

High-energy neutrinos

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Abstract

In the last decades, the interest in neutrinos raised strongly, not only because of the solution of the solar neutrino problem. This report is concerning high-energy neutrinos, this means neutrinos with energies $E_\nu > 100$ MeV. The new possibilities in detecting neutrinos in huge detector arrays, opened a completely new section of astrophysics and a new possibility of getting a better understanding of the Universe. The main part will be about possible galactic and extragalactic sources of high-energy neutrinos, followed by a small section about neutrino detection. To give a wide overview, there are also some sources included, which cannot describe the high-energy part of the neutrino spectrum.

1 Introduction

This report concerns high-energy neutrinos, high energy means in this case neutrino energies of $E_\nu > 100$ MeV. One of the main interest in researching high-energy neutrinos is to learn more about energetic astrophysical sources like binary stars and black holes in Active Galactic Nuclei (AGN). The first part discusses shortly atmospheric neutrinos (sec. 2.1) as main source of the discovered neutrinos. The atmospheric neutrinos build the background radiation in neutrino experiments, but on the other hand, they also can be used for calibration. The detection of neutrinos started in 1960. In this year, Greisen described a detector much like the present water-Čerenkov detectors (sec. 3). In the same year, the first atmospheric neutrinos have been detected by the two groups Kolar Gold Fields and Case-Wittwatersrand by detection of neutrino-induced muons:

$$\nu_\mu + N \rightarrow \mu + \text{anything.}$$

The next parts will be about different possible sources of high-energy neutrinos, as there are neutrino sources in the galactic plane (sec. 2.3), solar neutrinos (sec. 2.2), neutrinos from supernovas (sec. 2.4), other sources (sec. 2.5), and cosmological neutrinos (sec. 2.6). A last part describes a few important detection methods (sec. 3).

2 Neutrino production

2.1 Atmospheric neutrinos

Atmospheric neutrinos are produced from the decay of mesons and muons. These are produced by the interaction of cosmic-rays, especially protons (84 % of primary cosmic-rays) with the atmosphere ($p \rightarrow \pi^\pm \rightarrow \mu^\pm$):

$$\begin{aligned}\pi^+ &\rightarrow \mu^+ \nu_\mu, & \mu^+ &\rightarrow e^+ \nu_e \bar{\nu}_\mu, \\ \pi^- &\rightarrow \mu^- \bar{\nu}_\mu, & \mu^- &\rightarrow e^- \bar{\nu}_e \nu_\mu.\end{aligned}$$

For higher energies the kaon decays become more important, especially:

$$\begin{aligned}K^\pm &\rightarrow \mu^\pm \nu_\mu (\bar{\nu}_\mu), \\ K_L^0 &\rightarrow \pi^\pm e^\pm \nu_e (\bar{\nu}_e).\end{aligned}$$

From the upper equations one can follow, that the neutrinos are produced in following ratio for a given energy range:

$$\frac{\nu_e + \bar{\nu}_e}{\nu_\mu + \bar{\nu}_\mu} \approx \frac{1}{2}.$$

The calculation of the neutrino flux has to be done in three steps, (1) the primary cosmic-ray flux, (2) interaction with air, and (3) decay of mesons and muons in the atmosphere.

1. The flux in the atmosphere is dependent on the strength of the geomagnetic field, which causes a cutoff of low-energy rays and there is also a dependence on solar activity, due to solar winds. However, in the simplest way, it is given by the power law:

$$\Phi_\nu \sim E^{-\gamma}$$

with $\gamma \approx 2.7$ for energies up to 100 GeV and $\gamma \approx 3.7$ for higher energies.

