A New Possible Way to Explain DAMA Results

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Received January 10, 2014

ABSTRACT

Presently there is an effort to reconcile DAMA results with other Dark matter searching experiments such as CoGeNT, CRESST, CDMS and all LXe experiments. The author suggest a new model describing the Dark matter signal as a result of collisions of very light 0.5-2.5 GeV/c^2 WIMP with the hydrogen and compares it with currently accepted models of collisions with heavy nuclei (Na, Ge or Xe). The hydrogen target would come from the H-contamination of NaI(Tl), Ge and CaWO_4 crystals. The initial tuning indicates that one can explain the modulation amplitude of DAMA and CoGeNT with this model, assuming the WIMP-proton cross-section near 10^{-32} cm^2. This paper should be taken as a new idea, which will need a substantial new experimental input from all involved experiments.

Key words. DAMA experiment, Dark Matter search

1. Introduction

The DAMA experiment clearly observes a small oscillatory signal. The observed signal is a peculiar modulation of the counting rate of the 2-6 keV single-hit events (i.e. those in which only one of the many detectors in the set up fires) satisfying all the many requirements of the Dark Matter annual modulation signature. The observed yearly modulation is in phase with the Earth’s motion around the Sun. It has been discussed in the literature that the possible positive hints observed by the DAMA oscillatory signal can also be all explained in terms of a lower mass than originally expected Dark matter particle scattering off nuclei. DAMA is the first experiment to observe a clear oscillatory signal [Bernabei, 2013], as shown on Fig. 1.

CoGeNT (see Fig. 2) also measures a sign of oscillation; CRESST-II and CDMS experiments observe a hint of a signal. However, there is no hint of signal from any LXe Dark Matter searching experiments, such as Xenon-10, Xenon-100 or LUX.

Figure 3 presents a model-dependent status of the Dark matter search (Snowmass, 2013). Nominally, none of these experiments was designed to search for ∼1 GeV/c^2 mass. As Fig. 3, one can see clearly, that a WIMP mass below ∼5 GeV/c^2 would not be detected by most of present experiments.
Table 1. Maximum nuclear recoil energy as a function of the WIMP mass, for two targets, hydrogen and sodium, and assuming that the WIMP velocity relative to Earth is between 0 and the Galactic escape velocity of 800 km/sec, all modulated by the Earth’s velocity of 230±30 km/sec in the Galactic coordinate system. The table shows the calculated kinematical limit without the quenching factor. The quenching factors are ∼25% for Na and ∼97% for H.

| WIMP mass [GeV/c²] | Nucleus | Max. nuclear recoil [keV] |
|--------------------|--------|--------------------------|
| 0.5                | H      | 2.77                     |
| 0.6                | H      | 3.51                     |
| 0.7                | H      | 4.23                     |
| 0.8                | H      | 4.93                     |
| 0.9                | H      | 5.60                     |
| 1.0                | H      | 6.24                     |
| 1.5                | H      | 8.99                     |
| 2.0                | H      | 11.1                     |
| 2.5                | H      | 12.74                    |
| 3.0                | H      | 14.05                    |

| WIMP mass [GeV/c²] | Nucleus | Max. nuclear recoil [keV] |
|--------------------|--------|--------------------------|
| 0.5                | Na     | 0.28                     |
| 0.6                | Na     | 0.39                     |
| 0.7                | Na     | 0.53                     |
| 0.8                | Na     | 0.69                     |
| 0.9                | Na     | 0.86                     |
| 1.0                | Na     | 1.06                     |
| 1.5                | Na     | 2.27                     |
| 2.0                | Na     | 3.87                     |
| 2.5                | Na     | 5.80                     |
| 3.0                | Na     | 8.02                     |

indicates there is a great opportunity to explore a cross-section of $10^{-30} - 10^{-44}$ cm² if the mass is indeed low.

2. New idea to explain DAMA data

The author discusses a new idea explaining the DAMA signal as a scattering of a light ∼0.5-3 GeV/c² Dark matter particle with a light nucleus; specifically hydrogen present as a small OH or H₂O contaminations in NaI(Tl) crystals.

