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Implications on Inelastic Dark Matter from 100 Live Days of XENON100 Data

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The XENON100 experiment has completed a dark matter search with 100.9 live days of data, taken from January to June 2010. Events with energies between 8.4 and 44.6 $\mathrm{keV_{nr}}$ in a fiducial volume containing 48 kg of liquid xenon have been analyzed. A total of three events have been found in the predefined signal region, compatible with the background prediction of (1.8 ± 0.6) events. Based on this analysis we present limits on the WIMP-nucleon cross section for inelastic dark matter. With the present data we are able to rule out the explanation for the observed DAMA/LIBRA modulation as being due to inelastic dark matter scattering off iodine, at a 90% confidence level.

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The interaction rate of dark matter particles from the Galactic halo is expected to have an annual modulation, induced by Earth's motion around the Sun [1]. Such a modulation has in fact been observed in the DAMA/LIBRA experiment [2, 3]. It is however difficult to interpret this result as a signal from dark matter Weakly Interacting Massive Particles (WIMPs), given the null results from other direct dark matter searches [4]. In order to overcome these tensions, inelastic dark matter (iDM) has been proposed [5, 6] as a modification of the elastic WIMP model. iDM assumes that WIMPs scatter off baryonic matter by simultaneously transitioning to an excited state at an energy δ above the ground state ($\chi N \to \chi^* N$), while elastic scattering is forbidden or highly suppressed. This introduces a minimum velocity for WIMPs to scatter in a detector with a deposited energy E_{nr} [7]

$$\beta_{min} = \sqrt{\frac{1}{2M_N E_{nr}}}\left(\frac{M_N E_{nr}}{\mu} + \delta\right),$$

where M_N is the mass of the target nucleus, μ is the reduced mass of the WIMP/target nucleus system and δ is the energy difference between the ground and excited state of the WIMP. In particular, WIMPs with velocities lower than $\sqrt{2\delta/\mu}$ will not be able to scatter at all since the kinetic energy is not sufficient to allow the transition to the excited state. Therefore, the available fraction of WIMPs that can interact will be larger for more massive target nuclei, like iodine or xenon.

In contrast to elastic WIMP scattering, where an exponential recoil energy spectrum is expected [8], the velocity threshold of the inelastic scattering process leads to a spectrum in which the low energy component is suppressed and which peaks at non-zero recoil energies. The recoil energy at which the rate is maximal depends on δ and M_χ. The differential event rate is given by

$$\frac{dR}{dE_{\mathrm{nr}}} = N_T M_N A^2 F^2 \frac{\rho_\chi \sigma_N}{2M_\chi \mu^2}\int_{\beta_{\min}}^{\infty} \frac{f(v)}{v} dv,$$

where N_T is the total number of nuclei in the target, A is the atomic number of the target nucleus, F is the nuclear form factor, σ_N is the WIMP-nucleon cross section and ρ_χ and M_χ are the WIMP density and mass,

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respectively. $f(v)$ is the halo velocity distribution function. Another consequence of this minimum velocity is the higher sensitivity of the recoil spectrum to the tail of the WIMP velocity distribution, which enhances the annual modulation effect for inelastic over elastic WIMP scattering.

The XENON100 experiment [9] has recently reported results from a 100.9 live days dark matter search [10] in an energy interval between 8.4 and 44.6 keV_{nr} (keV nuclear recoil equivalent). The same data are used here to constrain the iDM model. Three events fall in the predefined WIMP search region for dark matter interactions, which is compatible with the background expectation of (1.8 ± 0.6) events, as described in [10].

To extract the DAMA/LIBRA allowed region in iDM parameter space, the procedure described in [4] has been followed, using an energy independent quenching factor of 0.08 for iodine and not considering ion channeling. The DAMA/LIBRA modulation amplitudes for different energies have been taken from [4], where they are extracted from figure 9 of [2]. Data have been grouped in 17 bins, of which the last one corresponds to the energy interval between 10 and 20 keVee. Different values of σ_n, δ and M_χ have been selected and for each of them the expected modulation amplitude in the DAMA/LIBRA experiment has been computed. The DAMA/LIBRA allowed region is then defined as those parameters for which $\chi^2(M_\chi, \delta) < 24.77$ for some value of σ_n, where 24.77 corresponds to the value that is excluded at 90% confidence level for a χ^2 distribution with 17 degrees of freedom.

