ELSEVIER

22 September 1994

PHYSICS LETTERS B

Physics Letters B 336 (1994) 141–146

Searching for dark matter with the enriched Ge detectors of the Heidelberg-Moscow $\beta\beta$ experiment

M. Beck [a], F. Bensch [a], J. Bockholt [a], G. Heusser [a], H.V. Klapdor-Kleingrothaus [a,1], B. Maier [a], F. Petry [a], A. Piepke [a], H. Strecker [a], M. Völlinger [a], K. Zuber [a,2], A. Balysh [b], S.T. Belyaev [b,1], A. Demehin [b], A. Gurov [b], I. Kondratenko [b], V.I. Lebedev [b], A. Müller [c]

[a] *Max-Planck-Institut für Kernphysik, 69029 Heidelberg, Germany*

[b] *Russian Scientific Center-Kurchatov Institute, 123 182 Moscow, Russia*

[c] *LNGS, Istituto Nazionale di Fisica Nucleare Gran Sasso, I-67010 Assergi, Italy*

Received 26 July 1993; revised manuscript received 22 July 1994
Editor: R.H. Siemssen

Abstract

For the first time a search for dark matter with isotopically enriched material is done, by using the Ge detectors of the Heidelberg-Moscow experiment. A measuring time of 165.6 kg d is used to set limits on the spin-independent cross section of weakly interacting massive particles (WIMPs). A background level of 0.102±0.005 events/(kg·d keV) was achieved (average value between 11 keV and 30 keV). It was possible to extend the exclusion range for Dirac neutrino masses up to 4.7 TeV.

1. Introduction

The observed dynamics of visible matter implies, that there is a large amount of yet unobserved matter in the Universe. $\Omega > \Omega_{bar} > \Omega_{lum}$; where Ω is the ratio of total density to critical density, Ω_{bar} corresponds to the baryonic density, extractable from early nucleosynthesis to be $0.01 \lesssim \Omega_{bar} \lesssim 0.1$ (see, e.g. [1]) and Ω_{lum} to the density of the visible matter in the Universe (for recent reviews on dark matter see [2,3]). The flat rotation curves of galaxies lead to the assumption, that possibly more than 90% of a galaxy's mass is present in the form of a dark halo, embedding the visible part. This is confirmed by the observed dynamics of binary galaxies, polar-ring galaxies and companions of galaxies, such as globular clusters or dwarf galaxies. Support for the existence of dark matter on even larger scales comes from mass estimations of galaxy clusters with the help of the virial theorem and the observed X-rays from gas in some clusters. The IRAS redshift survey (e.g. [4]) indicates a value of Ω near one, implying a huge amount of non-baryonic dark matter at large scales.

There are many proposals concerning the nature of dark matter. The dark halo of the galaxies may consist of baryonic matter, e.g. massive compact halo objects (MACHOs), such as black holes or brown dwarfs. Possible candidates for MACHOs have been found recently (for references see [6]). However, a lot of non-baryonic dark matter in the form of elementary

[1] Spokesmen of the collaboration.

[2] Present address: Institut für Hochenergiephysik, 69120 Heidelberg, Germany.

0370-2693/94/$07.00 © 1994 Elsevier Science B.V. All rights reserved
SSDI 0370-2693(94)01000-5

particles is needed if Ω is assumed to be unity possible candidates are light neutrinos, with masses in the eV range, or "weakly interacting massive particles" (WIMPs), with masses from a few GeV up to some TeV Among them are massive Dirac neutrinos or the lightest supersymmetric particle (LSP) (see, e g, [7]) Mixed dark matter models basing on resent COBE results favour 30% of hot and 70% of cold dark matter ([5])