2. The flux of cosmic ray particles can be expressed with some simplifications as follows [3]:

$$\frac{\partial I_i(E, x, \theta)}{\partial x} = -\mu_i(E)I_i(E, x, \theta) - \frac{m_i}{E\tau_i\rho(x)}I_i(E, x, \theta) + \sum_j \int dE' d\theta' \mu_j(E')S_{ji}(E', \theta', E, \theta)I_j(E', x, \theta'),$$

where I_i is the flux of cosmic rays particle i =nucleus, p, π , μ , etc., at the position x , with zenith angle θ and energy E ; m_i and τ_i are mass and decay lifetime; μ_i is the absorption coefficient of particle i ; ρ is the density of the atmosphere (in a first approximation $\rho(h) = \rho_0 \exp(-h/h_0)$); and S_{ji} is the probability of particle production $j \rightarrow i$. The first term represents a loss of flux by absorption (interactions), the second term is the loss by decay, and the third term is the production of the particle considered.

3. At last, the neutrino flux can be calculated from the second term in the equation above after solving the differential equation.

2.2 Solar neutrinos

As seen in the solar neutrino spectrum even the most energetic solar neutrinos produced in the hep-reaction (${}^3\text{He} + p \rightarrow {}^4\text{He} + e^+ + \nu_e$) do not reach energies much larger than 15 MeV and so as high-energy neutrinos are defined as neutrinos with energies $E_\nu > 100$ MeV, i.e., solar neutrinos are no source of high-energy neutrinos.

2.3 Neutrinos from the galactic plane

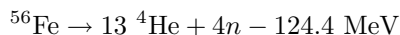
The existence of high-energy cosmic rays guarantees the existence of high-energy neutrinos, too. Because of the interaction of cosmic rays with the interstellar gas, there are neutrinos as pion decay products. So point sources can be found by observation of the cosmic ray or neutrino flux. In a first approximation, we can assume a constant cosmic ray density in the galaxy. Under this assumption, the flux at Earth of photons/neutrinos generated by pions produced in interaction with an object of matter density ρ and linear dimension R is given by [1]

$$\Phi_{\gamma(\nu)} = \Phi_{\text{CR}} f_A \left(\frac{\sigma_{\text{inel}}}{m_N} \right) (\rho R) \frac{2Z_{N\pi^0}}{\gamma + 1},$$

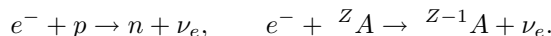
where $\Phi_{\text{CR}} \approx 1.8E^{-2.7} \text{ cm}^{-2}\text{sr}^{-1}\text{s}^{-1}\text{GeV}^{-1}$ is the cosmic ray intensity, including the energy power law for energies up to 100 GeV, σ_{inel} is the total inelastic pp cross section, m_N is the nucleon mass, $Z_{N\pi^0} = \frac{1}{\sigma} \int dx x^\gamma \frac{d\sigma}{dx}$ is the spectrum-weighted moment for production of pions (here $\gamma = 2.7$) and $f_A \approx 1.22$ is a correction factor (See fig.1).

2.4 Neutrino emission in supernova explosions

Neutrinos are also produced in type II supernova (SN II). This type occurs for massive stars ($M \approx 8M_\odot$). These stars can burn Silicon to Iron in a last phase. When the Iron core exceeds the Chandrasekhar mass ($M_{Ch} \approx 1.4M_\odot$ with the number of electrons per nucleon $Y_e \approx 0.4$), the gravitational collapse starts. The collapse is caused by the photo-disintegration:



and electron capture:



Such stars which undergo an SN II remain as neutron stars or black holes. In the case of a neutron star, the energy released is:

$$\Delta E = \left(-G \frac{M^2}{R} \right)_{\text{GS core}} - \left(-G \frac{M^2}{R} \right)_{\text{NS}},$$

