Some Practical Applications of Dark Matter Research

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Abstract

Two practical spin-offs from the development of cryogenic dark matter detectors are presented. One in materials research, the other in biology.

1 Introduction

I know it’s hard to believe and I certainly would never have believed it myself when the field started back in the 80’s, but there can be what could be called a “practical” aspect to research on direct detection of dark matter.

This is because with a very small energy left behind in a dark matter interaction, we must develop very sensitive detectors. In particular there has been an intensive development of cryogenic detectors which in virtue of their operation at very low temperature show a strong response to very small energies[1]. This can have unexpected consequences. I’d like to present two we have been involved with, one related to materials science and one in biology.

2 Cracks—the scare

The first begins with the early runs of the CRESST Cryogenic Dark Matter Detector in Gran Sasso in 1999 [2]. Much careful effort went into the design and construction of a low background setup, aimed at achieving only a few events per day. When it finally ran in Gran Sasso we found— to our horror—rates in the 1000’s per hour instead.
There followed several months of feverish search with all kinds of hypotheses, some plausible and others less so...electronics?...suspensions?...somebody touch the crystal with bare hands?...correlation with traffic in the Gran Sasso tunnel?...

The worst nightmare would of course have been a radioactive contamination. But on this there was one thing that saved us from complete desperation. Even if there is a fearsome radioactive background you don’t know anything about, there is one thing you do know: it must be Poisson distributed in time. However, the mysterious events were not Poissonian. They seemed to rather come in ‘bursts’, and this was confirmed by statistical analysis. So it wasn’t a radioactive contamination. But what the devil was it?

Fig. 1 shows the culprit. The detectors were sapphire (Al₂O₃) crystals held...
tightly in place by small (∼mm) sapphire balls. One sees some kind of fracture at the point of contact—“cracks” we called them. Apparently the “tight holding” which is used in cryogenic work to avoid problems with “microphonics” was too tight; enough to crack the very hard material sapphire. As soon as the sapphire balls were replaced by plastic stubs, which are evidently somewhat softer, the rate went down to to the expected level.

We all breathed a sigh of relief and that seemed the end of the story.

![Energy spectra from ‘crack’ events with a power law fit to one of the curves, yielding \( E^{-1.9} \) (solid line).](image)

**Figure 2:** Energy spectra from ‘crack’ events with a power law fit to one of the curves, yielding \( E^{-1.9} \) (solid line).

### 3 Cracks—the analysis

Several years later, however, the realization suddenly hit that we must have the world’s greatest data sample on ‘cracks’. Since the rate went down from thousands per hour to a few per day, the pulses detected in that period must have been essentially all “cracks”. And these were taken with good energy and time resolution, under low background conditions and with many, many, thousands of events. This splendid collection of well observed “cracks” ought to be of interest to somebody.

Indeed, several years later, in Finland, we found people knowledgeable about the subject and we began to look at the data [3].
The first thing we did was to plot the energy spectrum. This is shown in Fig. 2. "Looks just like earthquakes" was the first observation. Indeed the spectra seem to follow a power law, \( dN/dE \sim E^{-\beta} \) as do the magnitudes (Richter scale) of earthquakes.

Interpretation here is simpler than in seismology. In seismology it is non-trivial to find the energy spectrum for quakes since working back from the Richter scale (a kind of amplitude) to the whole energy of the event involves various assumptions and calculations. But the cryodetector is a type of calorimeter, one is just measuring the total energy directly. (On the other hand, it must be said that earthquake data has a much larger range, covering five or six orders of magnitude compared to the one or two here.)

But if we follow the standard lore of how to translate the Richter scale to an energy scale, we get a power \( \beta \approx 1.7 \) for earthquakes. Over different CRESST data sets the power was \( \beta \approx 1.7–2.0 \), suggestively close to the earthquake number. I'm not aware of any simple, basic, explanation for this power, nor for any of other ones we found in the analysis.

With this wealth of data various other interesting statistical aspects of the data can be studied. One is the “waiting time”, a statistic suitable for intermittent phenomena and often used in this kind of work. To every event we associate the time until the next event, and then plot the distribution of these “waiting” times.

For an ideal Poissonian source the waiting time distribution should be \( e^{-w/w_o} \) where \( w_o \) is the average waiting time or the inverse of the event rate. Fortunately we had such data available, since CRESST detectors are periodically calibrated with an external \( \gamma \) source—necessarily Poissonian. This is shown in Fig. 3 by the lower curve, and it has indeed the expected Poissonian form. On the other hand, the same plot for the cracks (upper curve) is well above a Poissonian at small waiting times, and in fact is well fit by a Poissonian times a power law, namely

\[
  w^{-\alpha} e^{-w/w_o}
\]

with \( \alpha \approx 0.3 \). Interestingly enough, an analysis of earthquake waiting times came up with the same fit with the same power [4]. Our power is not very well determined and this could be a coincidence, but it certainly is intriguing.

