ASHIPH Cherenkov counters in the KEDR experiment

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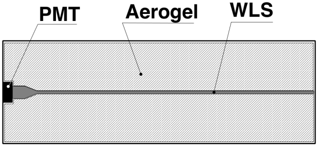
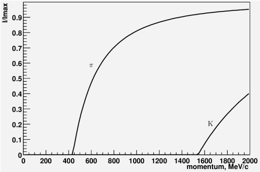
ASHIPH method for particle identification





$$P_{thr} = \frac{mc}{\sqrt{n^2 - 1}}$$

ASHIPH (Aerogel, SHifter, PHotomultiplier) method of light collection was suggested in 1992 (A. Onuchin et al. NIM A315, 1992, 517-520). Cherenkov light from particle in aerogel is collected by the wavelength shifter (WLS) placed in the middle of the counter and transported by WLS like a lightguide to photomultiplier (PMT):

- PMMA light guide doped with BBQ dye is used as WLS
- This method helped us significantly to decrease the PMT photocathode area (cost of the system)

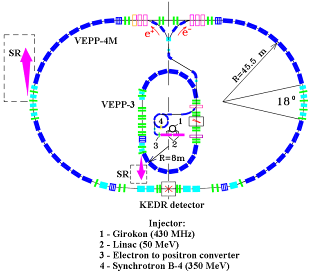
KEDR experiment at VEPP-4M collider

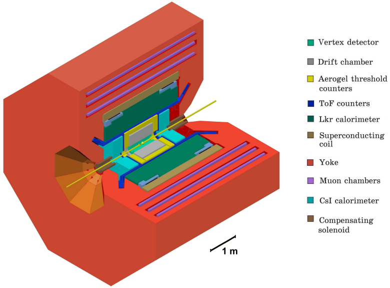
VEPP-4M collider:

- Symmetric e^+e^- collider
- $E_{c.m.}$ =2÷10 GeV
- L=(1÷80)×10^{30} cm^{-2} · s^{-1}
- Precise energy calibration:
  - Resonant depolarization technique: (5÷15)×10^{-6}
  - Compton backscattering: 3×10^{-5}

Physics program:

- Precise particle mass measurements: J/ψ, $\Psi(2S)$, $\Psi(3770)$, τ lepton, D mesons, Υ mesons
- Measurements of Ψ and Υ mesons lepton width
- R measurement in 2-10 GeV c.m. energy range
- $\gamma\gamma$ →hadrons and other 2γ processes
- Branching fractions measurements in charm and bottom quark systems

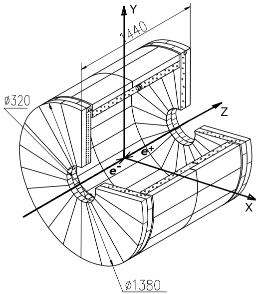


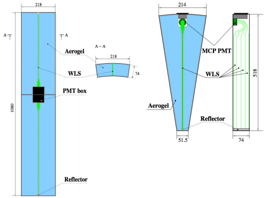


Experiments with the KEDR detector at the e^+e^- collider VEPP-4M in the energy range $\sqrt{s}$=1.84-3.88 GeV, Physics of Particles and Nuclei, 2023, Vol. 54, p. 185

The ASHIPH system of the KEDR detector

80 counters (first layer) of the KEDR ASHIPH system were under operation in detector from 2003 to 2011. Due to problems with PMT holders in magnetic field the system had poor geometrical and light collection efficiencies.





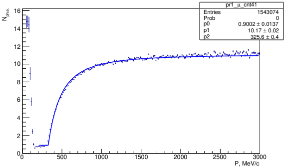
- 160 counters arranged in 2 layers;
- Solid angle 96% of 4π
- 1000 liters of aerogel with n=1.05;
- π/K-separation in the momentum range 0.6-1.5 GeV/c;
- 160 MCP PMT with multialkali photocathode ⌀18 mm able to work in the magnetic field up to 4.5 T (A.Yu. Barnyakov et al., NIM A845, 2017, 588);
- Fully installed in the detector in 2013. Now is in operation.

