CAN THE DAMA/LIBRA ANNUAL MODULATION SIGNAL BE EXPLAINED BY DARK MATTER?*

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I give a brief summary on the status of Dark Matter (DM) explanations of the annual modulation signal observed in DAMA/LIBRA. I stress that for spin-independent elastic scattering the issue of ion channeling is crucial. While in the presence of channeling a marginal compatibility is obtained between DAMA and other constraints, the DM interpretation is strongly disfavoured without channeling. A similar situation — though slightly less conclusive — applies also in the cases of spin-dependent and inelastic DM scattering.

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1. Introduction

The DAMA Collaboration has collected an impressive amount of data in their search for the scattering of weakly interacting dark matter particles (WIMPs) off sodium iodine. The combined data from DAMA/NaI (7 annual cycles) and DAMA/LIBRA (4 annual cycles) amounts to a total exposure of 0.82 ton yr [1], in a field where exposure is measured in units of kg days. DAMA/LIBRA has now provided further evidence for an annual modulation of the event rate in the energy range between 2 and 6 keVee, the claimed statistical confidence of the positive signal being 8.2σ [1]. The phase of the observed modulation (with maximum on day 144 ± 8) is in striking agreement with the expectation for a modulation in a WIMP scattering signal due to the rotation of the Earth around the Sun, with an expected maximum on day 152, June 2nd.

An interpretation of this effect in terms of spin-independent WIMP interactions is in severe tension with constraints from other experiments looking for direct WIMP detection, most notably with the data from CDMS [2] and XENON10 [3].

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Here I review the current status (Sec. 3), where details of our calculations can be found in Ref. [4]. For this calculation we assume the "standard halo model" for the DM distribution with a Maxwellian velocity distribution in the galactic frame, truncated at the escape velocity $v_{\rm esc}$, where we adopt as default values $\bar{v} = 220$ km/s and $v_{\rm esc} = 650$ km/s. In Sec. 2 the channeling effect is discussed, whereas in Sec. 4 I comment briefly on alternative particle physics scenarios as well as non-standard halos.

2. The channeling effect

In the analysis of DAMA data the channeling effect could potentially be important [5,6]. Typical events are quenched, *i.e.*, the recoiling nucleus loses its energy both electromagnetically as well as via nuclear force interactions, where the light yield in the scintillator comes mainly from the electromagnetic part. To take this effect into account the event energy is measured in equivalent electron energy (in keVee), defined by $q \times E_{\rm R}$ for the total nuclear recoil energy $E_{\rm R}$ in keV. For the elements in DAMA one has $q_{\rm Na} = 0.3$ and $q_{\rm I} = 0.09$. However, due to the crystalline structure of the target, for certain angles and energies of the particles no nuclear force interactions might happen and the entire energy is lost electromagnetically. Hence, for these so-called channeled events one would have $q \approx 1$, see [5,6]. The fraction f of channeled events relevant for DAMA depends on the recoil energy $E_{\rm R}$. Simple parametrization for this dependence according to the results of [6] are given in [4]. The predicted spectrum in DAMA receives then contributions from four types of events:

$$R(E) = \sum_{x={\rm Na,I}} \frac{M_x}{M_{\rm Na} + M_{\rm I}} \left\{ [1 - f_x(E/q_x)] R_x(E/q_x) + f_x(E) R_x(E) \right\} \,, \quad (1)$$

where the first term in the curled bracket corresponds to quenched events and the second to channeled (and therefore unquenched) events, each on sodium and iodine.

Channeling does not occur in liquid Nobel gases like in the XENON experiment. Since no information on channeling in germanium and silicon is available for us, we do not take into account channeling in CDMS. Note, however, that CDMS requires the coincidence of signals in phonons and ionisation and hence, since for channeled events the ratio of these two signals would be very different, they would not look like a WIMP signal defined by the characteristic coincidence of quenched events. Therefore, the fraction of channeled events corresponds effectively to an efficiency factor reducing the effective exposure. Hence, if channeling was indeed relevant for CDMS the final exclusion limits would be somewhat weaker.

Whether channeling in DAMA indeed takes place is a somewhat controversial issue. So-far it has not been confirmed by measurements at the relevant energies, and the results of [7] seem not to show evidence for channeling. However, as I will discuss, this question is rather important for the DM interpretation of DAMA. Reliable information (probably requiring dedicated measurements) on this effect would be rather important for any solid DM detector.