One possible experimental method to investigate WIMPs is given by semiconductor detectors While the Earth is moving through the dark halo of the Galaxy, some WIMPs will scatter with the nuclei of the detector, giving a small but detectable ionisation Since the cross section is in the range of the weak interaction, the expected event rates are of the order 1 event/kg day keV, and a detector with very low background activity is needed Depending on the nature of the particles (Majorana/Dirac) and the detector material used, the scattering is either mainly spin-dependent (s d, giving $\sigma^{s\,d} \propto J(J+1)$ with J denoting the spin of the nuclei in the detector) or spin-independent (s i) In the latter case, the cross section could be enhanced if the scattering is coherent over the nucleus: $\sigma^{s\,i} = \sigma^{coh} \propto N^2$, with N the number of neutrons [8]. For some particles both interactions may be possible e.g for certain regions of the parameter space of the lightest supersymmetric particle, a scalar part in its interaction is possible [7] Therefore spinless target nuclei (as ^{76}Ge) can set useful limits, too

The typical recoil energy E_{rec} of the nucleus in the detector reaches up to 10–100 keV, depending on the mass of the WIMP However, a major part of this energy goes into thermal excitations and only a small fraction is converted into ionisation, giving an equivalent electronic energy E_{ee} For Ge, the relative ionisation efficiency is only 25–30%, compared to an electron of the same energy Therefore a sufficiently low detector threshold of $\leq$10 keV is requested This gets more important for WIMP masses <100 GeV, as their recoil spectra are expected to decrease very steeply with recoil energy (see Fig 1).

The present exclusion limits from direct experiments have been set by Ge [9–12] and Si semiconductors [13], both with natural isotopic composition, and for mainly s d interacting WIMPs by NaI scintillators [14–16] Using detectors of enriched ^{76}Ge has

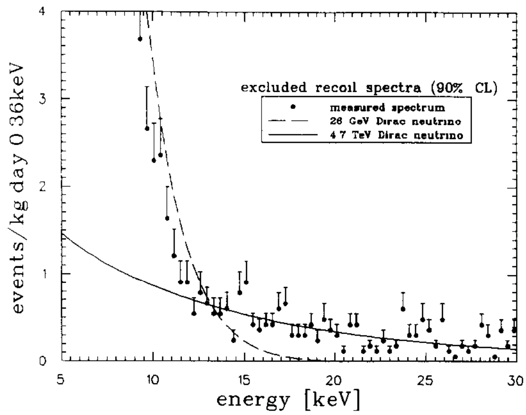

Fig 1 Low-energy spectrum of the second enriched detector corresponding to 165 6 kg d Error bars denote 90% confidence level The background counting rate in the energy range from 11 keV to 30 keV was determined to be 0 102±0 005 events/kg d keV Also shown are the expected recoil spectra of Dirac neutrinos with 26 GeV (dashed line) and 4 7 TeV (solid line), respectively

advantages compared to those with natural isotopic composition First, because of the depletion of ^{70}Ge by a factor of about 1000 the cosmogenic production of ^{68}Ge is suppressed and correspondingly the background is reduced (cosmogenics are produced by reactions of cosmic-ray particles with Ge nuclei of the detector, while the detector is not stored underground). Second, one expects a higher counting rate of spin-independently interacting WIMPs, since the coherent cross-section scales with the square of the neutron number N With the Heidelberg-Moscow experiment, for the first time it was possible to use an enriched Ge detector to set limits on the coherent cross-section of spin-independently interacting WIMPs

2. The Heidelberg-Moscow experiment

Searching for the neutrinoless double-beta decay of ^{76}Ge, the enriched detectors of the Heidelberg-Moscow experiment [17] are located in the Gran Sasso underground laboratory of the INFN in Italy (recent results on $0\nu\beta\beta$, $2\nu\beta\beta$, the double-beta decay mode accompanied by majoron emission ($0\nu\chi\beta\beta$) and electron decay can be found in [17–20]) The shielding of the surrounding rock corresponds to 3500 m w e, reducing the cosmic muon flux by a factor of $\approx 10^6$ In order to shield the external radioactivity, the detectors are mounted in a passive lead shielding· the 10 cm inner layer of ultra-low-activity lead (Johnson-Matthey LC2 Grade) is followed by another 20 cm layer of Boliden lead The whole shielding is covered by an airtight box, flushed with nitrogen gas to remove the air and therefore radon At present 3 enriched detectors with a total active mass of 6 kg and an isotopical abundance of 86% ^{76}Ge (7.8% natural abundance) are operated in the Gran Sasso. The active mass was determined with the help of the Monte Carlo code GEANT3 (version 3 14) and was checked experimentally with an x–y scan of the detectors using collimated γ sources