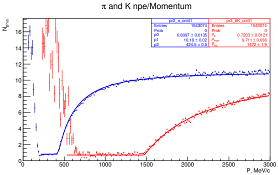
Efficiency in 2014

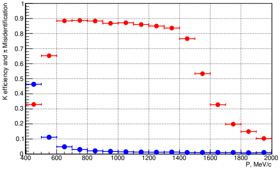
«Thick» counter – sum of the amplitudes in both layers

- To evaluate registration efficiency for kaons and pions with some momenta muons with corresponding momentum were chosen ($P_\mu = P_{K,\pi} * [m_\mu / m_{K,\pi}]$):
  - $600 < P_K < 1500\ MeV/c :\rightarrow 128 < P_\mu < 321\ MeV/c$
  - $600 < P_\pi < 1500\ MeV/c :\rightarrow 454 < P_\mu < 1135\ MeV/c$

$N_{ph.e.thr}$ =1.0 ph.e.







For tracks with $P > 1\ GeV/c$:

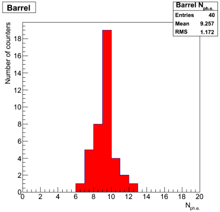
$$\mu = \mu_0 + \mu_{max} \cdot \frac{p^2 - p^2_{thr}}{p^2} = 10.32 \pm 0.03$$

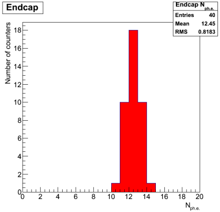
$$\varepsilon = 1 - e^{-\mu} = 99.997 \pm 0.001\%$$

π/K–separation better than 3σ in the range $P = 0.60 \div 1.50\ GeV/c$.

The sources of under threshold signal:

- Cherenkov light from δ-electrons in aerogel;
- Scintillation in PTFE wrapping;
- Cherenkov light in PTFE wrapping.



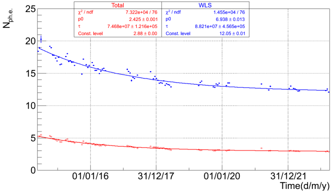


A.Yu. Barnyakov et al., Particle detection efficiency of the KEDR detector ASHIPH system, NIM A952, 2020

Long-term stability the ASHIPH system

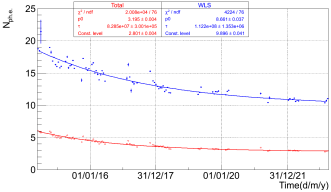
- We can separate the signal of Aerogel and WLS, i.e. separate causes degradation (QE of PMT or Aerogel).
- For calibration the cosmic muons with $P > 1\ GeV/c$ are selected.

1-160 counters

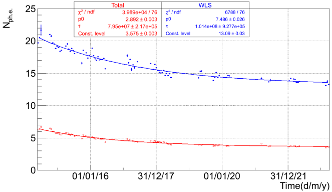


A_{max} $\simeq$5.5 ph.e., τ $\simeq$2.5 years, CL$\simeq$2.90 ph.e.

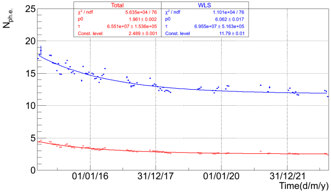
1st layer (List1)



1st layer (80-List1)



2nd layer (81-160 cnt)

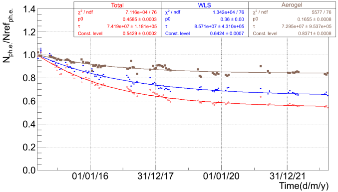


«Total» – area of the aerogel with electronics and WLS cut and indented from the walls.
«List1» – list from 21 counters with MCP PMT operating in the detector since 2003.