Table I shows maximum calculated nuclear recoil energy as a function of the WIMP mass, for two targets, hydrogen and sodium, and assuming that the WIMP velocity relative to Earth is between 0 and the Galactic escape velocity of 800 km/sec, all modulated by the Earth’s velocity of 230±30 km/sec in the Galactic coordinate system. The Table I shows the calculated kinematical limit without the quenching factor. The quenching factors are ∼25% for Na and ∼97% for H. In our calculations we will assume the H-contamination at a level of 1-3 ppm is likely. According to [Getkin, 2014], the final H-contamination may end up to be worse than 1-3 ppm, which was indicated by Hilger Co. Even at a level of ~10 ppm, spectroscopic properties of NaI(Tl) crystals are not affected [Getkin, 2014]. Generally, these companies keep air humidity to less than ~2% when machining the crystal and assembling the NaI(Tl) detector, although again this is proprietary information. But, knowing how hard it is to keep humidity in gases without appropriate filtration, it would seem to us that water contamination at a level of a few ppm is easily possible. Once in the detector, DAMA NaI(Tl) crystals are of course protected against the moisture by boil-off nitrogen; however, the sealed chamber is opened from time to time. The exact history of each crystal is probably not known, i.e., there may be variation among crystals.

In our calculations we will assume the H-contamination at a level of ~1 ppm.

A low mass WIMP of 0.5-2.5 GeV/c² represents a real experimental challenge at present, as it requires a low mass hydrogen target to be detectable. So far, existing experiments are providing the hydrogen target only as a small "unwanted" contamination, which limits the measured rate. For example, when such WIMP strikes a hydrogen atom, a resulting proton projectile may strike an electron, which gets excited into the conduction band of the NaI(Tl) crystal structure until it finds an activator (Tl), with a very low ionization potential of 6.108 eV, where the de-excitation occurs via small photonic emissions, mostly in visible spectrum [Knoll, 2010]. To avoid noise, DAMA sets the thresh-
old to 2 keVnr, which is equivalent to about 3-5 photoelectron signal.
The alkali halide inorganic crystals, such as NaI(Tl) or CsI(Tl), may have a unique advantage over other methods to detect the very low mass WIMP, if they have sufficiently high OH-contamination and if the threshold is above a single photoelectron PMT noise. This requirement may cut a large fraction of a good dark matter signal but it is necessary at the moment in the non-accelerator based searches.

The WIMP-proton scattering cross-section is not known at all present. We will treat it as an independent variable.

We calculate the rate per day as follows:
\[
\text{Rate} = \text{\sigma}_{WIMP}[cm^{-2}] \times \text{FLUX}_{WIMP}[cm^{-2}sec^{-1}] \times N_{\text{Target}}[cm^{-3}] \times \text{Target volume}[cm^3] \times \text{Time}[sec] \times \text{Detection efficiency}
\]
where Detection efficiency (DE) = QE (0.35) x Collection efficiency (0.5) x Threshold efficiency (1.0) = 0.117 for DAMA.

3. Other dark matter searching experiments

If the proposed H-contamination mechanism works for the DAMA experiment, it must also work for CDMSlite [Agnese,2013], CoGeNT [Aalseth,2013], and CRESST-II [Angloher,2011]. The peak amplitude for DAMA is ~300 events/30 days, for CoGeNT it is ~10 events/30 days; CDMSlite hints ~2.9 counts/keV/kg-day (no clear oscillation measured yet). Both CDMSlite and CoGeNT experiments are using ultra-pure Ge-crystals [Hansen,1982]. Hydrogen is the only gas which has been successfully used for high-purity Ge crystal growth. All commercial detector grade germanium is grown exclusively in hydrogen. Therefore, even the ultra-pure Ge has a H-contamination at a level of $\sim$2x10$^{15}$ atoms/cm$^2$, or ~50 ppb [Hansen,1982],[Brink,2014]. No real measurement was made on the actual crystals from these two experiments, which we encourage to do. The CRESST-II experiment is using CaWO$4$ crystals of total weight ~ 10 kg, which has also the H-contamination as these crystals are grown in the oxygen/air atmosphere that contain certain level of water, OH and other components [Getkin,2014].