3. Data reduction

In order to search for WIMPs as dark matter particles, a spectrum taken with the second enriched detector was used. A coincidence of two Constant Fraction Discriminators (CFD), which get their signal from two amplifiers with different time constants, was used to reduce the electronic noise, and to suppress microphonic events. With this setup a threshold of 11 keV for the second enriched detector was achieved (the thresholds of the other detectors are still higher) This threshold is somewhat higher than those achieved by other HP Ge detectors looking for WIMPs (between 2 and 4 keV, as reported in [10–12]), which is partly due to the larger detector size. However, the external disturbances due to microphonics and electronic noise are still dominating the background in the region of interest, which is a common problem of low-level Ge detectors, operating at thresholds of a few keV (see e g [10,21]). These events do not appear evenly distributed in time, but within bursts of typical a few hours duration and with an excess in the counting rate of 1–2 orders of magnitude These bursts occur e.g. when the detectors have been filled, resulting from the releases of thermal stresses in the cryostat system. Between these bursts, the counting rate of the second enriched detector in the energy range from 10 keV to 100 keV was at a level of a few events per hour. To remove the disturbed periods, a time filtering method was used the data taking period between April 1992 and August 1992 was divided into equal time intervals of 1h. For each interval N, the number of events between threshold and 100 keV, was determined The

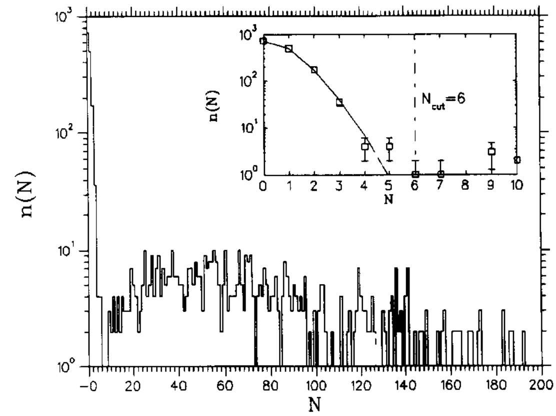

Fig 2 Distribution of N, the number of events between 11 keV and 100 keV in 1h, which was determined for all 2109 1h-spectra The disturbed 1h-spectra ($N \gtrsim 8$) are clearly separated from the undisturbed ($N < 8$) The included figure shows the distribution $n(N)$ of N (datapoints with error bars) together with the fitted poisson distribution (solid line, giving λ_p = 0 69 as parameter of the distribution), from which a cutoff value of N_{cut} = 6 was determined Less than 0 01% of the undisturbed 1h-spectra are removed accidentally this way

distribution $n(N)$ of N clearly shows the disturbed 1h-spectra ($N > 8$) being separated from the undisturbed $N \lesssim 8$ in the logarithmic presentation of Fig. 2. The included figure shows the distribution for $N \lesssim 8$ and the fitted poisson distribution, implying a cutoff at N_{cut} = 6 (rejecting all 1h-spectra with 6 or more events in the considered energy range). This cut was determined with the restriction to reject $\ll$ 1 of the poisson distributed 1h-intervals. 1441 out of 2109 1h-spectra have been added, corresponding to 165.6 kg d measuring time The resulting low-energy spectrum is shown in Fig 1 The background counting rate of this spectrum in the region of interest (11 keV to 30 keV) was determined to be 0.102±0 005 events/kg·d·keV, which is by a factor of ~5 better than that of other dedicated dark matter experiments with Ge detectors in this energy range