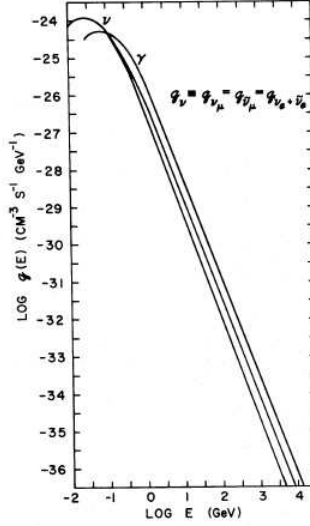


Figure 1: *Production spectra of photons and neutrinos produced by pion decay in interaction of cosmic rays in our galactic neighborhood with spectral index $\gamma = 2.67$, for the lower neutrino curve $\gamma = 2.75$ [5].*

where GS stands for giant star and NS for neutron star, the energy difference can be counted numerically to be [3]

$$\Delta E = 2.7 \cdot 10^{53} \text{erg} \left(\frac{M}{M_{\odot}} \right)^2 \left(\frac{R}{10 \text{ km}} \right)^{-1}.$$

The amount of energy spend for photo-disintegration is in the size of $1.4M_{\odot} \cdot 6 \cdot 10^{23} \cdot 3.2 \text{ MeV} \approx 6 \cdot 10^{51} \text{ erg}$, for the kinetic energy of an explosion in the order of $E_{\text{kin}} = \frac{1}{2} M_{\text{ej}} v^2 \approx 1 \cdot 10^{51} \text{ erg}$, with the ejecta mass of $M_{\text{ej}} \approx 10M_{\odot}$ and $v \approx 2000 \text{ kms}^{-1}$, the optical energy is much smaller, the amount taken away by gravitational waves is less than $2 \cdot 10^{51} \text{ erg}$, and so remain about 99 % of the energy loss for neutrino emission, as the most dominant part. One can calculate the average neutrino energy ϵ_{ν} out of the effective temperature T_{eff} . This is given by the radiation law:

$$T_{\text{eff}} = \left(\frac{\Delta E / \tau}{4\pi\sigma R_{\text{eff}}^2} \frac{1}{(7/8)g_{\nu}} \right)^{1/4},$$

where $\sigma = \frac{2\pi^5 k_B^4}{15h^3 c^2} \approx 5.67 \cdot 10^{-8} \text{ Wm}^{-2}\text{K}^{-4}$ is the Stefan-Boltzmann constant, $g_{\nu}/2$ the number of neutrino species, R_{eff} in the order of 10 km, and the cooling time τ in the order of 5-10 s. So $T_{\text{eff}} \approx 3 \text{ MeV}$, and therefore, $\epsilon_{\nu} = 3.15T_{\text{eff}} \approx 10 \text{ MeV}$. After this, it is possible to calculate the total neutrino flux:

$$\Phi_{\nu} = \frac{\Delta E}{\epsilon_{\nu}} \approx 2 \cdot 10^{58}.$$

On 23 February 1987, a supernova of type II called SN1987A occurred in the Large Magellanic Cloud at a distance of about 50 kpc from us. The computed flux on Earth equals:

$$\Phi_{\nu_E} = \frac{1}{4\pi d^2} \Phi_{\nu} \approx 6.4 \cdot 10^{14} \text{ m}^{-2}.$$

The KAMIOKANDE-II collaboration discovered eleven, IMB seven and Baksan in Baikal five neutrino events. The measured number of events, the energy of neutrinos, and the duration of the burst is roughly equal to the expected values. Fig.2 shows all neutrino events produced by SN1987A detected on Earth. The maximal energy in SN1987A is around $E_{\nu} = 40 \text{ MeV}$, this is only one order of magnitude below the high-energy level. So supernova explosions of more massive stars can be a possible source of high-energy neutrinos.

2.5 Possible other galactic neutrino sources

The mechanisms of high-energy neutrino production can be separated in two major parts: acceleration processes and annihilation processes. As seen in sec. 2.1, neutrinos can be produced in proton-decays and as protons build the major part of the primary cosmic-ray, it is important to study the proton acceleration.