The target is hydrogen from the H-contamination, the measured signal rate in all these experiments should scale as a ratio of the H-contamination level, the weight of detector, and detection efficiency. Table 2 shows the expected number of events per 30 days in the modulation peak amplitude. One can begin to get a hint of a possible agreement between this simple scaling model and data if one assumes that the WIMP-proton cross-section is between $10^{-31}$ and $10^{-32}$ cm$^2$.

Figure 5 shows our prediction for the modulation peak rate in several experiments as a function of cross-section, assuming the H-contamination as indicated, WIMP-proton scattering hypothetical, Dark matter density $0.3$ GeV/cm$^3$ in our nearby Universe [Catena, 2011]. The modulation amplitude peak was calculated from a differential rate based on these two extreme values of dark matter particle velocities: 1030 km/sec and 1060 km/sec–see Table 1.

Table 2. This paper calculation of expected number of events per 30 days in the peak, for DAMA, CoGeNT, CDMSlite and CRESST-II experiments, using the H-contamination as indicated in Fig. 5 weight of crystals and a using the nominal detection efficiency.

| Cross section [cm$^2$] | DAMA | CoGeNT | CDMSlite | CRESST-II |
|------------------------|------|--------|----------|-----------|
| $10^{-31}$             | 1069 | 16     | 23       | 366       |
| $10^{-32}$             | 107  | 1.63   | 2.35     | 37        |
| $10^{-33}$             | 107  | 0.16   | 0.23     | 3.7       |

4. Comparison with LHC experiments

It is interesting to compare our prediction for the DAMA WIMP-nucleon cross-section range with upper limits obtained by Tevatron and LHC experiments, where WIMP is measured in “WIMP + WIMP + jets” events [Beltran, 2010]. This is shown in Figure 6. It is clear that the accelerator-based cross-section upper limits are lower than values obtained from the H-contamination model. This may not be significant at this stage, but at some point it should be explained.

5. A new proposal for future experiments

One could attempt to detect diatomic molecular vibration, excited by gentle WIMP-proton “diffraction-like” scattering, and further reduce the threshold on the WIMP mass. To excite such vibrations, a very small energy deposit at a level of 1.8-4.3 eV is
Fig. 6. Upper limits of WIMP-nucleon cross-sections as a function of the WIMP mass, plotted for Tevatron [Beltran, 2010] and LHC [ATLAS, 2013],[CMS, 2013]. There is a large range of possible values of cross-section limits for $\sim 1 \text{ GeV}/c^2$ WIMP.

needed and still be able to detect de-excitations by the Bialakali photocathode [Vavra, 2004]. To do this, one could use so called "wet" fused silica, which has $\sim 1000$ ppm of OH-contamination by design. Or, one could use simply pure water, and "tune" for the OH-absorption lines. This avenue is presently not pursued because of a high single photoelectron noise. It could be, however, considered in future accelerator-triggered beam dump experiments searching for the dark matter production.

6. Conclusion

This paper suggests that the measured oscillation in the DAMA experiment may be caused by a scattering of the light mass WIMP (mass between $\sim 0.5$ and $\sim 2.5 \text{ GeV}/c^2$) on a hydrogen nucleus, which happens to be the H-contamination in the NaI(Tl) crystal.

For our choice of parameters for the H-contamination model, and taking into account the DAMA modulation peak rate of $\sim 0.01 \text{ cpd/kg/keV}$, we can explain it with the WIMP-proton scattering cross-section in the range $10^{-31}$-$10^{-32} \text{ cm}^2$ (see Fig. 5).

We are also proposing the H-contamination model to explain signals in CDMSlite, CoGeNT, and CRESST-II experiments. There is a hint that one could explain the count rate with the same range of cross-sections as DAMA experiment, simply scaling the rate by the H-contamination level, weight and detection efficiency.