The energy calibration was determined by routine-measurements, using ^{60}Co and ^{228}Th sources, giving several γ-lines between 238 keV and 2.6 MeV. The lines seen in the spectrum of the detector provide a cross check of our energy calibration. Unfortunately no line is seen in the measured spectrum below 100 keV, the lowest γ-line energy at 122 keV is resulting from the decay of ^{57}Co To check the calibration in the low-energy region we had to use a pulser system Low-energetic γ- or X-ray lines cannot be used due to the thickness of the cryostat system (several mm of copper). The error in the zero shift was determined to be ≤ 0.6 keV, but to be conservative, the whole spectrum was shifted by this value to higher energies It should be pointed out that this uncertainty in the energy calibration of the low-energy spectrum significantly affects only the exclusion limits of WIMPs with masses below some 10^2 GeV. The exclusion plot for larger masses is insensitive to errors in the energy calibration, since the recoil spectra for these masses are flat

4. Results

Since ^{73}Ge (the only stable Ge isotope with nonzero spin) is essentially absent (~ 0.04 %) in the enriched ^{76}Ge detectors, only limits for s i. (coherently) interacting WIMPs are derived. spectra of WIMPs

The predicted rate of recoils as a function of the recoil energy $E_{\rm rec}$ is given by

$$\frac{dR}{dE_{\rm rec}} \propto \int_{v_{\rm min}(E_{\rm rec})}^{v_{\rm max}} \frac{\sigma}{r\,E(v)}\,|F(E_{\rm rec})|^2\,n(v)\,dv \qquad (1)$$

where $n(v)$ denotes the distribution of the WIMP velocities in the halo with respect to the Earth, $v_{\rm min}$ is the minimal velocity of the WIMPs, giving the recoil energy of $E_{\rm rec}$ by a central collision, and $v_{\rm max}$ is constrained by the local galactic escape velocity $E(v) = \frac{1}{2}mv^2$ is the kinetic energy of the WIMPs with mass m and velocity v $r = \frac{4mM}{(m+M)^2}$ σ is the (coherent) elastic interaction cross section of the WIMP with the nucleus of mass M

Since for coherently interacting WIMPs the coherence is more and more lost with increasing recoil energy, a form factor according to [24] was introduced in (1) $|F(q^2)|^2 = \exp(-E_{\rm rec}/E_0)$, $E_{\rm rec}$ denoting the energy loss of the WIMP and E_0 the characteristic coherence energy: $E_0 = 3\hbar/2MR^2$ (M, R^2 are mass and the mean-square radius of the nucleus, $E_0(^{76}{\rm Ge})$=49.1 keV) This approximation differs only very little from the results of detailed calculations for ^{76}Ge, using the theory of finite fermi systems [25]

The recoil spectra are calculated under the assumption, that the whole density of the dark halo ($\varrho_{\rm DM}$ = 0 3 GeV/cm^3 [22]) consists of WIMPs with the considered mass, following a Maxwell–Boltzmann velocity distribution with $v_{\rm rms}$ = 270 km/s cutoff at an escape velocity of $v_{\rm esc}$ = 580 km/s. The distribution of the relative WIMP velocities was taken from Ref [23], using a value of $v_{\rm e}$ = 245 km/s (average value from April to August) as the Earth's velocity with respect to the halo Because of the relative motion of the Earth with respect to the dark halo, there should be an annual modulation in the relative velocity distribution, and therefore in the recoil spectra, too

Finally, the relative ionisation efficiency $f(E_{\rm rec})$ for ^{76}Ge was taken from Lindhard's theory [26] with the parameterisation mentioned in [2] The efficiencies given by Lindhard's theory had been confirmed for recoil energies down to 10 keV by several experiments. For a review see [27] and references therein

