Acoustic Method of Particle Detection and its Applications for Geophysics Studies by Means of a Neutrino Beam

Homage to Boris Analtol'evich Dolgoshein (1930-2010)

- The Thermo-Acoustic Mechanism
  - Basis Theory
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Alexander Borissov, Wayne State University, Bari, 14.09.2011
The Thermoacoustic Excitation Mechanism

- Instantaneous deposition of heat through ionization: \( t_{\text{deposition}} \approx \sigma/c \approx 10^{-7} \div 10^{-8} \) s
  \( \sigma \) - size of the region of energy deposition.

- Energy deposition → thermal expansion:
  \( \Delta V/V = \alpha \Delta T = \alpha \frac{\epsilon}{\rho C} \),
  \( \alpha \) - thermal expansion coefficient, \( \rho \) - density, \( C \) - heat capacity of the medium.

- Pressure pulse:
  \( p = K \frac{\Delta V}{V} = \frac{K \alpha}{\rho C} \epsilon = \Gamma \epsilon \),
  \( K \) - bulk modulus, \( \Gamma = K \alpha/\rho C \) - Grüneisen coefficient of the medium.

- Bipolar pulse due to spherical expansion of point like energy deposition:
  \( p(r, t) \propto \frac{\epsilon_0 \alpha v_l^2}{C} \frac{d}{dt} \frac{\delta(t-t/v_l)}{r} \),
  \( v_l \) - velocity of longitudinal acoustic wave, and \( r \) - distance. Note that \( t_{\text{expansion}} \propto \sigma/v_l \gg t_{\text{deposition}} \).

- Wavefront from shower/beam heating a volume of matter as a sum of point-like sources:
  \( p(r, t) \propto \frac{\alpha v_l^2}{C} \frac{d}{dt} \int \frac{1}{r} \epsilon dV \)

- Wave peak wavelength and frequency:
  \( \lambda \approx 2\sigma, f = v_l/2\sigma \)

(G.A. Askaryan, Atomnaya Energia 3, 152, 1957.)
Production of Acoustic Signal from $\nu$ Cascade

- In water or ice, for $E_\nu = 10^{20}$ ev, 95% of the cascade energy is contained within a cylinder of length 20 m and radius 20 cm.
- The energy deposition can be considered as a continuous distribution of individual heating centers.
- Radiation is emitted coherently along the cascade axis leading to a confinement of the signal to narrow pancake due to a superposition of waves.
- Sound waves $\sim$ tens kHz.
- Attenuation length $\sim$ 10 km.

Test-Beam Experiments

Brookhaven NL (Harvard, SLAC) 1979

200 MeV proton beam (LINAC)
Spill time 3 to 20 us
Beam diameter 4.5 cm
Energy deposited in water $10^{19} \rightarrow 10^{21}$ eV
Bipolar pulses observed
Dependency on $C_p$, $T$ and on beam diameter confirmed (about 10% uncertainty)

Recent measurements (2000’s)

Uppsala: 177 MeV $p$
$E = 10^{16} - 10^{17.5}$ eV
Bipolar pulse observed
Unclear dependence on temperature
Other contribution to observed pulses?

ITEP Synchrotron: 100, 200 MeV $p$
$E = 10^{15} - 10^{20}$ eV
Measured pressure increases linearly with $E$

Erlangen Laser Nd-YaG
$E = 10^{17} - 10^{19}$ eV
Dependence on $C_p$ confirmed
ITEP antenna / surface EAS array

Sensitivity -135 dB re V/μPa

Events sample dominated by surface Background

Therhalbedral antenna / NT200+

Deployed at 100m
Noise studies
Event search

Bipolar pulse on 4 hydrophones

Angular distribution of bipolar pulses for 2 months data acquisition

(G.Riccobene, Neutrino 2008)
South-Pole-Acoustic-Test-Setup in IceCube

Measure ice properties:
attenuation length, wave refraction, noise

3 strings in IceCube holes 72, 78 47
7 stages per string
stage = 1 transmitter + 1 sensor

surface digitization (200 / 400 kHz)
GPS phased array

String-D
100 m longer

Improved glaciophones
Improved transmitters

New HADES glaciophone

Pinger tests:
movable transmitter used in 6 holes (water filled)

AAL to measure sound velocity (Aachen)

(G.Riccobene, Neutrino 2008)
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(R.Nahnhauer, DESY, www-zeuthen.desy.de/arena)
Possibility of Muon Acoustic Calorimetry

- Sound signal from electromagnetic showers simulated in dense medium (iron and tungsten) by GEANT. Approach is somehow analogous to neutrino hadron cascades in water or ice.
- Showers were originated from muon energy losses ($B_2$ term) in dense medium by means of $e^+e^-$ pair production and bremsstrahlung photons.
- Muon energy loss: $\frac{dE_\mu}{dz} = B_1(1 + B_2E_\mu)$, where $B_1 = 0.424\rho Z/A$, GeV/m and $B_2 = 1.25 \cdot 10^{-4}Z$, $1/\text{GeV}$.
- Signal/noise ratio was calculated as function of $E_\mu$. Thermal noise estimate: $N = \sqrt{2kT\Delta F\rho v_l/S_{det}}$.
- $\frac{\delta E_\mu}{E_\mu} \sim 0.3$
  at $S/N = 1$, $E_\mu = 1 \div 10 T\text{eV}$, $E_{\text{thresh}} = 1 \div 20$ GeV in 2000 $X_0$ of W.
  Could be continued...