Following this procedure it is possible to compute for every point in the allowed region the lowest cross section which is compatible with DAMA/LIBRA at 90% confidence level. The resulting cross section can be used to predict a scatter rate in XENON100 and this can be compared with the actual rate measured in XENON100. As an example to illustrate the difference between the predictions from the DAMA/LIBRA data, figure 1 shows the expected spectrum in XENON100, taking into account exposure and data quality acceptance, and the 90% confidence level cross section from DAMA/LIBRA, for different choices of M_χ and δ in the allowed region. The WIMP velocity has been averaged over the data taking period to account for annual modulation effects.

With this data a limit on σ_N can be extracted for every pair of M_χ and δ values using both the Feldman-Cousins method [11] and the optimum gap method [12]. We assume a Maxwellian WIMP velocity distribution with characteristic velocity $v_0 = 220\,\text{km/s}$ and escape velocity $v_{\text{esc}} = 544\,\text{km/s}$, a local WIMP density of $0.3\,\text{GeV/cm}^3$, Earth's velocity $v_\oplus = 29.8\,\text{km/s}$ [4] and Helm form factors [13]. Figure 2 shows the extracted limit for $\delta = 120$ keV using the Feldman-Cousins method. The 90% confidence region explaining the DAMA/LIBRA modulation is also shown. It is excluded by the new XENON100 limit at 90% confidence level.

The systematic application of this procedure to the DAMA/LIBRA data for all points in the δ-M_χ space results in the gray area in figure 3, which shows the allowed parameter space. To compare this result with other experiments, for each allowed point in the δ-M_χ space the lowest cross section in the 90% signal region for the DAMA/LIBRA data is compared with the 90% confidence level limit cross section predicted by the other experiment. In case the value from DAMA/LIBRA is higher than for the experiment compared, that point in the parameter space is excluded.

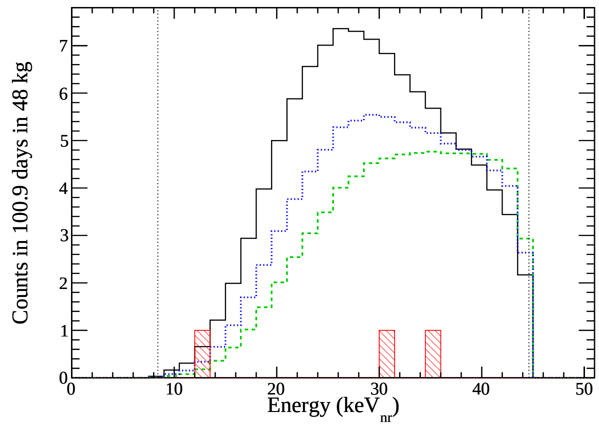

FIG. 1: Expected iDM nuclear recoil spectrum in XENON100 for 100.9 live days measured between January and June for a WIMP with $M_\chi = 50$ GeV, $\delta = 110\,\text{keV}$ (black, solid); $M_\chi = 55$ GeV, $\delta = 115\,\text{keV}$ (blue, dotted), and $M_\chi = 60$ GeV, $\delta = 120\,\text{keV}$ (green, dashed) and a σ corresponding to the lower 90% confidence limit of the DAMA/LIBRA signal. The XENON100 observed spectrum is shown in red. Vertical dotted lines show the analysis energy interval.