Possible accelerating point sources are:

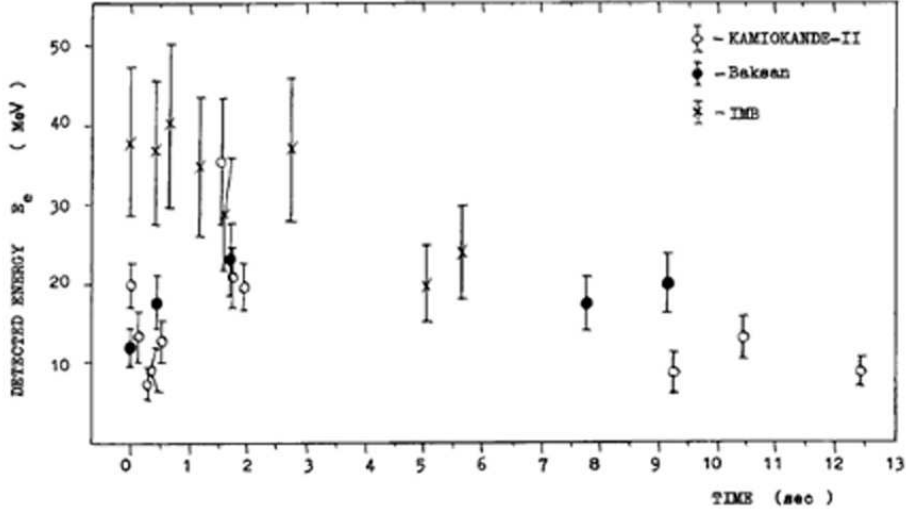


Figure 2: *Energie of all detected neutrino events at 7.35 UT on 23 February 1987. The time of the first event in each detector is set to $t = 0$ [6].*

- Young supernova remnants: In the inner acceleration, protons can be accelerated in the occurring rotating magnetic fields in the expanding shell in a supernova, especially in heavy stars, that remain as neutron stars or black holes; as a second effect an external acceleration is possible by reflection on two shock fronts running towards each other.
- Binary systems: In a system of, for example, a neutron star and a red giant, the neutron star attracts mass from the second star, which forms an accretion disc. Because of the strong magnetic field of the neutron star, strong electro-magnetic fields are produced in the disc.
- Active galactic nuclei (AGN): Around a black hole thick accretion discs exist. The matter flowing to the center is strongly accelerated and therefore transformed in a hot, electrically conducting plasma, that causes strong magnetic fields. One part of the attracted matter is absorbed by the black hole, but the other part is deflected by the magnetic field, forming two plasma jets perpendicular to the accretion disc, in which protons can be accelerated to very-high energies up till 100 PeV.
- Gamma-ray bursters (GRBs): GRBs have become one of the best motivated high-energy neutrino sources. But still the inertial mechanism of GRBs is not understood completely. The phenomenon consists of three parts. Possible candidates as central engine of GRBs are the merge of two neutron stars, a neutron star and a black hole, or two black holes. The second part is a relativistic expansion of the fireball, where masses in Earth size are accelerated to 99.9 % of the speed of light. Third there must be a conversion of kinetic energy by internal shocks in internal energy, which is then radiated as γ rays by synchrotron and inverse-Compton radiation of shock-accelerated electrons [7].

The most evident sources for neutrino production in annihilation processes are evaporating black holes and annihilation or decay of heavy particles, namely neutralinos χ .

2.6 Cosmological neutrinos

The existence of the cosmic microwave background radiation suggests the existence of a cosmic neutrino background. In the early Universe at temperatures higher than 1 MeV, neutrinos, photons, and electrons were in thermal equilibrium ($e^+e^- \leftrightarrow \gamma\gamma$ and $e^+e^- \leftrightarrow \nu\bar{\nu}$).