Possibility of Neutrino Exploration of the Earth

(1): “Neutrino Exploration of the Earth”, A. De Rujula, S.L. Glashow, R.R. Wilson, G. Charpak, Physics Reports (Review Section of Physics Letters) 99, No 6 (1983) 341-396.: “...how the neutrinos produced by a multi-TeV proton synchrotron may be used for purposes of geological research. Project GENIUS (geological exploration by neutrino-induced underground sound) is designed to search for deposits of oil and gas at large distances from the accelerator. It depends upon the coherent sound signal produced at depth by millions of neutrino interactions along the underground neutrino beam.”

For the development of GEMINI and GEOSCAN projects see talk of A.Vaniachine.

Dedicated grants were started by B.A.Dolgoshein in MEPFI in 1983, main results published:

- A.B.Borissov “Methods of Utilization of High Energy Neutrino Beams in Geology and Geophysics” Ph.D. Thesis, Moscow Physical Engineering Institute, 1988, adviser Prof. B.A.Dolgoshein, it was used for grant reports.
Estimates for Neutrino Beam from Proton Accelerator

From (1) and dedicated grants:

- Number of protons per cycle: \( N_p = 10^{15}(E_p/10 TeV) \), \( E_p \) - energy of protons
- Cycle of accelerator: \( T = 1 \text{ min}(E_p/10 TeV) \)
- Length of neutrino decay channel: \( l_{dc} = 7.5 km(E_p/10 TeV) \)
- For grants, \( \nu \) spectra have been simulated, \( E_{\nu}^{\max} = 0.43(0.95)E_{\pi(K)} \)
- Estimated in (1) mean energy of neutrino beam: \( E_{\nu} \approx E_p/18 \)
- Cross section of neutrino interaction: \( \sigma^{\nu_{tot}} = 0.5(\sigma^{\nu_{n}} + \sigma^{\nu_{p}}) = 0.84 \cdot 10^{-38} cm^2/GeV \cdot E_{\nu} \)
- Range of neutrino: \( R_{\nu} = 1/N_A \rho \sigma^{\nu_{tot}} = 2. \cdot 10^9 km/(\rho/1g/cm^3)(E_{\nu}/1GeV) \)
- Energy deposition of the beam: \( dW/dz = W_i(\rho/1g/cm^3)(E_p/10 TeV)^3, W_{\pi,K} = 60, 170 \text{ erg/cm} \)
- Transverse size of the region of energy deposition: \( \sigma = \sigma_i(L/1000 km)(10 TeV/E_p), \sigma_{\pi,K,charm} = 22, 56, 200 \text{ m}, L - \text{ distance from accelerator} \)
Generation of Sound by Neutrino Beam

From dedicated grants:

- Amplitude of acoustic signal: \( P(\text{din/cm}^2) = |P_{\text{max}} - P_{\text{min}}| \)
  \[ = 2.2 \cdot 10^{-6} \cdot A \cdot (\rho/1g/cm^3)(E_p/10TeV)^{4.5} \cdot (1000km/L) \cdot (1km/R)^{0.5}, \]
  \( R \) - depth of \( \nu \)-beam
- Mean frequency: \( f(\text{Hz}) = 1.5v_l/2\pi\sigma = 12.4(v_l/1km/s)(1000km/L)(E_p/10TeV) \)
- Seismic noise was estimated from (1).
- \( S/N = 2.4 \cdot 10^{-4}A(1km/s/v_l)(E_p/10TeV)^{5.2}(1000km/L)^{2.2} \cdot (1km/R)^{0.5} \approx 10^{-5} \)
  for \( E_p = 10TeV, \ R = 1 \text{ km}, \ L = 1000 \text{ km} \)
- Accumulation of signal/noise: \( S_{\text{acc}}/N = S/N \sqrt{n_{\text{pulses}}N_{\text{det}}} \)
For grants, after consultations with geologists, acoustic signals have been calculated in different rocks with real parameters.

- Sound attenuation length of oil collector or oil is more than 10 times smaller than for oil-free standard rocks.
- Vertical profile of density of oil deposit has a certain structure, but in average, density of deposit is smaller than the density of standard rock.

$\Rightarrow$ Expected acoustic signal from neutrino beam passing oil-reached geological layers (or below them) is expected to be more than 10 times smaller relative to signal from neighboring layers.
Reasons:

- Monitoring of muon (and neutrino) beam by a new remote method. Acoustic signals have been measured in steel stack of muon filter (Zh.Eksp.Teor.Fiz) and hanged up steel rod (l=274 cm, d=4.5 cm), to reduce seismic noise (preprint IHEP 92-66).