Long-term stability the ASHIPH system

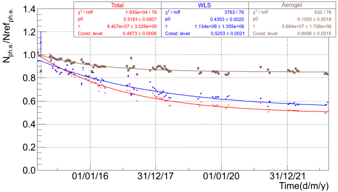
Normalaized $N_{ph.e.}$ to 2014

1-160 counters



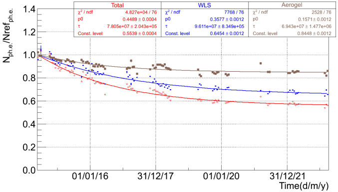
- QE of PMT: ∼34.63%
- Aerogel: ∼16.19%

1st layer (List1)



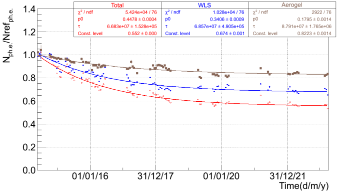
- QE of PMT: ∼39.84%
- Aerogel: ∼15.43%

1st layer (80-List1)



- QE of PMT: ∼33.83%
- Aerogel: ∼15.44%

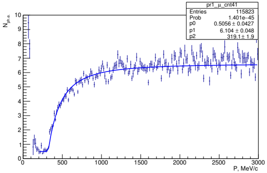
2nd layer (81-160 cnt)



- QE of PMT: ∼33.49%
- Aerogel: ∼17.21%

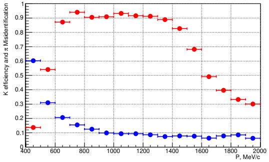
Efficiency in 2023

«Thick» counter – sum of the amplitudes in both layers

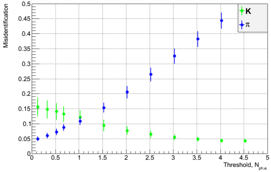


$$\mu = \mu_0 + \mu_{max} \cdot \frac{p^2 - p_{thr}^2}{p^2} = 6.33 \pm 0.09$$

$$\varepsilon = 1 - e^{-\mu} = 99.82 \pm 0.01\% (P > 1\ GeV/c)$$

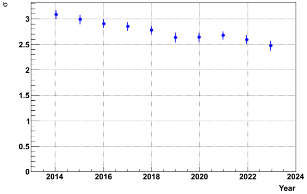


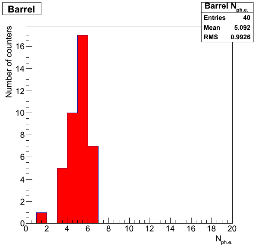
Two layer system efficiency ($N_{ph.e.thr}$ =1.0 ph.e.)



$600 < P < 1500\ MeV/c$

$600 < P < 1500\ MeV/c$, $N_{ph.e.thr}$ =1.0 ph.e.





Branching fraction of $J/\psi \to 2(\pi^+\pi^-)\pi^0$, $K^+K^-\pi^+\pi^-\pi^0$, $2(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$

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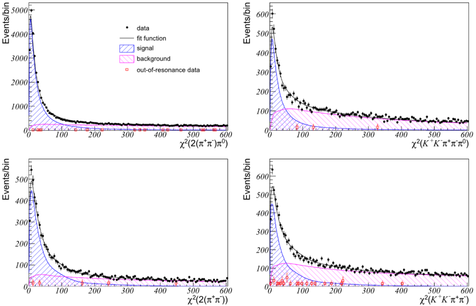
Distributions of χ^2 from kinematic fits



Data: $\int L \bigtriangleup t$=1.32 pb^{-1}

π/K-identification:

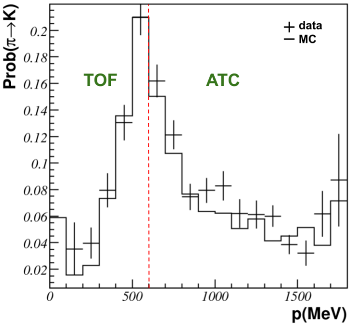
- P<600 MeV/c – barrel part of the time-of-flight system of scintillation counters (ToF)
- P>600 MeV/c – system of Cherenkov counters (ATC)

$$B_i = B_{mh} \frac{N_i^{peak} - N_i^{cont} \cdot L/L^{cont}}{N_{mh}^{peak} - N_{mh}^{cont} \cdot L/L^{cont}} \frac{\varepsilon_{mh}^{MC}}{\varepsilon_i^{MC}} \frac{R_i^{MC}}{R_i^{exp}},$$

