Cascade Reconstruction in the Baikal Experiment

Bair Shaybonov

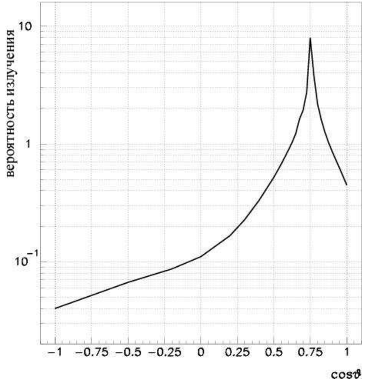
on behalf of the Baikal Collaboration

15.10.2013

Cherenkov Radiation from Cascades

- $N_{tot}^{ch} = BE_0$,
  - $B = 1.04 - 1.16 \times 10^8\, TeV^{-1}$ for EM cascades,
  - $B \simeq 0.86 \times 10^8\, TeV^{-1}$ for hadronic cascades
- $\Psi(\theta, E, x)$:
  - weakly depends on E, x
  - photons are emitted at all angles

$\Psi(\theta)$

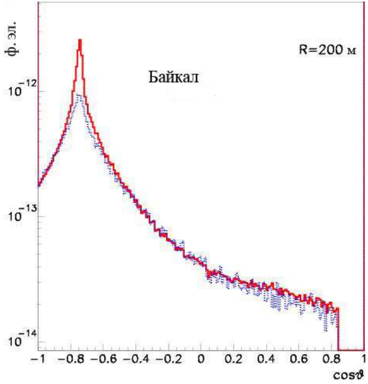


Simulation results:

- Anisotropy of $\Psi(\theta)$ remains up to 200 m in water $\rightarrow$ allows to reconstruct cascade direction by amplitude information

- We have tabulated $\bar{n}_{pe}(\rho, z, \theta, \varphi, \tau)$ in a volume $10^8 m^3$ around cascade taking into account spectral dependence of
  - Light velocity
  - Light Absorption ($L_a = 22$ m at $\lambda = 475$ nm)
  - Light Scattering ($L_s = 30 \div 50$ m and $\cos\bar{\phi} = 0.88$)

$\bar{n}_{p.e.}$ at $R = 200m$ from cascade



Reconstruction Technique

Reconstruction of cascade position

$$\chi_t^2 = \frac{1}{(N_{hit}-4)} \sum_{i=1}^{N_{hit}} \frac{(T_i(\vec{r}_{cas},t_0)-t_i)^2}{\sigma_{ti}^2},$$

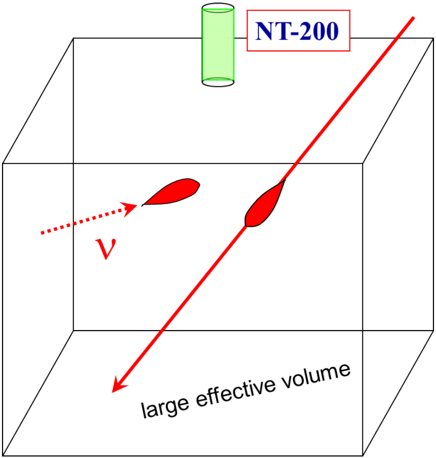
where $T_i(\vec{r}_{cas}, t_0)$ - time of flight of unscattered photons

Reconstruction of cascade direction and energy

$$L_A = -\sum_{i=1}^{N_{hit}} \ln P_i(A_i, E_{cas}, \vec{\Omega}_{cas}(\theta, \varphi)),$$

P_i are calculated from tabulated $\bar{n}_{pe}(\rho, z, \theta, \varphi, \tau)$ and $\vec{r}_{cas}$

Search Strategy



NT200:

- 192 OM at 8 strings
- 72 m height, 42 m diameter
- 1100 m depth, 200 m above lake bed
- 15 inch Quasar PMT
- Pair of OMs are switched in local coincidence

- 100 TeV cascades are seen up to 100 m from the detector
- Search cascades in the external water volume
- Need to reject huge background from atm μ

Experimental Test of the Reconstruction Technique

Light Source

- Nearly Isotropical light source
- 147 m far from the center of NT-200

Reconstruction Accuracy

- $\delta R/R \approx 8\%$
- $\delta \lg I \approx 30\%$

Background Rejection

First cuts to reject atm μ

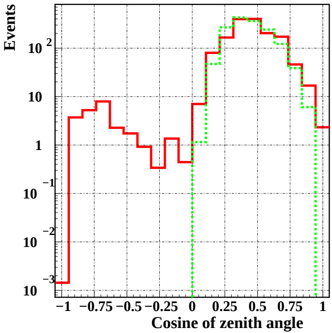
- $N_{hit} > 15$
- $t_{min} = min(t_i - t_j) > -10$ ns, where i-th OMs is higher than j-th at the same string
  - rejects events with downward moving light front

Survival events:

- Reject atm μ by a factor of 10^3
- Only nearly horizontal muons generated cascades pass these criteria
- 82% (94%) of triggered OMs have time (amplitude) response from cascade

Cascade Reconstruction

- Reconstruct cascade position by χ_t^2 minimization
  - if time residual on OM is > 15 ns it is excluded and minimization repeats
- Reconstruct cascade energy and direction by L_A minimization