- Signals from U-70 $\mu$-beam simulate ones from $\nu$-beam of multi-TeV accelerators, e.g., the UNK. Planned at UNK neutrino beam was directed on lake Baikal.

- Method of detecting of ultraweak signals from $\nu$-beam would naturally begin with large energy evolution. Proposals for grants were submitted in 1992, 1993.

- Study of effects of the excitation and propagation of waves induced by a $\mu$-beam.
Acoustic Signal from Muon Beam of U-70

- Agreement of calculated signal ($v_{l}^{\text{tab}} = 5.8 \text{ km/s}$, $\Gamma = 0.1$) with measured (left plots) supports the thermoacoustic excitation as the predominant mechanism for iron.
- Observed bipolar pulse corresponds in shape to calculated in (1) pulse from $\nu$ beam (top-right).
- Linear dependence of measured signal with intensity of muon (neutrino) beam (bottom-right) supports continuous distribution of energy deposition.
- Measured from the fronts of acoustic signals velocity of longitudinal acoustic wave ($v_{l} = 5.7 \text{ km/s}$) is in agreement with tabulated values ($v_{l}^{\text{tab}} = 5.8 \div 6.1 \text{ km/s}$).

a,b - signals from top and bottom acoustic transducers on the steel rod. 1 - data, 2,3 - calculations without/with accounting of amplification.

Dependence of amplitude of signal from the intensity of muon beam.
Possibility of Forecast of Earthquakes

- Variation of $v_l/v_t$ in the region of earthquake occurs shortly before the earthquake. Velocity of transverse wave ($v_t$) is almost the same. (D.Rais “Mechanics of Earthquake” 1983; M.A.Sadovski “Deformation of geophysical medium and seismic process”, Moscow, Science 1987, in Russian).

- Maximum variation of $v_l/v_t$ is proportional to the magnitude of the earthquake. The struck occurs after $\sim 10\%$ of the time of the variation period. (T. Rikitake “Earthquake Prediction Reserarch”, 1985; Geophysical conditions in the regions of strong earthquakes, Moscow, Science 1983, in Russian).

- It is hard to analyze waves from the explosions on the surface due to many reflections (K. Kasahara “Earthquake Mechanics”, 1985).

\[ \Rightarrow \] Usage of neutrino beam as an underground source of longitudinal acoustic waves allows to:

- determine $v_l$ in the region of earthquake by means of the registration of the time of signal,
- apply already existing systems for measurement of seismic noise,
- use stable decay channel for observation of time dependence of the variation of $v_l$.

Summary: Timelines

B.A. Dolgoshein ("Possibility of acoustic detection of neutrinos in the ocean", 1981, Sov.Phys. Usp. 24, 244.):

- 1957  "...It is possible to detect ionizing radiations in water by using an acoustic signal."
  (G.A. Askaryan, Atomnaya Energia 3, 152 (1957).)

- 1976  "The most interesting application of this technique is in detection of hadron cascades triggered by high-energy cosmic neutrinos deep in the ocean"
  (G.A. Askaryan and B.A. Dolgoshein FIAN SSSR Priprint 160, Moscow, 1976.)

- 1979  "Accelerator-beam experiments sound-radiation mechanism appears to rest largely on thermal expansion of the water."  (L. Sulak et al, Nucl. Instr. and Methods 161, 203 (1979).)

- 1981  "Possible to consider the possibility of building a neutrino telescope with an angular accuracy of \( \sim 1^{\circ} \). Using this technique in the neutrino astronomy of superhigh energies (\( \leq 10^{15} \) to \( 10^{16} \) eV) requires the development of \( \sim 10^{11} \) tons (10 km \( \times \) 10 km \( \times \) 1 km) of ocean water."


- 1983 ÷ 1993 Studies of neutrino usage for geology and geophysics, acoustic signals from muon beam on U-70.  (B.A.Dolgoshein et.al. papers)


- 2010 LHC is operational with 3.5 TeV proton beam.
• Experiment OPERA (Oscillation Project with Emulsion-tRacking Apparatus) to test of the phenomenon of neutrino oscillations: $\nu_\mu \rightarrow \nu_\tau$. (http://operaweb.lngs.infn.it/, and http://en.wikipedia.org/wiki/OPERA_project)

• Intense and energetic beam of muon neutrinos travels 732 km kilometers. A beam is generated by collisions of accelerated protons with a graphite target after focusing pions and kaons in the desired direction.

• The facility CNGS (CERN Neutrinos to Gran Sasso) has been built at CERN between 2000 and 2005 and it started operation in summer 2006.

• OPERA is collecting data since 2008.

⇒ It looks like a prerequisites to study ultraweak acoustic signals from the neutrino/muon beam at CERN...
The 6.3-magnitude quake struck at 0330 (0130 GMT) very close to L’Aquila and Gran Sasso.

About 100 people were dead, about 1,500 people were injured.

Altogether, 26 cities and towns have been damaged. In L’Aquila, 95km (60 miles) north-east of Rome, about 10,000 buildings have been damaged.