In order to get exclusion limits for the cross-section, the same procedure as reported in [10] is used We calculate the rate of recoils as a function of the equivalent electronic energy ($E_{\rm ee} = f(E_{\rm rec})\ E_{\rm rec}$) with the cross section σ as free parameter. The resulting spectra are compared with the 90% upper count limits of each channel (assuming poisson distribution) This is done for the energy range between 11 keV and 30 keV The cross-section is varied until the calculated recoil spectrum rises over the 90% upper limits of 3 consecutive channels ($\approx$1 keV) of the measured spectrum No background model is subtracted, therefore the cross-section limits obtained by this method can be considered to be conservative. Fig 3a shows the excluded cross-sections as a function of the WIMP mass. The influence of the loss of coherence can clearly be seen when comparing (a) (not corrected for loss of coherence) and (b) (corrected for loss of coherence) This effect is less important with lower thresholds. In order to compare our exclusion limits with the results obtained with natural Ge detectors, we reanalyzed the spectra of [10,11], using our evaluation program and input parameters We were able to reproduce the result of [11]. Ref. [10] we could reproduce within a factor of 2-3. The exclusion plot of [10] and the predicted cross-sections of Dirac neutrinos $\nu_{\rm D}$ with a standard weak interaction are also shown in Fig 3a.

With the spectrum depicted in Fig 1 it is possible to improve the existing limits on WIMP masses $\gtrsim$ 50 GeV and to extend the excluded $\nu_{\rm D}$ mass range up to 4 7 TeV (90% CL) Since the threshold of the detector

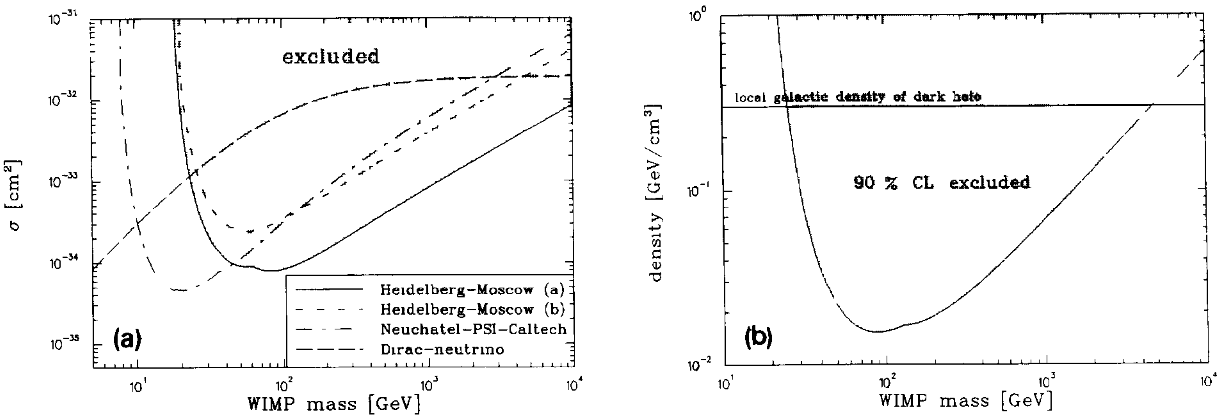

Fig 3 a) Limits for the scattering cross-section of WIMPs off ^{76}Ge from the Heidelberg-Moscow experiment WIMPs of a given mass with cross sections σ above the lines labeled (a) and (b) are excluded as main component of the dark halo For coherently interacting WIMPs the cross section has been corrected for loss of coherence (narrow dash-dotted line, (b)) to be directly comparable to the theoretical cross section Dirac neutrinos (dashed line) e g with masses between 26 GeV and 4 7 TeV are excluded Exclusion limits obtained by the Neuchâtel/PSI/Caltech experiment (using natural Ge) are represented by a wide dash-dotted line b) Exclusion plot for the density of coherently interacting neutral dark matter particles with a standard weak coupling, obtained by the Heidelberg-Moscow $\beta\beta$ experiment The horizontal line at 0 3 GeV/cm^3 represents the local density of the dark halo assumed in the data evaluation for Fig 2

used (11 keV) is higher than those of other HP Ge detectors searching for Dark Matter (as reported in [10–12]), and since the steeply falling recoil spectra of WIMPs with smaller masses require low thresholds, no improvement of the limits for masses below ~50 GeV was achieved.