3. Spin-independent elastic scattering

Fig. 1 summarises our results [4] assuming standard halo properties, showing the allowed region from DAMA together with the constraints from CDMS-Si, CDMS-Ge and XENON. First we discuss the fit to DAMA data alone (without constraints from CDMS and XENON). We find two islands in the (m_χ, σ_p) plane where DAMA can be accommodated. The best fit point is obtained at $m_\chi = 12\,\text{GeV}$, $\sigma_p = 1.3\times10^{-41}\,\text{cm}^2$, $\chi^2_{\text{DAMA,min}} = 36.8/34$ d.o.f., with an excellent goodness of fit of 34%. There is also a local minimum at $m_\chi = 51$ GeV with $\chi^2_{\text{local}} = 47.9$. This solution is disfavoured with respect to the best fit point at about 3σ for 2 d.o.f. ($\Delta\chi^2 = 11.1$). The low and high WIMP-mass solutions correspond to channeled and quenched scatterings on iodine, respectively. In contrast to the situation when all events are assumed to be quenched (see light curves), it turns out that scattering on sodium is

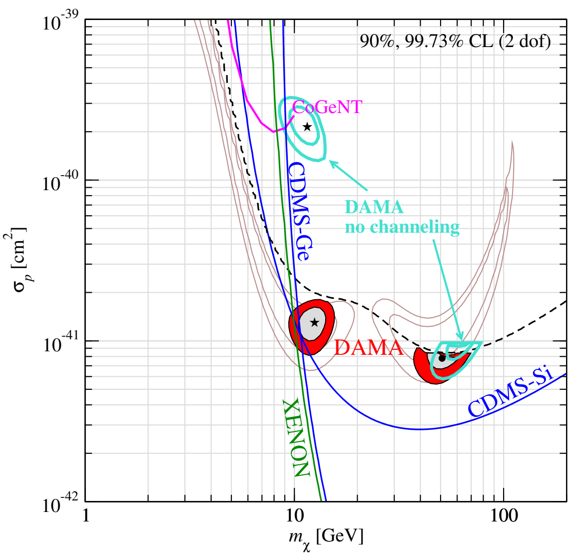

Fig. 1. Allowed regions at 90% and 99.73% C.L. for WIMP mass and scattering cross-section on nucleon for DAMA, and exclusion contours for CDMS-Si, CDMS-Ge, XENON10, CoGeNT at 90% C.L. For details see text and Ref. [4].

not relevant once channeling of iodine events takes place. The reason is that quenched events on sodium require a similar WIMP mass as channeled events on iodine (*i.e.*, $m_\chi \simeq 10$ GeV) but a much larger cross-section σ_p (due to the A^2 dependence of the total cross-section on the nucleus), and therefore, are highly suppressed once channeled scattering on iodine takes place. In principle there would be also a solution from channeled events on Na, around $m_\chi \simeq 5$ GeV. However, it turns out that in this case the un-channeled events on Na still contribute to the signal, and indeed prevent fitting the data with the channeled Na events. Note that the solution around $m_\chi \simeq 50$ GeV is excluded by some orders of magnitude by XENON and CDMS-Ge, and therefore we focus in the following on the low-mass region $m_\chi \simeq 10$ GeV.

The gray contours in Fig. 1 correspond to an alternative method of fitting DAMA. Instead of using the detailed spectral information of the annual modulation, we fit the time dependence of their signal integrated over energy, using Fig. 6 of [1]. For the gray contours in Fig. 1 we use these data for the energy intervals 2 to 6 keVee and 6 to 14 keVee, where in the latter interval data are consistent with no annual variation. We observe from Fig. 1 that using the spectral information gives significantly stronger constraints on the allowed region. This is illustrated in Fig. 2 (left), showing the 36 data points on the modulation amplitude A_i used in our default analysis. While the prediction from the best fit point nicely follows the data (solid curve), moving to smaller WIMP masses leads to a modulation signal more peaked at the lowest energies. Therefore, although it is still possible to obtain the integrated signal in the interval from 2 to 6 keVee, the spectral shape is clearly inconsistent with data, as illustrated for $m_\chi = 6$ GeV by the dashed curve.

Finally, we mention the implication of the data on the time averaged rate observed in DAMA. Parameter values above the dashed curve in Fig. 1 are excluded because they would lead to a higher event rate than observed. This leads to additional constraints for the high-mass solution. In Fig. 2 (right) we show the observed rate together with the predictions for the two local minima. Note that for the DAMA/LIBRA exposure of 0.53 t yr statistical errors are not visible at the scale of the plot. Clearly, solutions predicting a relatively large rate require that the un-identified background drops rapidly in order to give space for the WIMP signal. In particular, the solution at $m_\chi = 51$ GeV requires that the background drops to zero in the first energy bin. Although this cannot be excluded *a priori*, at least such a background shape seems unlikely. The issue is less severe for the best fit point at $m_\chi = 12$ GeV, since the ratio of modulation amplitude to average rate increases for decreasing WIMP mass. However, any point close to the dashed line in Fig. 1 is affected by this problem.

