### New Journal of Physics An Institute of Physics and Deutsche Physikalische Gesellschaft Journal

# Improved limits on WIMP–<sup>129</sup>Xe inelastic scattering

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New Journal of Physics 2 (2000) 15.1–15.7 (http://www.njp.org/) Received 3 April 2000; online 13 July 2000

**Abstract.** Improved limits on WIMP–<sup>129</sup>Xe inelastic scattering have been obtained by analysing a statistics of  $\simeq 2500$  kg day, collected by the low radioactivity  $\simeq 6.5$  kg DAMA liquid xenon scintillator deep underground in the Gran Sasso National Laboratory of the INFN.

#### 1. Introduction

In this paper we present a new measurement for the direct detection of WIMPs by investigating the WIMP–nucleus inelastic scattering, producing low-lying excited nuclear states [1]–[3]. In this case, a possible WIMP signal can be identified from the presence of characteristic peaks in the measured energy spectrum as a result of the emission of successive de-excitation gamma rays from the excited nuclear states. Although this experimental approach can in principle be a good signature for WIMPs, very long exposures are necessary in order to attain a sufficiently high sensitivity, as was pointed out in [3]. For this reason very few experimental results have been achieved so far by employing this technique. In particular, two experiments of this kind had previously been carried out: the first one searched for the excitation of low-lying states in <sup>129</sup>Xe [5]. In both cases—as well as in the present one—a modest sensitivity was attained; however, they practically indicate the possibility of future experiments with suitable exposed masses (a proper set-up weight should in this case be of the order of several tons) to have e.g. an independent investigation of the effect observed in [6]–[8] exploiting the annual modulation of the WIMP wind. We note that the excited level analysed here allows one to investigate only candidates



**Figure 1.** Measured energy distributions from 30 to 60 keV (2530.2 kg day statistics) and from 60 to 300 keV (2257.7 kg day statistics). The energy bins used and the statistics are marked on each plot.

with spin-dependent interactions. However, the possibility of searching for spin-independent coupled WIMPs with the present approach can also be considered (see for example [9]) when one is investigating levels which de-excite by E2 transitions.

Here, according to [5], we have searched for the inelastic excitation of <sup>129</sup>Xe by dark matter particles with spin-dependent coupling. In particular, only the de-excitation channel from the level at 39.58 keV has been considered, since the contribution from the isomeric state at 236.14 keV is strongly suppressed by the space factor, as was explained in [5]. Finally, we recall that the de-excitation from the 39.58 keV level can give rise to emission of a  $\gamma$  ray (7.5%), a K internal conversion (75%) and an L internal conversion (17.5%) [10]; therefore, for each WIMP event the measured energy should be given as the sum of the energies of all the de-excitation products and of the recoil energy.

#### 2. Experimental results

The LXe DAMA set-up (with  $\simeq 6.5$  kg, i.e.  $\simeq 2$  l, of liquid xenon scintillator) has already produced several results [5],[11]–[15], profiting also from various improvements realized since its installation. The gas used is Kr-free xenon enriched in <sup>129</sup>Xe to 99.5% by the company ISOTEC. The inner vessel for the LXe is made of OFHC low radioactivity copper ( $\leq 100 \ \mu Bq \ kg^{-1}$  for U and Th and  $\leq 310 \ \mu Bq \ kg^{-1}$  for potassium). The scintillation light is collected by three EMI photomultipliers (PMTs) with MgF<sub>2</sub> windows, working in coincidence. The measured quantum efficiency for normal incidence has a flat behaviour around the LXe scintillation wavelength (175 nm); depending on the PMT, its value can range between 18% and 32%. The PMTs collect



**Figure 2.** Examples of the expected energy distribution in the LXe detector due to inelastic excitation of the 39.58 keV nuclear level of <sup>129</sup>Xe: (a)  $M_W = 20$  GeV, (b)  $M_W = 50$  GeV, (c)  $M_W = 100$  GeV, (d)  $M_W = 200$  GeV and (e)  $M_W = 400$  GeV. For each event the sum of the energies of all the de-excitation products from the excited nuclear level plus the detected energy of the recoil nucleus is considered. The detector features have been properly taken into account. The differential energy spectra are normalized with respect to one interaction.

the scintillation light through three windows (7.6 cm in diameter) made of specially cultured crystal quartz (the total transmission of the LXe ultraviolet scintillation light is  $\approx 80\%$ , including reflection losses). A low radioactivity copper shield inside the thermo-insulation vacuum cell surrounds the PMTs; then, 2 cm of steel (the insulation vessel thickness), 5–10 cm of low radioactivity copper, 15 cm of low radioactivity lead,  $\approx 1$  mm of cadmium and  $\approx 10-15$  cm of polyethylene plus paraffin are used as outer shields. The environmental radon near the external insulation vessel of the detector is removed by continuously flushing high purity nitrogen gas inside a sealed Supronyl envelope, which enwraps the whole shield. The latter envelope has recently been replaced by a sealed plexiglass box. Home-made (Saes Getters, Milan) getters in the gaseous phase that had previously been activated at 400 °C (outlet impurities <1 ppb for any component, O<sub>2</sub>, N<sub>2</sub>, CO, etc.) operate in the purification line; another one operates in the liquid phase to further purify the xenon from possible residual degassing under running conditions of the inner detector vessel. A radon trap with a coil in a bath at 195 K and 3 bar is also present on the line to remove radon and other possible impurities which condense at this pressure and temperature.