Another point concerns not earthquakes but material studies. As can be seen from Fig. 2 the energy threshold in this data was in the keV’s. This corresponds to breaking only some hundreds of bonds in sapphire. It turns out this is many orders of magnitude more sensitive than previous work in the subject, where it’s more like \( 10^7 \) bonds [3]. Possibly, with a dedicated setup, one could get down to the single bond level. This would be an exciting possibility and we have some thoughts about what such an apparatus might look like [5].

Briefly, we can advertise the following points from this study and for the cryodetector:

- A new technology for studying microfracture. With unparalleled sensitivity. Perhaps to the few atom level with a dedicated setup.
Figure 3: Distributions of waiting times for ‘cracks’ (upper curve) and photons from an external calibration source (lower curve). The lines are fitted as (lower) a simple Poissonian $e^{-w/w_0}$ and to (upper) $w^{-\alpha}e^{-w/w_0}$ with $\alpha = 0.3$.

- The method provides a direct, absolute measurement of the total energy, as opposed to previous work either in seismology or materials study.
- There are striking similarities with earthquakes. Despite the stupendous difference in energy scale, and big material differences, there appear to be close and even quantitative similarities. Something universal must be at work. This is a challenge to theory. Is there, for example, a relation between the exponents $\alpha$ and $\beta$?

4 The cryodetector in mass spectrometry

My second story begins even earlier, in 1991. It rests upon a very deep physical insight, namely:

$$20 \text{ keV} = 20 \text{ keV}$$

The history of this profound observation is the following. Mass spectroscopy with macromolecules is a valuable and frequently used tool in molecular biology. In such fields as genomics and proteomics time-of-flight studies are performed with very big molecules and their fragments. The biologist will have a, say, 20 keV accelerator in the basement. As opposed to the particle or nuclear
physicist who at most will deal with heavy nuclei, the biologists is concerned with macromolecules in the many kD range. (One D= Dalton= 1 H atom.) With such enormous masses, and given that $E = \frac{1}{2}Mv^2$, a chunk with 20 keV will not be moving very fast at all.

![Figure 4: Time-of-flight spectra comparing the cryodetector (upper curve) and a conventional detector (lower curve) in the study of proteins associated with the liver disease HELLP. Numbers attached to the peaks are the masses. Fig 2 of ref [7].](image)

Now in practically all familiar detectors, Geiger counters, scintillation counters,... the initiating event is the ejection of an electron, leading to ionization, scintillation... But as we learn in elementary atomic physics, the cross section for hitting an electron depends on velocity and is maximum when $v(\text{projectile}) \approx v(\text{atomic electron})$. Thus with big, slow, molecules, as we get into the hundreds of kD or more, detection becomes more and more difficult and inefficient.

Mulling upon this problem now and then, one day I suddenly came upon the deep insight Eq 2. The cryodetector, being a kind of calorimeter, doesn’t care if the molecule is slow. It works on heat, energy, not velocity. For a cryodetector a huge, slow, 20 keV protein is the same thing as a 20 keV electron!?

...Theoretically. As many of our senior, seasoned participants at the conference will know, most good, simple-sounding ideas have a catch. Could this really work? But after discussion with my brother Marv, who is a microbiologist and who found the idea interesting, it was actually tried out by Damien Twerenbold and collaborators [6]. It actually worked!
This in turn has lead to the production of commercial devices. A result with one of these is shown in Fig.4, where the results with a cryodetector are compared with that for a conventional detector in looking for rare proteins associated with the liver disease HELLP [7]. A couple of nice peaks (masses in boldface), lost in the noise with the conventional detector, show up nicely with the cryodetector.

Our group at the MPI, has furthermore developed improved detectors optimized for good timing for improved time-of-flight accuracy. This also naturally leads to background reduction and tests showed very high sensitivity, reaching attomoles [8].

For the application of the cryodetector in mass spectrometry we can thus note

- It really appears to be true that “20 keV ≈ 20 keV” for the cryodetector
- In principle the technique has no mass limitation (one of our students once tried to launch a whole virus – results unclear)
- The technique has a very high sensitivity, useful in rare protein studies and diagnostics
- Good timing can give high mass resolution; one could possibly see the modification of a single base

5 Conclusions

These two examples of ‘cracks’ and mass spectrometry are not the last we’ll see from this still relatively young technology and many are being actively discussed and tried out [9]. It will be interesting to see what’s still coming.

References

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Recent developments on cryodetectors, including diverse applications, are presented at the LTD meetings. See LTD-11 in Tokyo (2005) and LTD-12 in Paris (2007).