Limits on cold dark matter from the Gotthard Ge experiment

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Data from a high purity Ge detector operated in the Gotthard underground laboratory, corresponding to 51.6 kg day, were used to set limits on cold dark matter. In particular, Dirac neutrinos with masses between 10 and 2400 GeV are ruled out. A new lower limit on the half-life for the decay of the electron into weakly interacting particles of 1.9×10^{23} yr at 68% CL was also derived.

There are several indications, for instance from the dynamics of stars and gas in galaxies, that the universe contains a large amount of dark matter, about 3–10 times more than luminous matter [1]. The theory of galaxy formation favors cold dark matter (CDM), made from heavy, say more than a few GeV, non-relativistic weakly interacting particles. Such particles would be gravitationally bound in galaxies and would form a non-co-rotating halo in which stars would orbit. CDM particles can, with a small probability, hit a nucleus of normal matter and transfer recoil energy to it. As the energies are low, the differential cross-section is generally expected to be isotropic. Although small, say a few keV, the recoil can be measured if the nucleus belongs to the active part of a detector, making direct detection of dark matter possible. Ge detectors, with their relatively large masses and low energy threshold, are ideally suited for CDM searches. The background levels achieved in several experiments give a sensitivity to some viable dark matter candidates, in particular Dirac neutrinos with standard weak coupling, in a given mass range [2,3]. Dirac neutrinos have vector coupling, in which case the nucleus reacts coherently, giving rise to large cross-sections.

We have been operating a 1140 cm^3 high purity Ge detector for three and a half years in the Gotthard underground laboratory to search for double beta decay [4]. More recently we modified the experimental set-up to simultaneously perform a CDM search. The detector consists of an array comprising eight ^{nat}Ge crystals, of which four have a volume of 140 cm^3 and four a volume of 145 cm^3. The eight crystals are housed in a single cryostat made from copper to reduce the natural radioactivity. The cryostat is surrounded by 15–25 cm of copper and 18–20 cm of low activity lead to shield against local radiations. In addition, both detector and shielding are contained in a cover which is continuously flushed with nitrogen to expel radon gas. No veto counter against cosmic rays is necessary as the muon flux is suppressed by a factor of roughly 10^6 due to the 3000 m.w.e. rock overburden. A separate electronic circuit is used in three of the crystals for the low energy events relevant here. The preamplifiers of the crystals are connected to spectroscopy amplifiers, the unipolar outputs of which are going into individual ADC channels, whereas the bipolar outputs are fed into low threshold discriminators to strobe the ADC. Data are read out whenever one of the crystals fires and written, along with the absolute time, event by event on disk.

We have tried various ways of lowering the thresh-

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old of our detector array and of reducing the background in the keV region, where one may expect recoil events. It turns out that although the response of our eight crystals is identical above 10 keV, they behave quite differently below that energy. We thus chose the best crystal for CDM search. Its background is to a large extent due to microphonics resulting from the release of thermal stresses in the cryostat superstructure as the liquid nitrogen in the dewar boils off. Fortunately, these microphonics are not distributed evenly in time, but come in bursts which are particularly frequent after the dewar has been refilled. Between bursts the average count rate above 1.4 keV is 3.5 per minute in all three crystals. We thus first perform a time plot of the count rate, and cut all two-minute periods in which it is above a threshold of 6 counts per minute. Doing so reduces extensively the microphonics at a cost of 25% live time. Since the Poisson distribution allows the random occurrence of counts per bin above our threshold with 5% probability we lower the live time by that amount. Then we reconstruct the spectrum of each crystal using the two other ones in anticoincidence, with a threshold around 2 keV. This further contributes to the reduction of microphonics, without increasing the dead time. The spectrum left after these cuts for our best crystal, the only one we use in the following, is shown in fig. 1. It corresponds to 1662 h of live time (51.6 kg day).

The energy calibration is somewhat delicate since the background lines are too weak to be used. Therefore we had to perform the calibration in two steps. First we determined the offset with a precision pulser connected to the crystal through an attenuator. The offset position is given by extrapolation to infinite attenuation. Second we determined the slope using the lines from a radioactive ^{60}Co source and the ^{137}Cs background line. In order to obtain an accurate calibration we developed an automatic procedure based on peak fitting. The stability was checked systematically by a weekly calibration with the pulser. In all, the energy for a given channel can be determined to within 0.05 keV below 15 keV.

Looking at the spectrum in fig. 1 one can notice that above 1.8 keV the electronic noise is negligible and that the background looks reasonably low and smooth. Our raw spectrum constitutes a significant improvement over those of ref. [2] and even of ref.

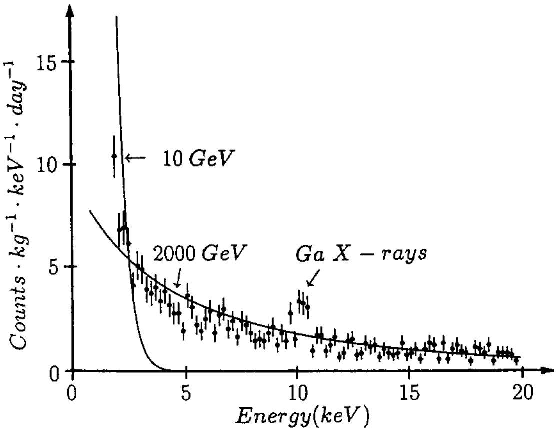

Fig 1. The low energy spectrum of our best crystal, from 1662 h of data (live time, 51.6 kg day) The peak at 10.37 keV is due to Ga X-ray emission after electron capture in ^{68}Ge. Also shown are the expected recoil spectra for Dirac neutrinos of mass 10 and 2000 GeV.

