnetic field additionally suppresses residual $\gamma / n$ background by $\sim 20\%$ in comparison with the same thickness solid block.
After 15 cm of lead shield residual $\gamma$ background rate on hydrogen target (passing through collimator hole):

$$E_{\gamma} > 10\text{MeV} \rightarrow \approx 3\text{M/sec}$$
$$E_{\gamma} > 50\text{MeV} \rightarrow \approx 100\text{k/sec}$$
$$E_{\gamma} > 100\text{MeV} \rightarrow \approx 30\text{k/sec}$$
$$E_{\gamma} > 500\text{MeV} \rightarrow \approx < 1\text{k/sec}$$
Neutron rate was estimated by two independent ways: Pythia generator (photoproduction on energies greater than 3GeV (thanks to Sasha Somov) and DINREG package (courtesy of Pavel Degtiarenko).

Both packages give same order number of neutrons and $K_L$ starting from energies 1GeV (140 neutrons per second for Pythia).

For low momenta energies number of neutrons in DINREG packages increases faster.

Inclusion of magnetic field, (non-magnetic) iron and polyethylene spacers in beam shutter will reduce neutron background significantly.

Placing Be target in magnetic field can reduce number of produced neutrons up to 25%.
Muons will be removed by swiping magnet after beam shutter. Nevertheless special attention is needed for muon protection.

Muon pair production via Bethe-Heitler process has been simulated in GEANT to estimate $\mu$ production rate.

Additional muons expected from pions decay (less energetic though).

Be target and lead beam shutter give roughly the same amount of muons, muons produced in lead are softer.

About half of muons have momentum higher than 2GeV/c; 10% of muons with momentum above 6GeV and ~ 1% of muons with momentum above 10GeV.

Number of produced muons of both signs for 3.2µA beam current and 1% radiator ~ 6M/sec.
Summary

- $K_L$ beam facility at 12 GeV opens horizons for new physics. We expect a lot of new ideas and original proposals.
- Hall D setup and spectrometer perfectly fit $K_L$ beam facility needs.
- High intensity $\gamma$-beam is needed to provide measurements in $K_L$ beam with order of magnitude higher statistics than other beam facilities can provide.
- Big advantage of $\gamma$-beam is that it provides low neutron contamination $K_L$-beam.
- Neutron background is comparable with $K_L$-beam intensity. It is seen, that there are ways for further background reduction.
- Estimated $K_L$ and background rates need to be verified with existing measurements, such as $NINA$ experiment data.
- $K_L$ and background rates need to be measured experimentally during few days of low intensity test beam running. It will also give us more precise estimation of radiation levels caused by $K_L$ beam production.