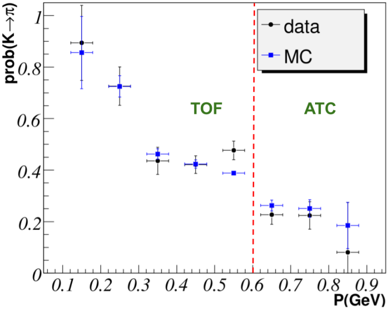
B_{mh} – branching fraction of J/ψ multihadron decays,
N_i^{peak} – number of selected X_i signal events at the J/ψ peak after subtracting the background from decays other than $J/\psi \to X_i$,
N_i^{cont} – number of selected X_i signal events out of peak,
N_{mh}^{peak} and L – number of selected multihadron events and the integrated luminosity at the J/ψ peak,
N_{mh}^{cont} and L^{cont} – same off-peak quantities,
ε_{mh}^{MC} and ε_i^{MC} – MC estimated detection efficiencies for J/ψ multihadron decays and decays $J/\psi \to X_i$,
R_i^{exp} and R_i^{MC} – fractions of signal events in candidate events for $J/\psi \to X_i$ decays, for experimental data and MC simulation

Branching fraction of $J/\psi \to 2(\pi^+\pi^-)\pi^0$, $K^+K^-\pi^+\pi^-\pi^0$, $2(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$

$P_{\pi\to K}$ misidentification was determined from the decays $J/\psi \to \pi^+\pi^-\pi^0$



$P_{K\to\pi}$ misidentification was determined from the decays $\varphi \to K^+K^-$



D-mesons mass

- Data: $\int L \triangle t$=4.06 pb^{-1}
- Invariant mass of the D-meson (beam-constrained mass):

$$M_{bc} = \sqrt{\left(\frac{W}{2}\right)^2 - \left(\sum_i \vec{p_i}\right)^2}$$

- Energy difference between D-meson and beam:

$$\triangle E = \sum_i \sqrt{(m_i^2 + p_i^2)} - E_{beam} \approx 0$$

- D-meson mass determined from fit to M_{bc} and $\triangle E$ (and $\triangle p$ for D^0)

$$-2 \log \mathcal{L}(\alpha) = -2 \sum_{i=0}^{N} \log p(\mathbf{v}_i|\alpha) + 2N \log \int p(\mathbf{v}|\alpha) d\mathbf{v},$$

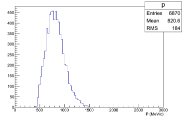
  where $\mathbf{v} = (M_{\rm bc}, \Delta E, \Delta|p|)$ are the variables that characterize one event, $p(\mathbf{v}|\alpha)$ is the probability distribution function (PDF) of these variables depending on the fit parameters $\alpha = (M_D, \langle \Delta E \rangle, b_{uds}, b_{DD})$:

$$p(\mathbf{v}|\alpha) = p_{sig}(\mathbf{v}|M_D, \langle \Delta E \rangle) + b_{uds} p_{uds}(\mathbf{v}) + b_{DD} p_{DD}(\mathbf{v}).$$

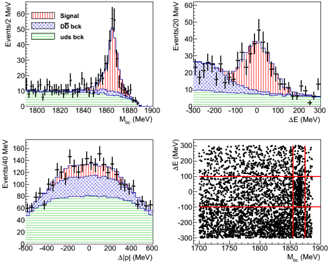
- The shape of the distribution of signal events and background events is extracted from the Monte Carlo simulation
- For right calculation $\triangle E = E_\pi + E_K - E_{beam}$ π/K-identification is required

D^0-meson

D^0 reconstructed in channel $K^-\pi^+$ (3.95±0.03% from PDG)



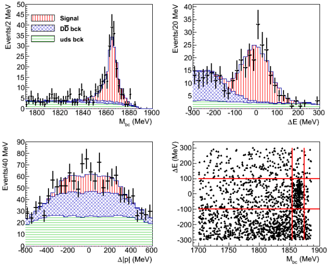
- W/o ATC for π/K-identification



Number of events in signal area

N_{sig}	208.05
N_{uds}	72.27
N_{DD}	24.35

- With ATC for π/K-identification
  - 450<P<1500 MeV/c
  - THICK counter, threshold 0.5 ph.e.