Quality cuts

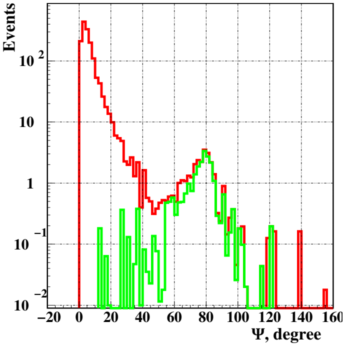
- $N_{hit}^t > 18$
- $\chi_t^2 < 3$
- $L_A < 20$
- $\xi_{rec} < \xi_{max}$, where
  - ξ_{rec} - likelihood of hit OMs to be hit and unhit OMs to be unhit,
  - ξ_{max} - maximal likelihood of 100 simulated cascades
- 3 bottom layers of OMs were removed from the analysis

Cascade Reconstruction

- Reconstruct cascade position by χ_t^2 minimization
  - if time residual on OM is > 15 ns it is excluded and minimization repeats
- Reconstruct cascade energy and direction by L_A minimization

Quality cuts

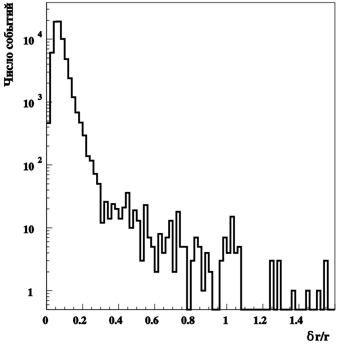
- $N_{hit}^t > 18$
- $\chi_t^2 < 3$
- $L_A < 20$
- $\xi_{rec} < \xi_{max}$, where
  - ξ_{rec} - likelihood of hit OMs to be hit and unhit OMs to be unhit,
  - ξ_{max} - maximal likelihood of 100 simulated cascades
- 3 bottom layers of OMs were removed from the analysis



Reconstruction Accuracy

- $\delta r \approx 7\%$
- $\delta \lg E \approx 20\%$ $(\delta E \approx 60\%)$
- $\psi_{med} = 4.5^\circ, \bar{\psi} = 6.2^\circ$

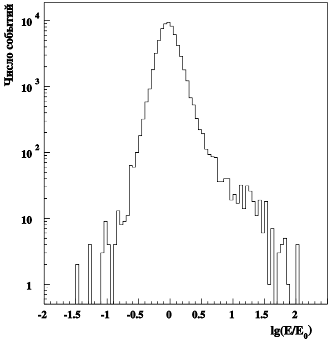
Relative position error



Reconstruction Accuracy

- $\delta r \approx 7\%$
- $\delta \lg E \approx 20\%$ $(\delta E \approx 60\%)$
- $\psi_{med} = 4.5^\circ, \bar{\psi} = 6.2^\circ$

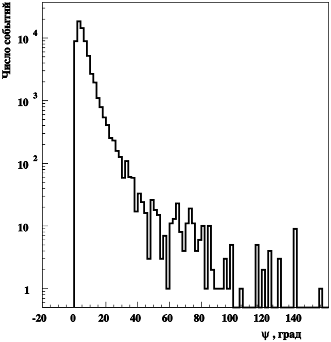
Energy error



Reconstruction Accuracy

- $\delta r \approx 7\%$
- $\delta \lg E \approx 20\%$ $(\delta E \approx 60\%)$
- $\psi_{med} = 4.5^\circ, \bar{\psi} = 6.2^\circ$

Anglular error



Experimental Data

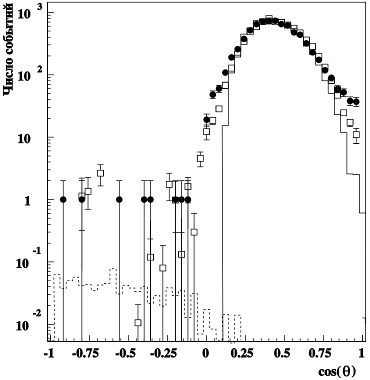
1038 days (April 1998 to February 2003) of data were analyzed

Statistics:

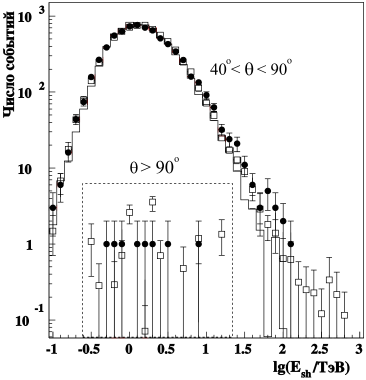
- 18384 events ($N_{hit} > 15$ и $tmin > -10$ нс)
- $\simeq$ 9300 events ($N_{hit} > 18$, $tmin > -10$ нс, $\xi_{rec} < \xi_{max}$, $\chi_t^2 < 3$, $L_A < 20$, 3 bottom layers of OMs were removed from the analysis)

Final Cuts

Zenith angle distribution



Energy distribution



Additional cuts for ν events separation:

$E > 130$ TeV $(40^\circ < \theta < 90^\circ)$ и $E > 10$ TeV $(\theta > 90^\circ)$

Results

- Average number of ν events N_{mod} from some astrophysical models

Model	$N_{mod}(\nu_{e,\mu,\tau})$	$\Delta E_{90\%}$, PeV	$n_{90\%}/N_{mod}$
S05	0.7	$0.10 \div 30$	3.4
P $p\gamma$	4.4	$0.30 \div 100$	0.5
M $pp + p\gamma$	1.7	$0.02 \div 500$	1.4
MPR	1.4	$0.10 \div 100$	1.8
SeSi	2.4	$1.00 \div 50$	1.0

- Upper limit on E^{-2} diffuse ν flux of all flavors ($\nu_e : \nu_\mu : \nu_\tau = 1:1:1$):

$$\Phi_\nu E^2 < 2.9 \times 10^{-7} \mathrm{cm}^{-2} \mathrm{s}^{-1} \mathrm{ster}^{-1} \mathrm{GeV}$$