[3], where the corresponding noise level is at 3 keV. The peak at 10.37 keV is due to the Ga X-rays emitted after electron capture in ^{68}Ge [^{68}Ge, which has a half-life of 288 days, was cosmogenically produced in the crystals in the ^{70}Ge(n, 3n)^{68}Ge reaction before the detector was taken underground]. The X-ray line provides a cross-check of our energy calibration. Its intensity in our spectrum is roughly a factor 2 respectively 5 less than in those of ref. [2] and ref. [3].

We then compare our spectrum to expectations. We assume, as described in ref. [1], that the dark matter has a local density of 0.3 GeV cm^{-3}, a Maxwell velocity distribution with $\langle v^2\rangle^{1/2}=261$ km s^{-1} truncated at the escape velocity $v_e=640$ km s^{-1}, and that the relative earth to halo velocity is 230 km s^{-1} (we measured between June and September). Then for a given mass m of a CDM particle we calculate the expected recoil spectrum, assuming an isotropic differential cross-section. Realistically our experiment is only sensitive to dark matter candidates with vector coupling, for which the cross-section is large because the nucleus reacts coherently. Coherence is not total, however, and we correct for this by introducing a form factor in the differential cross-section [2]. We also take into account that a Ge recoil nucleus ionizes only about 30% as much as an electron of equivalent energy (see ref [5] for a review on this subject). The exact ratio in function of recoil energy was taken from the Lindhard theory [6], with the parameterization of Robinson [7]. The calculated spectrum is then folded with the response function, the energy resolution being 800 eV FWHM at low energy. The comparison with the calculated spectra of ref. [3] is difficult since no information is given there about the applied correction for the loss of coherence.

The calculated spectrum is then confronted with the measured one, shifted up by 0.06 keV to take into account the uncertainty on the energy calibration. This way the true energy is less than the one we assume with 90% probability. Maintaining the mass m constant we vary the total cross-section σ until 3 consecutive data points out of the 66 between 1.8 and 15 keV are more than 1.2 standard deviation below the calculated spectrum. We interpret this cross-section value as 90% upper limit on the cross-section for the given mass. The area in the σ versus m plane that we can rule out this way is shown in fig. 2 Also shown is the predicted cross-section as a function of mass for heavy Dirac neutrinos (ν_D) with standard coupling. One sees that ν_D with masses between 10 and 2400 GeV are ruled out. Majorana fermions with axial coupling are expected to have much smaller cross-sections and our experiment has essentially no sensitivity to them.

Our analysis does not use any background subtraction. The disadvantage is that it can only produce limits, but not show the existence of dark matter. The advantage is simplicity and complete model independence, therefore we consider our limits to be reliable. They are somewhat more restrictive than those of ref. [3], limits on σ for a given m being better by a factor 2–4. They are, however, not quite good enough to rule out Dirac neutrinos of any mass with effective coupling $\sin^2\phi_z$ as explained in ref. [8]. Using the limits of ref. [3] referred to in ref. [8] leads to a much less stringent exclusion curve than that actually shown in fig. 1 of ref. [8]. In the future we hope to gain in sensitivity by taking advantage of the yearly modulation of the earth–halo relative velocity.

The low energy part of the spectrum can also be used to look for the decay of the electron into weakly interacting particles. One channel could be $\bar{e}\to \bar{\nu}_e\nu_e\nu_e$ [9]. The decay of a K-shell electron would leave a hole, giving rise to an X-ray cascade resulting in a peak at 11.10 keV, the binding energy of a 1s electron in Ge. With our resolution this peak could be distinguished from the Ga peak. For this analysis we use the sum spectrum of all three crystals. From a fit with two gaussian peaks and a parabolic background we derive a lower limit on the half-life of the electron of $1.9(1.2)\times10^{23}$ yr at the 68(90)% confidence level, almost an order of magnitude better than the previous one [10].

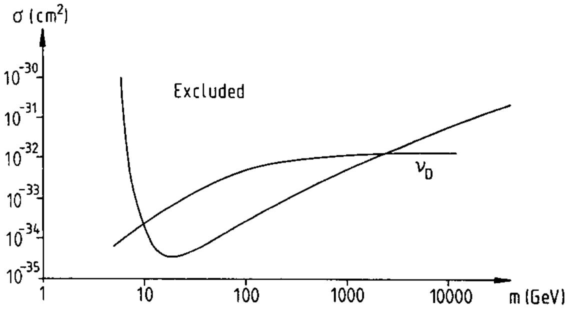

Fig. 2. Exclusion plot for CDM from our experiment CDM candidates with given mass m and interaction cross section σ above the curve are excluded. In particular Dirac neutrinos ν_D with standard coupling between 10 and 2400 GeV are ruled out

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