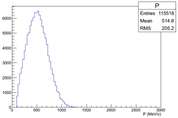


Number of events in signal area

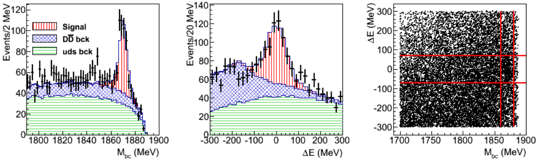
N_{sig}	160.20
N_{uds}	23.24
N_{DD}	9.56

Increases the signal-to-background ratio by 2.2 times

D^+ reconstructed in channel $K^-\pi^+\pi^+$ (9.38±0.16% from PDG)



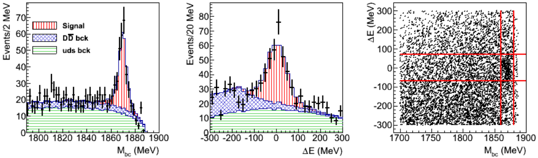
- Without ATC for π/K-identification:



Number of events in signal area

N_{sig}	617.94
N_{uds}	290.42
N_{DD}	102.28

- With ATC for π/K-identification:



Number of events in signal area

N_{sig}	351.01
N_{uds}	113.70
N_{DD}	30.37

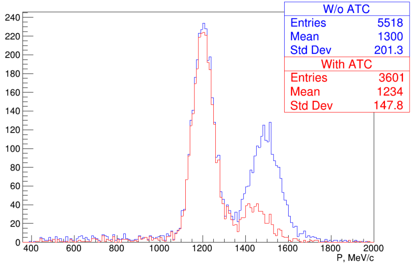
- TOF
  - P<600 MeV/c
  - $\triangle TOF =$ $T_{TOF} - T_{K(P_K)}$>-0.8
- de/dx
  - P<600 MeV/c
  - ProbK>0.50
- ATC:
  - 450<P<1500 MeV/c
  - THICK counter, threshold 0.5 ph.e.

Increases the signal-to-background ratio by 1.5 times

Branching fraction of $J/\psi \to p\bar{p}$

- Data: $\int L \triangle t$=1.32 pb^{-1}
- $Br(J/\psi \to p\bar{p}) = \frac{N^{obs}_{p\bar{p}}}{N^{tot}_{J/\psi} \cdot \varepsilon_{det}}$ (PDG: $(2.17 \pm 0.07) \times 10^{-3}$)
- Event selection:
  - Polar angle: $47 \div 133^o$
  - Centrality
  - $0 < \chi^2$/nhits<1.5, nhits>55
  - $cos\theta \leq -0.996$
  - Muon system: number of hits in the 1st layer ≤ 2, in 2 and 3 layers is 0 hits
  - $0.1 <$E/p$(q^+) < 0.6$, $0.1 <$E/p$(q^-) < 3$
  - Threshold 0.2 ph.e. on track in ATC

