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Particles and the Cosmos – 2019/20
Werkcollege 12
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Problem 24 Atmospheric neutrinos

The Super-Kamiokande experiment measured atmospheric neutrinos, generated through interactions of cosmic rays in the atmosphere.

- How does the Super-Kamiokande experiment detect neutrinos?
- How are neutrinos generated through interactions of cosmic rays in the atmosphere?
- What ratio of ν_μ/ν_e do we expect?
- Super-Kamiokande observed the flux of muon neutrinos as a function of zenith angle. Did they measure the expected ratio of ν_μ/ν_e for upward and downward going neutrinos?

Problem 25 Solar neutrinos

For many decades a deficit in the flux of electron neutrinos has been recorded from the Sun. This is known as the solar neutrino puzzle. The breakthrough has been achieved by the SNO experiment.

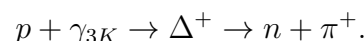
- Describe the detection principle of the SNO experiment.
- How did the SNO experiment solve the solar neutrino puzzle?

Problem 26 Interactions of high-energy cosmic rays with the cosmic microwave background

High-energy cosmic rays (protons) can interact with the photons of the 3 K microwave background. If the protons exceed a minimum energy E_{GZK} , high-energy pions are produced via the interactions



or



This effect has been predicted in 1965 by the physicists Greisen, Zatsepin, and Kuz'min. Hence, the name GZK effect. These interactions take place if the energy of the 3 K photons exceeds $m_\Delta c^2 = 1232$ MeV in the rest frame system of the protons.

- Calculate the threshold energy E_{GZK} for a proton.
Hint: the energy of the photons is given as $\epsilon_\gamma \approx 2.5$ meV.

- Knowing that the density of the 3 K photons is $n_\gamma = 411$ photons/cm³ and the cross section for the above mentioned interactions is $\sigma_{p\gamma} = 300 \mu\text{b}$ (1 b=10⁻²⁴cm²), calculate the mean free path of the protons in units of [Mpc].

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Lecture web site: <http://particle.astro.ru.nl/goto.html?partcos1920>