The entropy for relativistic particles is given by [4]

$$S = \frac{4}{3}k_B \frac{R^3}{T} \rho$$

after the Stefan-Boltzmann law is the energy density $\rho \sim T^4$, and therefore, we find that

$$S = (Ta)^3 = \text{constant}.$$

Furthermore, the energy density obeys the following condition:

$$\rho = \frac{g}{(2\pi)^3} \int E(\mathbf{p})f(\mathbf{p})d^3p,$$

where $E^2 = |\mathbf{p}|^2 + m^2$, g is the number of internal degrees of freedom, the space partition function $f(\mathbf{p})$ is given by Fermi-Dirac (+) or Bose-Einstein (-) statistics:

$$f(\mathbf{p}) = [\exp((E - \mu)/kT) \pm 1]^{-1}.$$

For thermal equilibrium, the chemical potential μ , since the contribution of non-relativistic ($m \ll T$) is much smaller than for relativistic ones, this part can be neglected and so the result for the energy density in the radiation-dominated phase of cosmology can be computed to:

$$\rho_R = \frac{\pi^2}{30} g_{\text{eff}} T^4,$$

where the number g_{eff} of effective degrees of freedom is given by:

$$g_{\text{eff}} = \sum_{i=\text{bosons}} g_i \left(\frac{T_i}{T}\right)^4 + \frac{7}{8} \sum_{i=\text{fermions}} g_i \left(\frac{T_i}{T}\right)^4.$$

From this relations follows that

$$\rho_{\nu_i} = \frac{7}{16} \rho_\gamma.$$

Next, using the number of the degrees of freedom and entropy conservation, it follows that

$$(T_\gamma a)_B^3 (1 + 2 \cdot \frac{7}{8}) + (T_\nu a)_B^3 \sum_{i=1}^6 \rho_{\nu_i} = (T_\gamma a)_A^3 + (T_\nu a)_A^3 \sum_{i=1}^6 \rho_{\nu_i},$$

where B stands for before ($kT > m_e c^2$) and A for after ($kT < m_e c^2$). Since the neutrinos had already decoupled, their temperature developed proportional to a^{-1} , and therefore, the last terms on both sides can be canceled

$$\frac{11}{4} (T_\gamma a)_B^3 = (T_\gamma a)_A^3.$$

Since $T_\gamma = T_\nu$ before the annihilation phase of the electron-positron pairs (at temperatures below $kT < 1$ MeV, $\gamma\gamma \rightarrow e^+e^-$ becomes depressed because of the Boltzmann factor, after that the photons reheat, because of the annihilation), this relation follows for the temperatures:

$$\left(\frac{T_\gamma}{T_\nu}\right)_B = \left(\frac{11}{4}\right)^{1/3} \approx 1.4$$

and so the temperature of the neutrino background can be computed with the knowledge of $T_{\gamma_0} = 2.728$ K to $T_{\nu_0} = 1.95$ K. Furthermore, it is possible to calculate the particle density, the energy density, and the average energy:

$$n_{\nu_0} = 336 \text{ cm}^{-3}, \quad \rho_{\nu_0} = 0.178 \text{ eV cm}^{-3}, \quad \langle E_\nu \rangle_0 = 5.28 \cdot 10^{-4} \text{ eV}.$$

So the cosmological neutrino background can be neglected as a possible source of high-energy neutrinos, but not the cosmological microwave background. The photopion cross-section grows very rapidly to its maximum of $540 \mu\text{b}$ for photons with energies corresponding to the microwave background ($\epsilon \simeq 7 \cdot 10^{-4}$ eV) and proton energies around $10^{18} - 10^{21}$ eV. As seen before, AGN and χ -particles (sec. 2.5) are possible sources for these energetic protons.

