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More on molecular excitations: Dark matter detection in ice

J. Va'vra

SLAC, Stanford University, CA94309, USA

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ABSTRACT

In this paper we investigate di-atomic molecules embedded in ice crystals under strain. In this environment coherent vibrations of many OH-bonds may be generated by one WIMP collision. The detection of such multiple-photon signals may provide a signature of a 100 GeV/c^2 WIMP. To do a proper lab test of "WIMP-induced" multi-photon emission is very difficult. We suggest that Ice Cube make a search for multi-photon events, and investigate whether the rate of such events exhibits yearly modulation.

1. Introduction

A recent paper [1] discussed the possibility of exciting molecular vibrations of di-atomic molecules when a nucleus, either oxygen or hydrogen, is struck by a Dark Matter (DM) particle. An example of such a molecule is H_2O, which has 3 vibrational modes involving the OH-bond (two are stretching and one is bending, or scissoring). Such vibration leads to single-photon emission, mostly in the IR wavelength region, or to the emission of heat; the emission of visible wavelength photons is suppressed by at least 4–6 orders of magnitude.

Assuming that the DM-nucleus scattering cross section is $\sim 10^{-44}$ cm^2 or even smaller, a very large target is needed. An example of one such detector is the Ice Cube experiment, with its huge active volume (1000 m x 1000 m x 1000 m), large detection system of 5160 PMTs, and ice with its large photon attenuation length of more than ~100 meters. Fig. 1 shows the expected Ice Cube experiment interaction rate as a function of WIMP-nucleus cross section; it is huge. However, a simple calculation shows that it is impossible to detect DM with a sufficiently high S/N ratio using the present PMTs,[1] if we assume a single photon is produced per WIMP collision.

However, ice under extreme pressure is a much more complicated substance than the OH-molecular system. As discussed in this note, coherent effects may lead to multi-photon emission, and so we consider what happens if a 100 GeV/c^2 WIMP mass hits either the oxygen nucleus or the proton embedded in the strained crystal structure of ice.

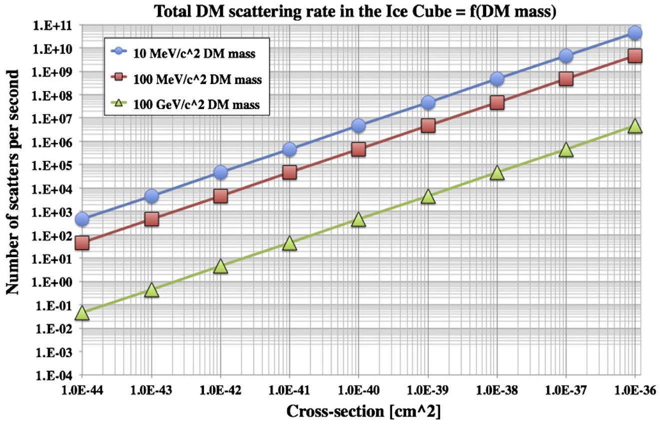

Fig. 1. Expected Ice Cube experiment interaction rate as a function of WIMP-nucleus cross section for different WIMP mass values and assuming that the WIMP has a velocity of 500 km/sec relative to Earth.

2. The crystal structure of ice

Ice has very rich molecular structure, with at least fifteen forms observed experimentally. Fig. 2 shows the hexagonal ice crystal structure type Ih, found in most locations on Earth. Fig. 3 shows its possible phases as a function of temperature and pressure [3]; we see that as long as the ice pressure is below ~0.2 GPa, it remains type Ih. Fig. 4 shows the ice temperature as a function of depth, as measured in Amanda near the South Pole [4]. We can see that

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E-mail address: jjv@slac.stanford.edu.

[1] Average Ice Cube PMT noise is ~280 Hz/PMT.

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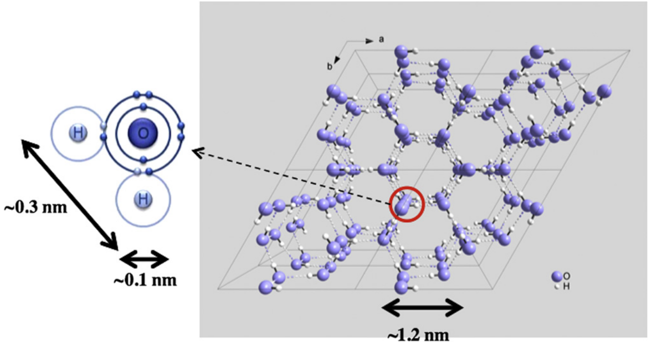

Fig. 2. Hexagonal ice crystal structure Ih, found in most locations on Earth. There are many OH-bonds within each hexagon. One can see the approximate sizes of the hexagon, a water molecule, and a hydrogen atom. From the point of view of this paper, this is similar to a system of many springs.