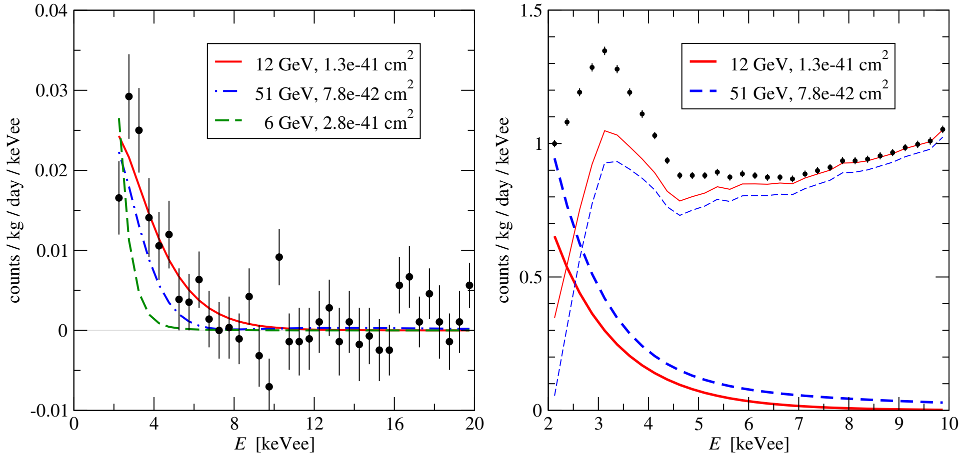

Fig. 2. Left: Energy distribution of the annual modulation amplitude from DAMA/NaI and DAMA/LIBRA data together with the prediction for three examples of WIMP masses and scattering cross-sections. Right: Energy distribution of the time averaged rate observed in DAMA/LIBRA, together with the prediction for two examples of WIMP masses and scattering cross-sections (thick curves) as well as the corresponding un-identified background (thin curves).

From Fig. 1 we find that the parameters allowed by DAMA data at 90% C.L. are excluded by the 90% C.L. limits of CDMS-Si, CDMS-Ge, and XENON. If all data are combined by adding the individual χ^2 functions we find the minimum at $m_\chi = 9.5$ GeV and $\sigma_p = 1.2 \times 10^{-41}$ cm^2 with $\chi^2_{\text{global,min}} = 59.3/(45-2)$ d.o.f., which corresponds to a 5% goodness of fit. The so-called Parameter Goodness of fit test [8] can be used to test the consistency of data sets. Applied to this problem we find that DAMA data are consistent with all the other data only at a probability of 1.2×10^{-5}. This corresponds roughly to the probability of a 2.9σ fluctuation in both data sets at the same time.

These results apply if channeling is assumed according to [6]. Fig. 1 shows that in the absence of channeling the DAMA regions are much stronger disfavored — if not ruled out by CDMS-Si data, with some additional constraints from the CoGeNT [9] experiment. We conclude that the issue of channeling is crucial for the interpretation. See also [10] in this context.

4. Alternative scenarios

Here I mention a few ideas which have been proposed to reconcile the DAMA result with the other constraints.

- *Spin-dependent scattering* (SD) on protons allows to circumvent the constraints from CDMS and XENON, since their elements have even numbers of protons, compared to the odd number for NaI in DAMA. However, recent results from PICASSO [11], COUPP [12], and KIMS [13] exclude large part of the allowed parameter space. Furthermore, such an explanation seems to be disfavoured by constraints on neutrinos from WIMP annihilations in the sun from SuperKamiokande [14], see *e.g.*, [15, 16] (modulo some model dependence, since it might be possible that in some models annihilation channels into neutrinos are suppressed).

- *Inelastic scattering* of a DM particle to a nearly degenerate excited state (iDM) has been proposed in [17], see [18–22] for recent analyses. A splitting of order 100 keV between two DM states changes the kinematics of DM scattering, which improves the compatibility of DAMA with other experiments. However, also in this case tight constraints apply, in particular from CRESST-II [23] and XENON10 [24].

  The question of channeling is also important for SD and iDM scattering. In the presence of channeling some part of the parameter space for SD scattering is still compatible with DAMA [11] and for iDM a new low-mass region appears in the presence of channeling [22].

- *DM interacting only with electrons* might lead to an observable signal in DAMA if the high-momentum tail of the bound state electron wave function is explored [25]. Such a scenario would avoid bounds from nuclear recoil searches, and the PAMELA cosmic ray anomaly might also point towards a leptophilic DM [26]. This scenario has been investigated in detail in [27]. There we have shown that even under the assumption of tree-level interactions only with leptons, DM-nucleon scattering is induced at loop level, which will dominate by far over electron scattering since the latter is suppressed by the high-momentum wave function. In the case of an axial–axial DM-lepton vertex the loop is forbidden. In this case however, the spectral shape of the modulation does not fit the DAMA data shown in Fig. 2 (left), and the required cross-sections are ruled out by neutrino constraints from SuperK. For a CDMS analysis of electronic events see [28].

- *Other ideas* include mirror world DM [29], DM with electric or magnetic dipole moments [30], resonant DM [31], momentum dependent DM [32], or form factor DM [33]. Many of these proposals still have problems to provide a convincing explanation of the DAMA signal and suffer from tension with constraints from one or the other experiment seeing no signal for DM.

- *Non-standard DM halos* have been considered in [4] for spin-independent elastic scattering and in [19] for inelastic scattering. Changing the mean velocity dispersion and allowing for highly asymmetric distributions (with respect to radial and transverse directions) lead to an improvement of the fit, though the required properties of the halo seem to be rather un-likely from an astrophysical point of view. The iDM scenario has some dependence on the escape velocity, since in that scenario events come mainly from the high-velocity tail of the distribution. The hypothesis of a DM stream has been considered in [34, 35], which seems to provide only a marginal improvement but requiring rather extreme assumptions on the stream.

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