3 Neutrino detection methods

Because of the small cross-section of neutrinos, is it not possible to observe them directly, therefore most modern detectors for high-energy neutrinos are water Čerenkov-detectors. A huge amount of water is needed because of the small cross-section of the neutrino, so the neutrinos can be detected indirectly by detecting the emission of Čerenkov-light. The basic reactions are:

- $\nu_e + e^- \rightarrow \nu_e + e^-$ elastic scattering (ES)
- $\nu_e + d \rightarrow p + p + e^-$ charged current (CC)
- $\nu_x + d \rightarrow p + n + \nu_x$ neutral current (NC)

To protect the detectors from cosmic rays, they are installed in mines kilometers below the ground or detect only upward-going neutrinos, coming from the opposite site of the Earth. Examples for modern detectors are SUPER-KAMIOKANDE (50000 tons pure water surrounded by 11000 photomultipliers in a mine 1000 m underground, detection-area 740 m^2), NESTOR (10 strings each carrying 90 photomultipliers in the Mediterranean at a depth of 2400 m, detection-area $> 20000 \text{ m}^2$), or ICE CUBE (80 detectorstrings in the ice of the Antarctica, detection-area $\approx 1 \text{ km}^2$).

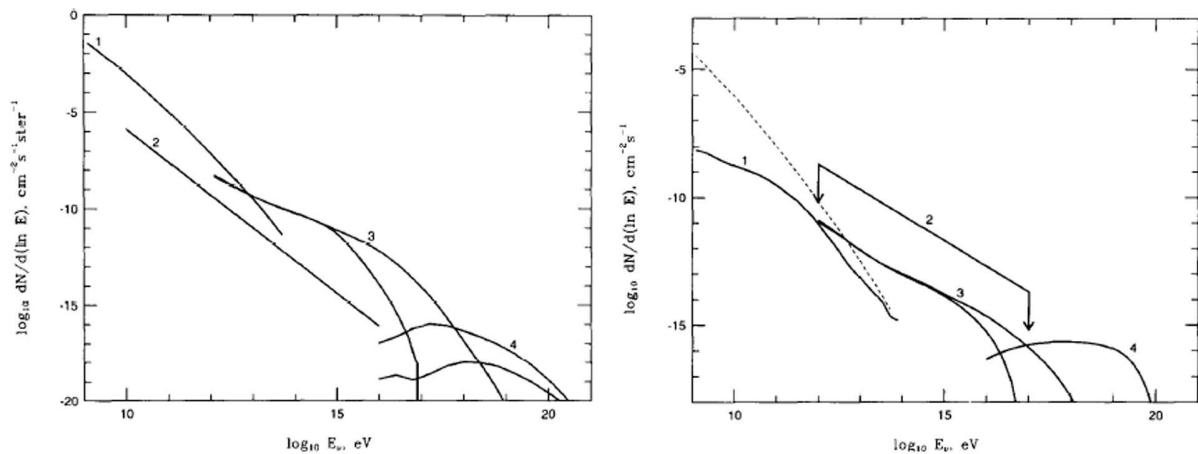


Figure 3: *Left: Summary of isotropic neutrino fluxes of energy above 1 GeV. (1) atmospheric neutrinos; (2) diffuse galactic neutrinos; (3) diffuse extragalactic neutrinos; (4) cosmological neutrinos - maximum and minimum prediction. Right: Summary of source neutrino fluxes of energy above 1 GeV. (1) neutrinos generated by cosmic rays in the Sun; (2) a galactic neutrino source; (3) extragalactic neutrino source; (4) AGN jet emission. The atmospheric neutrino background within 1 is shown with a dashed line [1].*

4 Summary

In fig. 3, the expected fluxes for high-energy neutrinos with energies above 1 GeV are shown. One of the main interests why studying high-energy neutrinos is to detect and analyze supernova explosions, binary stars, AGNs or other objects in the sky which are opaque for photons. Another important field is the search for dark matter, namely the search for neutralinos χ as possible source of high-energy neutrinos. So the problems in detecting neutrinos (they only interact by weak-interaction) is their great advantage, too. They can travel huge distances through the Universe without being affected and so even point sources can be located. The new generation of neutrino detectors opens a completely new field of astrophysics.

References

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