A low noise pre-amplifier is connected to each PMT. The amplitudes of each PMT pulse and the amplitude of the sum pulse are recorded for every event; the shape of the sum pulse is recorded by a Lecroy transient digitizer. The energy dependence of the detector resolution was measured to be  $\sigma/E = 0.056 + 1.19/\sqrt{E}$ , with E in kilo-electron-volts. In figure 1 the energy distributions from 30 to 60 keV (2530.2 kg day statistics) and from 60 to 300 keV (2257.7 kg day statistics) are shown.

The inelastic processes involving the 39.58 keV level are studied by estimating the expected energy distribution for each WIMP mass ( $M_W$ ). For this purpose, the deposited energy is written as  $E_{det} = E^* + q_{Xe}E_{rec}$ , where  $E_{rec}$  is the kinetic energy of the recoil nucleus quenched by the



**Figure 3.** Model-independent exclusion plots at 90% confidence level for spindependent coupled WIMPs: full line, present limits for the 39.58 keV level; and broken line, the result of [5].

factor  $q_{Xe}$  to give it in terms of electron equivalent units and  $E^*$  is the sum of all the deposited energies of the de-excitation products (we can assume safely that all the energy is contained in the LXe detector, that is  $E^* \simeq \Delta E$ , where  $\Delta E$  is the transition energy). Assuming that there is an isotropic differential cross section in the centre of mass frame, the expected distribution of the differential rate as a function of  $E_{det}$  can be written as

$$\frac{\mathrm{d}R}{\mathrm{d}E_{det}} = \frac{1}{q_{Xe}} \frac{\mathrm{d}R}{\mathrm{d}E_{rec}} = \frac{\rho_W N_T \sigma_I^{as} M_N c^2}{2q_{Xe} M_W \mu^2} F^2(E_{rec}) \int_{v_{min}(E_{rec})}^{v_{max}} \frac{1}{v} \frac{\mathrm{d}n}{\mathrm{d}v} \,\mathrm{d}v \tag{1}$$

with  $v_{min} = v_{min}^0 + v_{thr}^2/(4v_{min}^0)$ ,  $v_{min}^0 = [M_N E_{rec}/(2\mu^2)]^{1/2}$  and  $E_{rec} = (E_{det} - E^*)/q_{Xe}$ . Note that  $v_{min}^0$  assumes the form of the minimal velocity in the elastic scattering case.  $N_T$  is the number of target nuclei;  $\rho_W$  is the local halo density, assumed equal to 0.3 GeV cm<sup>-3</sup>;  $\mu$  is the WIMP–nucleus reduced mass;  $v_{thr}^2 = (2\Delta E/\mu)c^2$  is the square of the minimal velocity which a WIMP would need to have in order to excite the level considered;  $M_N$  is the nucleus mass;  $\sigma_I^{as}$  represents the asymptotic value of the inelastic cross section for WIMP velocity much greater than  $v_{thr}$ ; dn/dv is the quasi-Maxwellian WIMP velocity (v) distribution in the Earth's frame, whose local velocity is assumed here to be  $v_0 = 220 \text{ km s}^{-1}$ ; and  $v_{max}$  is the maximal (escape) WIMP velocity in the Earth reference frame, being the escape velocity in the galactic frame equal to 650 km s<sup>-1</sup>.  $F^2(E_{rec})$  represents the form factor which takes into account the finite size of the nucleus [11, 16]. In addition, a Gaussian convolution is used to broaden the  $dR/dE_{det}$  given above to properly take into account the energy resolution of our detector. Measurements of the quenching factor  $q_{Xe}$  for recoiling xenon nuclei in a pure liquid xenon scintillator have been carried out both with a neutron source and with a neutron generator; the value used in the following is 0.44 [13]<sup>†</sup>. Typical expected energy distributions for various  $M_W$  are shown in figure 2.

<sup>†</sup> This is a conservative value with respect to the measured  $q_{Xe} = (0.55 \pm 0.11)$  [13]. In every case, even varying it from 0.25 to 1, only a few per cent variation in the final result would be attained here (mainly because of the asymmetrical behaviour of the expected energy spectrum and of the shape of the measured one). We take this occasion to remark that differences in the  $q_{Xe}$  values measured in different set-ups can exist, showing that  $q_{Xe}$  has a certain dependence upon the achieved xenon purity.