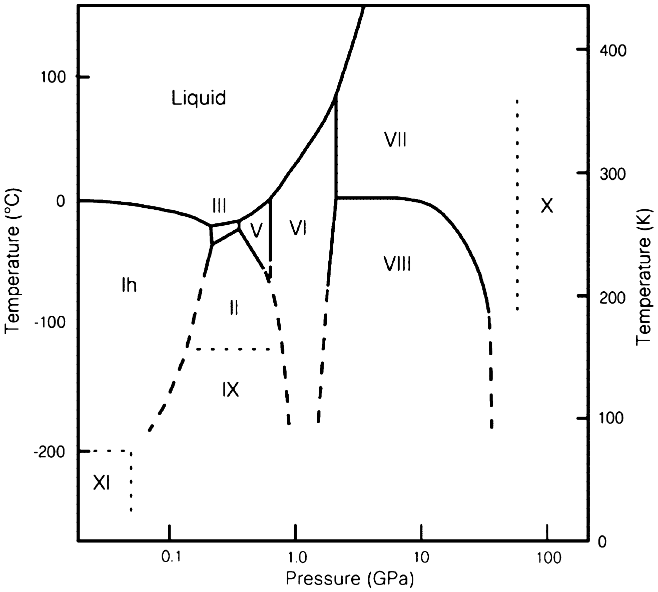

Fig. 3. Ice phases as a function of pressure and temperature [3]. Ice crystal structure type Ih is found in most locations on Earth. The ice type in the area of the Ice Cube experiment is believed to be Ih, stressed to ~23 MPa, although we were not able to find an experimental proof of its pressure. As ice pressure increases, the type changes.

the ice temperature increases with pressure; it approaches −20 °C at a depth of ~2500 meters.[2] The pressure approaches ~230 bars, or ~23 MPa, for ice ~2500 meters below the surface, based on gravitational force alone. Therefore we might expect, based on the phase diagram of Fig. 3, that the ice lattice configuration remains type Ih for ice ~2500 meters below the surface. However, we point out that we are neglecting possible stresses due to slow horizontal ice movements over uneven bedrock shape,[3] or long-term effects over geological time of ice under stress, effects of long-term bombardment by cosmic rays, etc.

Whatever ice-type Ice Cube has at a depth of ~2500 meters, it is reasonably uniform, judging from the long light and sound attenuation lengths observed (the sound attenuation length of ice near the Ice Cube experiment is more than ~300 meters [2], and the light attenuation length is ~110 meters on average). This indicates a great degree of crystal uniformity, and only a small presence of dust or voids.

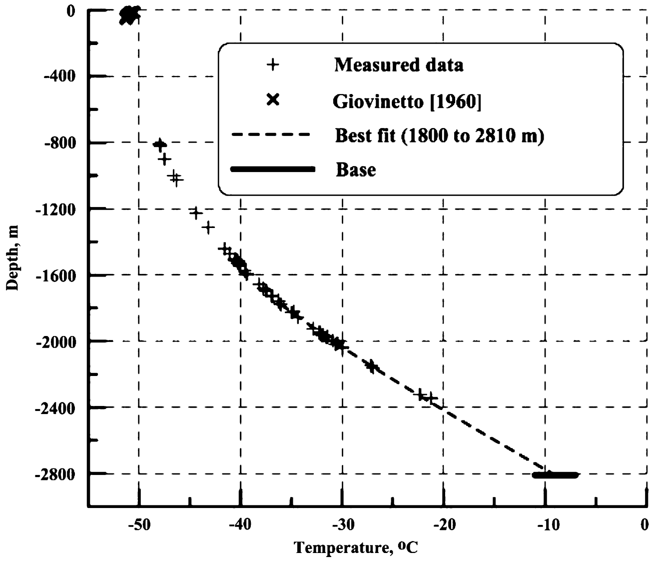

Fig. 4. Ice temperature measured in Amanda boreholes as a function of depth [4].

It is also known that ice under stress can yield triboluminescence.[4] For example, ice in the Ice Cube detector holes, 2500 meters below the surface, produced triboluminescence after it was subject to large stresses due to ice expansion (detector enclosures were designed to withstand pressure up to ~690 bars); it was observed that the triboluminescence light decays exponentially over several years. Finally, bursts of triboluminescence photons (~200 counts/sec lasting over a second) were observed when 5ml blocks of purified H_2O ice (Ih) at temperatures just below 0 °C were dropped into liquid nitrogen while viewed by a photon counter [8].

3. Maximum nuclear recoil energy

Fig. 5 shows a maximum recoil energy of ~60 keV for a 100 GeV/c^2 WIMP traveling with a velocity of ~500 km/sec striking an oxygen nucleus, and ~8 keV if it strikes a hydrogen nucleus. Such an impact would certainly break off the oxygen or hydrogen nucleus from its molecular bond in the hexagonal lattice. This would upset the local electrostatic balance in one single hexagon, thus leading to its deformation.

4. Calibration of photon yield in ice

In this section we argue that we do not have a relevant calibration test, which would enable us to predict the photon yield per unit of energy deposited by a WIMP-like particle.

The only calibration of which we are aware are results from two references, one used a continuous UV photon beam [7], and the other used a pulsed ~0.5 MeV electron beam [6]. Fig. 6 shows the result from a pulsed electron beam striking ice held at a temperature of 88 °K. We see a prompt Cherenkov peak followed by

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[2] The Amanda experiment quotes ice temperatures between −43 °C at 1450 meter depth and −20 °C at 2450 m depth [5].

[3] The Antarctic ice is actually moving very likely non-uniformly. Near the South Pole, ice slowed down because high mountains underneath are blocking its movements. Nevertheless, ice under the Ice Cube experiment still moves slightly as measurements with inclinometers, located below a depth of 2800 meters, indicate. Therefore there is a pressure buildup on this ice region, both from sides and from upward forces driven by a shape of the bedrock.

[4] Triboluminescence is an optical phenomenon in which light is generated through the breaking of chemical bonds in a material when it is pulled apart, ripped, scratched, crushed, or rubbed. Although it is known phenomenon, it has not been studied quantitatively in detail.