Using the same evaluation method, a second exclusion plot was obtained by assuming the existence of neutral particles with a standard weak interaction (e g see Dirac neutrino curve in Fig 3a) in the dark halo (Fig 3b) It is possible to exclude a density of heavy Dirac neutrinos with masses m_W above the solid line, since they would produce more events in the measured spectrum than observed

5. Summary

With the Heidelberg-Moscow $\beta\beta$ experiment using large detectors of isotopically enriched ^{76}Ge an improved background level in the spectra above 11 keV was achieved in comparison to detectors using natural Ge Due to the extremely low background, it was possible to improve the cross section limits for WIMP masses larger than 50 GeV, since the observation of the flat recoil spectra of these WIMPs requires a low background in the higher energy region rather than a low threshold One can expect a further improvement of the limits, if the threshold of the enriched detectors can be reduced by only a few keV.

Acknowledgements

The experiment is supported by the Bundesministerium fur Forschung und Technologie der Bundesrepublik Deutschland, the State Committee of Atomic Energy of Russia and the Istituto Nazionale di Fisica Nucleare of Italy The authors would like to thank especially Profs E Belotti, N. Cabibbo, L. Maiani and P Monacelli of the INFN for their continuous generous support. Furthermore, we would like to thank D. Landis and N Madden from LBL, Berkely, for their help in the electronics optimization M B. ist supported by the Konrad-Adenauer-Stiftung

References

[1] TP Walker et al, Ap J 376 (1991) 51
[2] PF Smith, J D Lewin, Phys Rep 187 (1990) 203
[3] J R Primack, D Seckel, B Sadoulet, Ann Rev Nucl Part Sci 38 (1988) 751
[4] A J S Hamilton, Ap J 406 (1993) L47

[5] M Davis, FJ Summers, D Schlegel, Nature 359 (1992) 393,
A N Taylor, M Rowan-Robinson, Nature 359 (1992) 396
[6] B Sadoulet, Nucl Phys B (Proc Suppl) 35 (1994) 117
[7] J Ellis, R A Flores, Phys Lett B 300 (1993) 175,
A Bednyakov, H V Klapdor-Kleingrothaus, S Kovalenko, to appear in Phys Rev D (1994)
[8] M W Goodman, E Witten, Phys Rev D 31 (1985) 3059
[9] C Arpesella, E Bellotti, A Bottino (eds), Nucl Phys B 35 (Proc Suppl) (1994)
[10] D Reusser et al , Phys Lett B 255 (1991) 143
[11] D O Caldwell et al , Phys Rev Lett 61 (1988) 510
[12] S P Ahlen et al , Phys Lett B 195 (1987) 603
[13] D O Caldwell et al , Phys Rev Lett 65 (1990) 1305
[14] A Bottino et al , Phys Lett B 295 (1992) 330
[15] K Fushimi et al , Phys Rev C 47 (1993) R425
[16] H Ejiri, K Fushimi, H Ohsumi, Phys Lett B 317 14
[17] H V Klapdor-Kleingrothaus Proc III Int Symp on Weak and Elektromagnetic Interactions in Nuclei, WEIN'92 (Dubna, 1992), World Scientific, Singapore, 1993, Progr Part Nucl Phys 32 (1994) 261
[18] A Balysh et al (Heidelberg-Moscow Collaboration), Phys Lett B 283 (1992) 32
[19] M Beck et al (Heidelberg-Moscow Collaboration), Phys Rev Lett 70 (1993) 2853
[20] A Balysh et al (Heidelberg-Moscow Collaboration), Phys Lett B 298 (1993) 278
[21] J Morales et al , Nucl Instr and Meth A 321 (1992) 410
[22] R A Flores, Phys Lett B 215 (1988) 73
[23] K Freese et al , Phys Rev D 37 (1988) 3388
[24] A Gould, Ap J 321 (1987) 571
[25] M A Nikolaev and H V Klapdor-Kleingrothaus, Z Phys A, to be published
[26] J Lindhard et al , K Dan Vidensk Selsk , Mat -Fys Medd 33 (1963) 10
[27] B Sadoulet et al , Ap J 324 (1988) L75