**Figure 4.** Limits on the relic halo density for the photino, higgsino and  $\nu_M$  as functions of the WIMP mass from the WIMP–<sup>129</sup>Xe inelastic scattering (full lines). The broken lines are the previous limits of [5]. We recall that the halo density is expected to range between 0.2 and 0.7 GeV cm<sup>-3</sup>. For the astrophysical and nuclear physics assumptions used here, see the text.

At this point, considering the 39.58 keV nuclear level of the <sup>129</sup>Xe, we evaluate for each WIMP mass the energy interval which offers the best limit on the exclusion plot for matching the experimental energy distribution with the expected one; these intervals contain from 85% of the total events (30–60 keV) at  $M_W = 12.6$  GeV to 98% (30–200 keV) above 200 GeV. No peak is evident in any of these intervals; therefore, for each given  $M_W$ , the maximal contribution for the WIMP–<sup>129</sup>Xe inelastic scatterings considered is calculated according to  $\sqrt{N_{\delta E}}/[\epsilon_{\delta E}(M_W) \times$  statistics], where  $N_{\delta E}$  is the number of counts inside the energy interval  $\delta E$  (determined as mentioned above),  $\epsilon_{\delta E}(M_W)$  is the fraction of events expected inside  $\delta E$  for the given  $M_W$  and, finally, 'statistics' is given in kg day. The ratio  $\sqrt{N_{\delta E}}/\text{statistics}$  ranges between  $1.16 \times 10^{-2} \text{ counts day}^{-1} \text{ kg}^{-1}$  (30–50 keV) and  $1.50 \times 10^{-2} \text{ counts day}^{-1} \text{ kg}^{-1}$  (30–200 keV).

#### 3. Calculation of the exclusion plots

According to [5], the inelastic point-like cross section for non-relativistic processes can be written as a function of the WIMP velocity:

$$\sigma_I(v) = \frac{\mu^2}{\pi M_N} |\langle N^* | M | N \rangle|^2 \left( 1 - \frac{v_{thr}^2}{v^2} \right)^{1/2} = \sigma_I^{as} \left( 1 - \frac{v_{thr}^2}{v^2} \right)^{1/2}$$
(2)

assuming an isotropic differential cross section in the centre-of-mass reference system. There  $\langle N^*|M|N\rangle$  is the inelastic matrix element for the transition considered, which was discussed e.g. in some detail in [3] for the spin-dependent case. We note that the velocity dependence of  $\sigma_I$  is due to kinematics; in fact, in the elastic scattering case (for which  $\Delta E = 0$ ) this dependence disappears. We assume in the following that the square of the inelastic matrix element,  $|\langle N^*|M|N\rangle|^2$ , would depend weakly on velocity for the transition considered and, therefore,  $\sigma_I^{as}$  will not depend on the WIMP velocity. The expression for the total expected rate

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in the case of point-like interactions becomes:

$$R_{I,point-like} = \int_{v_{thr}}^{v_{max}} \frac{\rho_W v}{M_W} N_T \sigma_I(v) \frac{\mathrm{d}n}{\mathrm{d}v} \mathrm{d}v = \frac{\rho_W \langle v \rangle}{M_W} f N_T \sigma_I^{as} \tag{3}$$

where  $\langle v \rangle$  is the mean velocity of the WIMPs in the Earth's rest frame and

$$f = \frac{1}{\langle v \rangle} \int_{v_{thr}}^{v_{max}} (v^2 - v_{thr}^2)^{1/2} \frac{\mathrm{d}n}{\mathrm{d}v} \mathrm{d}v$$

is a suitable space phase factor (see [5] for details). Finally, to account for the finite size of the nucleus considered,  $R_{I,point-like}$  should be multiplied by the square form factor weighted over the  $E_{rec}$  distribution,  $\langle F^2(E_{rec}) \rangle$  [11, 16].

Using the measured rate and properly taking into account the experimental parameters and form factor, we have calculated the model-independent exclusion plot (90% confidence level) of  $\sigma_I^{as}$  versus WIMP mass for spin-dependent coupled WIMPs. In figure 3 the contour obtained from the present data for the 39.58 keV nuclear level of <sup>129</sup>Xe is shown (full line). In figure 4 the exclusion plot for the relic halo density as a function of the WIMP mass is shown. As in [5], the calculations have been performed for the photino and higgsino according to the model of [3] and for the Majorana heavy neutrino ( $\nu_M$ ) according to [1]–[3],[17, 18]. In particular, in the calculations for the photino the values for the inelastic matrix element given in [3] have been used, whereas in the higgsino case these values have been scaled—up to  $M_W = 40$  GeV—according to the factors quoted in [3].

#### 4. Conclusions

The present measurements have allowed us to achieve an improvement by a factor of about two in the excluded relic abundance for the heavy Majorana fermions considered by studying inelastic processes with respect to those of [5]. A great enlargement of the exposed mass would be necessary in order to achieve more competitive sensitivities.

#### Acknowledgments

We gratefully acknowledge Professor S d'Angelo for useful discussions on related topics. We thank Mr A Bussolotti and Mr A Mattei for their technical help and the LNGS staff for support.

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