Momentum distribution (MeV/c) of the tracks candidates



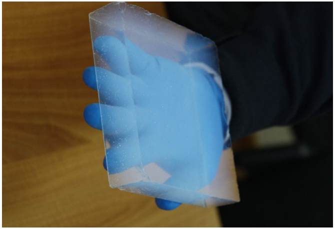
Summary

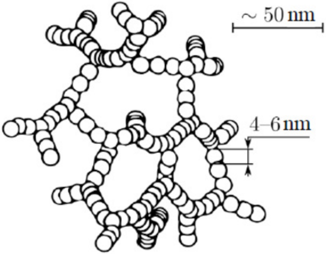
- The ASHIPH technique of Cherenkov light collection was developed in BINP.
- The fully installed ASHIPH system began its operation at the KEDR detector in 2014 and effectively operated at the current time.
- Long-term stability the ASHIPH system are investigated.
- The amplitude in $N_{ph.e.}$ decreased to the current time by 55% over 9 years. The main reasons of the lightout degradation:
  - QE of PMT $\sim$ 35%
  - Aerogel $\sim$ 16%
- The efficiency of the system for particles of different momenta is investigated:
  - Average number of photoelectrons for relativistic cosmic muons that cross both counter layers is 6.33$\pm$0.09 in current time (2023 year)
  - Detection efficiency for muons with ($450 < P_\mu < 1100\ MeV/c$) is 88.23% for threshold on the amplitude equal to 1.0 ph.e.
  - Detection efficiency for under-threshold muons ($130 < P_\mu < 300\ MeV/c$) in the same approach is 10.06%
  - These data correspond to π/K–separation 2.5σ in the momentum range from 0.6 to 1.5 GeV/c.
- A review use of the ASHIPH system for the analysis of physical processes at the KEDR detector is presented.

BACKUP

Aerogel

S.S.Kistler, "Coherent Expanded Aerogels and Jellies“, Nature, 1931,vol. 127, p. 741.

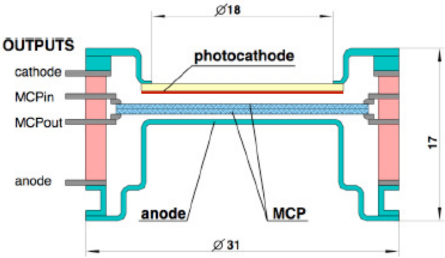


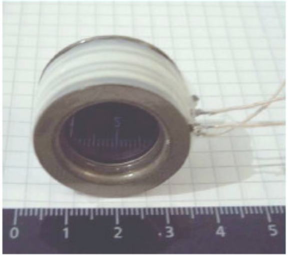


$SiO_2 + H_2O(1\div5\%)$

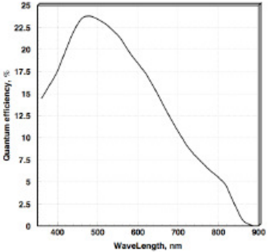
$$n^2 = 1 + 0.438 \cdot \rho$$

n=1.006...1.070 – synthesis
n=1.070...1.130 – sintering





Manufacturer: "Ekran FEP" (Novosibirsk)
Borosilicate glass window
Multialkali (Sb-Na-K-Cs) photocathode
Maximum QE at λ=500nm
Two MCPs with channel diameter of 7 μm
Channel bias angle 13°
Single anode



Operation in the KEDR detector

HV system:

- High voltage source (HVS) – 6 HV converters H40N (EMCO: 4000 V, 3.75 mA, 15 W) in one standard CAMAC 4M module was developed at BINP.
- High voltage module (HVM, PNPI, St. Petersburg) – 10 modules of 16-ch active HV dividers provide tuning of voltage for each counter from 2500 to 4000 V.
- Maximum current per channel ∼100 mkA.

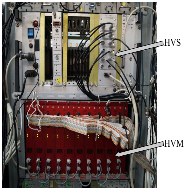
DAQ system:

- The counters are read out by 28 A6 boards.
- A6 board supported in special the KLUKVA standard developed at the BINP.
- A6 has 6 channels with 10-bits flash ADC which makes measurements each 55 ns and save them in a pipe-line register.
- The register is blocked when the detector trigger system generate positive decision.
- Five amplitude values are read out for each channel.

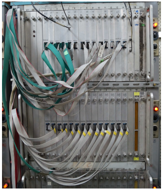
Slow control system:

- The system monitors the dark count rates of the PMTs and provides HV power control.
- In case of emergency each counter is switched off by active HV divider individually.
- Monitoring of the gain stability and the counters efficiency is performed twice per week during calibration runs with LED and cosmic particles.

HV system



KLUKVA standard



1 ph.e. amplitude from DB