Dark matter searches with the Super-Kamiokande detector

Katarzyna Frankiewicz for the Super-Kamiokande collaboration
National Centre for Nuclear Research, 00-681 Warsaw, Poland
E-mail: katarzyna.frankiewicz@ncbj.gov.pl

Abstract. A search for dark matter as WIMPs (Weakly Interacting Massive Particles) using neutrino data collected with the Super-Kamiokande detector in years 1996-2014 has been performed. No excess of $\nu$'s from possible dark matter sources such as Sun, Earth and Galactic Center was found compared to the expected atmospheric $\nu$ background. Event samples including both electron and muon $\nu$'s covering a wide range of neutrino energies were used, with sensitivity to WIMP masses down to tens of GeV.

1. Introduction

Dark matter neither emits nor absorbs electromagnetic radiation and therefore cannot be observed directly with telescopes. However, there is a great diversity of ongoing global efforts to detect or produce dark matter particles. Indirect detection experiments focus on the search for the products of WIMP annihilation, e.g. $\nu$'s, among the cosmic rays. Neutrinos can be produced directly or in subsequent decays of mesons and leptons. They provide very good information on their source position and energy spectra generated in WIMP annihilation processes.

Super-Kamiokande (SK) is the 50 kton water Cherenkov detector located in the Kamioka Observatory of the Institute for Cosmic Ray Research, University of Tokyo [1]. The experiment was designed to search for proton decay, study solar, atmospheric and man-made $\nu$'s, and keep watch for supernovae. Detection of neutrino interactions is based on observation of charged particles, which produce Cherenkov radiation while moving faster than $c$ in water. The Cherenkov light projected onto the walls of the detector and recorded by photomultipliers gives information to reconstruct energy, the direction and identity of the particle.

2. Analysis

In the conducted searches it is assumed that atmospheric neutrino data collected with the SK detector could be described by two components: WIMP-induced $\nu$'s (signal) and atmospheric $\nu$'s (background). The best combination of signal and background that would fully explain the data will be searched for using a fit method. Separate Monte Carlo sets are used to simulate signal and background to avoid correlations. The background simulation is available for the atmospheric $\nu$'s in large datasets corresponding to 2000 years of the running of the experiment.

In order to simulate the signal, DarkSUSY [2] and WimpSim [3] are used. The models are prepared for three possible sources (Sun, Earth and Galactic Center), various masses of dark matter particles and different annihilation channels.

There are 18 data samples used in the analyses, including both $\nu_e$-like and $\nu_\mu$-like event...
categories. Each sample is binned in momentum and the cosine of the angle between event
direction and direction of the Sun, Earth or the Galactic Center (depen on considered source).
The signal and background contribution to the analysis bins differs which enables for an effective
discrimination. The signal is largely peaked in the direction of the source, while the background
is not. Additional constraints can be obtained based on neutrino energy information and
proportions of signal/background in various event subsamples. Based on the simulation we
perform a fit to the collected data and estimate how many WIMP-induced $\nu$’s can be contained
in SK data so far.

3. Results

3.1. Solar WIMP search
No significant excess of $\nu$’s from the Sun has been observed. The derived 90% upper limit on
the muon-neutrino flux from dark matter annihilation was converted to upper limits on WIMP-
nucleon cross-section using DarkSUSY [2]. Different types of dark matter interaction with a
nucleus, either an axial vector in which WIMPs couple to the nuclear spin (spin dependent,
SD) or a scalar interaction in which WIMPs couple to the nucleus mass (spin independent, SI)
were considered separately. We assumed a standard dark matter halo with local density 0.3
GeV/cm$^3$ [4], a Maxwellian velocity distribution with an RMS velocity of 270 km/s and a solar
rotation speed of 220 km/s. The results are plotted together with other experimental results in
Fig. 1 for SD coupling and Fig. 2 for SI coupling for the isospin-invariant case. The uncertainties
related to the WIMP capture process are indicated by the shadowed regions (detailed description
can be found in [5]).

Figure 1: 90% CL upper limits on SD WIMP-proton
cross section are shown in red solid with uncertainty bands
to take account uncertainties in the capture rate for the $b\bar{b}$,
$W^+W^-$ and $\tau^+\tau^-$ channels from top to the bottom. Also
limits from other experiments: IceCube (dashed brown),
BAKSAN (dot-dashed pink), PICASSO (long-dashed blue)
and SIMPLE (long dot-dashed blue) are shown. The black
shaded region is the 3$\sigma$ CL signal claimed by DAMA/LIBRA
(see [5] for references).

Figure 2: 90% CL upper limits on the SI WIMP-nucleon
cross section. Also event excesses or annual modulation signals
reported by other experiments: DAMA/LIBRA (black, 3$\sigma$
CL), CoGeNT (magenta, 90% CL), CRESSTII (violet, 2$\sigma$
CL), CDMS II Si (blue, 90% CL), and limits: IceCube (dashed
brown), SuperCDMS (dotted cyan), CDMSlite (long dot-
dashed blue), XENON10 S2-only (dash triple dot dark green),
XENON100 (dash double dot green) and LUX (long-dashed
orange) are shown (see [5] for references).

3.2. Earth WIMP search
For the Earth, the SI interaction dominates in the capturing process. The rate at which dark
matter particles are captured in the Earth depends on their mass. If it almost matches one of
the heavy elements in the Earth, the capture rate will increase considerably (see Fig. 3). The
preliminary results of sensitivity studies are plotted together with other experimental results in
Fig. 4.
3.3. Galactic WIMP search

No significant signal contribution of WIMP-induced $\nu$'s from the Milky Way is allowed by the data in addition to the atmospheric neutrino background. Based on the limit on WIMP-induced diffuse neutrino flux as a function of $M_X$, we can derive 90% CL limits on dark matter self-annihilation cross section $\langle \sigma_A V \rangle$ for each annihilation channel, as shown in Fig. 5. The line at the $\langle \sigma_A V \rangle = 3 \cdot 10^{-26}$ is the expectation for dark matter produced thermally in the Universe's evolution [7].

Acknowledgments

Author wish to acknowledge the Super-Kamiokande collaboration. This work have been supported by the National Science Centre, Poland (2015/17/N/ST2/04064, 2015/18/E/ST200758) and the European Union (H2020 MSCA-RISE-GA641540-SKPLUS) grants.

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