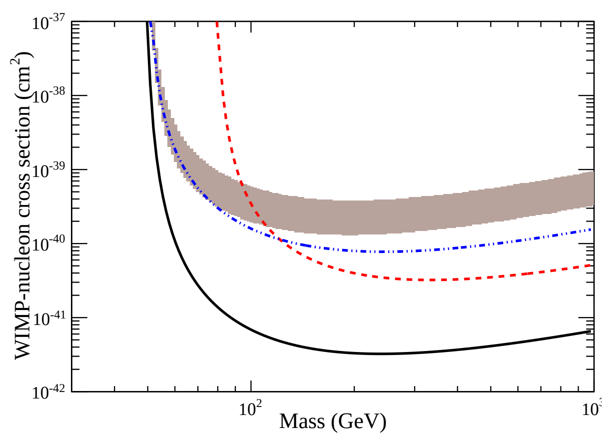

FIG. 2: DAMA/LIBRA 90% confidence level signal region for $\delta = 120$ keV (gray region). Superimposed are the 90% confidence level exclusion curves for XENON100 (black, solid), CDMS [14] (red, dashed) and ZEPLIN-III [15] (blue, dash-dotted). The whole DAMA/LIBRA WIMP region is excluded by XENON100.

Previous constraints from CDMS [14, 16], CRESST [17] and EDELWEISS-II [18] involve target nuclei with different masses than iodine, and thus sample a different region of the WIMP velocity distribution. Thanks to the similar mass of xenon and iodine, constraints inferred from liquid xenon experiments are robust with respect to uncertainties in the astrophysical parameters. This has already been shown by ZEPLIN-III [15] and XENON10 [19]. These data, however, left a small fraction of the spectrum available for iDM, due to the limited exposure. With the XENON100 data the whole DAMA/LIBRA parameter space is incompatible with the iDM explanation at 90% confidence level. This result is independent of the statistical method used to analyze the data.

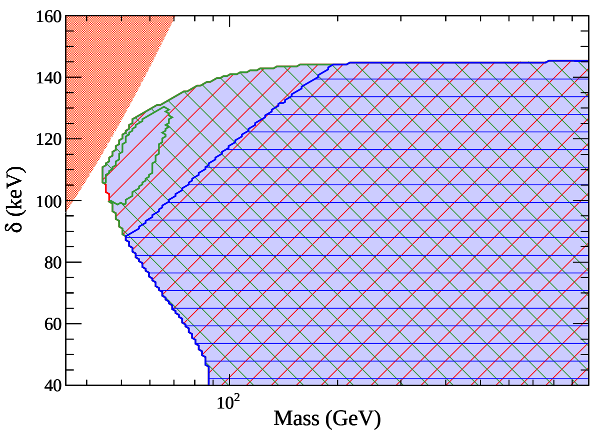

FIG. 3: Parameter space to explain the DAMA/LIBRA annual modulation with iDM (light blue area), and parameter space excluded by the CDMS-II [14] experiment (blue horizontal lines), the ZEPLIN-III [15] experiment (green descending lines). XENON100 (red ascending lines) excludes the whole allowed DAMA/LIBRA region. The orange region corresponds to the parameter space which is not accessible to any xenon experiment. $v_0 = 220\,\text{km/s}$ and $v_{esc} = 544\,\text{km/s}$ have been assumed.

Due to the cutoff at low energies associated with the iDM interactions, the results can strongly depend on the chosen astrophysical parameters. To ensure the robustness of the present result, the calculations have been repeated for $v_{esc} = 500\,\text{km/s}$ and $v_{esc} = 600\,\text{km/s}$. The conclusion remains unchanged. A source of systematic uncertainty often discussed in liquid Xenon experiments is the conversion between measured light and nuclear recoil energy, the so called $\mathcal{L}_{\text{eff}}$ [20]. For this study, however, this effect is very small due to the larger energies of inelastic interactions compared to elastic ones.

An alternative explanation for the DAMA/LIBRA annual modulation based on iDM WIMPs scattering off the Tl impurities in the NaI(Tl) crystals has recently been proposed [21]. Due to the small mass of Xe compared with that of Tl, it is not possible to further constrain the allowed parameter space than already done by the results of the CRESST [17] experiment.

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