As the H-contamination may vary from crystal-to-crystal in the DAMA experiment, one may observe different rates.

To make this calculation credible, we suggest to DAMA, CDMS, CoGeNT, and CRESST-II collaborations to perform the FTIR analysis on their crystals to determine the H-contamination.

LXe or LAr experiments do not have the hydrogen contamination, and therefore any DM signal detected by these methods would directly contradict the proposed model in this paper.

7. Acknowledgements

I also would like to thank CDMS people for discussing ideas of this paper, especially P. Brink, R. Partridge, G. Godfrey, and M. Kelsey. I also thank Ferilando Da Silva Queiroz for discussions regarding reconciliation of ideas of this paper and their publication [Profumo, 2014]. I would like to thanks Prof. E. V. Kolb for providing several references, which allowed me to enter the up-to-date status of the collider WIMP searches.

References

R.Bernabei et al., arXiv:1308.5109, 2013.
K.A.Kudin et al., Functional Materials 18, No.2 (2011).
A. Getkin, private communication.
N. Shiran, A. Getkin, private communication.
G. Gerbier et al., Astroparticle Physics II (1999) 287-302.
J. Ninkovic et al., Nucl. Instr. & Meth. A 564 (2006) 567.
S. Profumo and F. Queiroz, arXiv:1401.3253v1, Jan. 17, 2014.
F. Queiroz, private communication, 2014.
W.L. Hansen et al., IEEE Trans. on Nucl. Sci., Vol. NS-29, No.1, Feb. 1982
P. Brink, CDMS collaboration, private communication, 2014.
R. Agnese et al., arXiv:1309.3259v3, Dec. 20, 2013.
C.E. Aalseth et al., arXiv:1208.5737v3, Apr. 29 2013.
G. Angloher et al., arXiv:1109.0702v1, Sep. 4 2011.
G. Knoll, Radiation detection and measurement, Wiley, ISBN: 978-0-470-13148-0, 2010.
R. Catena and P. Ullio, arXiv:1111.3556v1, 15 Nov., 2011.
M. Beltran et al., arXiv:1002.1179v2, 2010.
ATLAS collaboration, arXiv:1002.1179v2, 2013.
CMS collaboration, CMS PAS EXO-12-048, 2013.
J. Va’vra, Molecular excitations: a new way to detect Dark matter, arXiv:1402.0466v1, Feb. 3 2014.

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References

R.Bernabei et al., arXiv:1308.5109, 2013.
K.A.Kudin et al., Functional Materials 18, No.2 (2011).
A. Getkin, private communication.
N. Shiran, A. Getkin, private communication.
G. Gerbier et al., Astroparticle Physics II (1999) 287-302.
J. Ninkovic et al., Nucl. Instr. & Meth. A 564 (2006) 567.
S. Profumo and F. Queiroz, arXiv:1401.3253v1, Jan. 17, 2014.
F. Queiroz, private communication, 2014.
W.L. Hansen et al., IEEE Trans. on Nucl. Sci., Vol. NS-29, No.1, Feb. 1982
P. Brink, CDMS collaboration, private communication, 2014.
R. Agnese et al., arXiv:1309.3259v3, Dec. 20, 2013.
C.E. Aalseth et al., arXiv:1208.5737v3, Apr. 29 2013.
G. Angloher et al., arXiv:1109.0702v1, Sep. 4 2011.
G. Knoll, Radiation detection and measurement, Wiley, ISBN: 978-0-470-13148-0, 2010.
R. Catena and P. Ullio, arXiv:1111.3556v1, 15 Nov., 2011.
M. Beltran et al., arXiv:1002.1179v2, 2010.
ATLAS collaboration, arXiv:1002.1179v2, 2013.
CMS collaboration, CMS PAS EXO-12-048, 2013.
J. Va’vra, Molecular excitations: a new way to detect Dark matter, arXiv:1402.0466v1, Feb. 3 2014.