One Model Explains
DAMA/LIBRA, CoGENT, CDMS, and XENON

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Many experiments seek dark matter by detecting relatively low energy nuclear recoils. Yet since events from ordinary physics with energies in the 1-100 KeV range are commonplace, all claims of signals or their absence hinge on exhaustive calibrations and background rejection. We document many curious and consistent discrepancies between the backgrounds which neutrons can produce versus the picture of neutrons and claims of neutron calibration found in dark matter literature. Much of the actual physics of neutrons is either under-recognized or under-reported, opening up new interpretations of current data. All signals seen so far, including those presented tentatively such as CoGENT, or the bold claims and time dependence of DAMA/LIBRA, appear to be consistent with neutron-induced backgrounds. At the same time it is the burden of proof of experimental groups to support their claims no possible background could matter, not ours. The existing hypotheses about backgrounds stated by experiments, accepted at face value and as published, make possible a variety of neutron-induced events to be registered as dark matter signals.

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The Background Is the Hypothesis

Recently three experiments seeking direct detection of particle dark matter have reported potential signals. The data of DAMA/LIBRA[1], CoGENT [2], and CDMS[3] are sufficiently different that no theoretical model to explain all experiments has come forth. Even more recently, the XENON experiment [4] seems to undercut the others by finding no signal. The range of data reported does not seem to be consistent. Here we discuss a model for all the data available, with the remarkable feature that everything observed is explained without invoking any new physics.

Our model is neutron backgrounds. Neutrons are often cited in experimental reports. But there are odd discrepancies between what neutrons do in Nature and how they are treated in the literature. Rumors that neutrons are under control have been greatly exaggerated. Neutrons may explain all “signals” found so far. The news has some positive elements: Flaws in assessing neutron reactions may also be causing rejection of actual dark matter events.

Our “hypothesis” for the data comes from numerous questions that have not been raised or answered in the public record. It is important that debate over the background phenomenology of dark matter searches cannot be restricted to collaboration insiders. In the usual case “discovery” experiments find new phenomena, permitting backgrounds to be hashed out by the insiders of large collaborations. Yet backgrounds are everyone’s business when backgrounds become the sole criteria of finding new physics.

The premises of dark matter searches are unique. Experiments define “signals” to be “events not accounted for by known backgrounds.” This matters. The events themselves are very ordinary. Unlike other tests of fundamental physics, finding an event does not violate a symmetry. Events can come from myriad causes. Discovering “new physics” always involves inverse questions that are more interesting than the calibrations. The inverse question of neutron backgrounds is given a putative signal not predicted by your neutron calibration, how will you know an un-calibrated kind of process did not make it? This question is especially important for neutrons, whose interactions display great variety and rapid energy dependence. Yet the inverse question is remarkably undeveloped. There is unfinished work in the “exhaustive characterization” of backgrounds needed for experiments to make a convincing case.

This paper contains provocative information of an interdisciplinary kind. It is due to contradictions between
“neutron physics” cited in dark matter searches and neutron physics found in neutron-nucleus reactions. We might hear from one group or other that “there are no neutrons, so don’t worry." Plenty of literature show neutrons exist, and experiments will eventually have to be seriously concerned, whatever the degree of denial now. Our mission is to document misleading or incomplete information that has been used, gaps between what has been done and what is perceived, and consequences of not using information that is known.

The author is not a member of any dark matter collaboration. Nobody but collaboration members know what the collaborations discuss among themselves. It is important this does not matter. Such things cannot make any difference in comparing what was reported important this does not matter. Such things cannot make any difference in comparing what was reported with what exists. The internally self-consistent treatment of neutrons found in dark matter circles sometimes causes a certain complacency. For example the estimates of neutron fluxes from experiments - which range from “no effect” to “the main background,” depending on what is read - consistently refer to a special kind of neutron that was calibrated. We will find those special neutrons do not really exist. Then outside information about real neutrons often upsets the estimates. The contradictions put readers in the position where asking serious questions is appropriate. This does not take away from the dedication of experimenters to getting things correct. Asking questions of the experimenters is not supposed to need a license, and if some of our concerns turn out to be over-conservative, there is every reason to put them on the record in case they matter elsewhere.

It is also not our burden of proof to show our proposals are final. The burden of proof goes the other way, and is held by the experiments making claims. We will show that “undiscussed problems” cast serious doubt on claims that backgrounds have been understood. The only way dark matter can ever be discovered is by full disclosure and full participation of a community allowed to express criticism.

To summarize the paper: We find the existing hypotheses about backgrounds stated by experiments, accepted at face value and as published, make possible a variety of neutron-induced events to be registered as dark matter signals.

1. Alternative Interpretations

The gaps in the literature about neutron-induced backgrounds suggest alternative interpretations. While anyone outside a collaboration tends to be limited to order of magnitude estimates (Section II B), the alternatives are interesting in their own right, because they take into account new information:

- We propose that the rise of response below 1 KeV observed by CoGENT[2] is the same rise seen in high-purity Germanium detectors from Auger-M electrons. Neutron capture and activation can produce it.

Some dark matter literature will suggest that CoGENT has the finest energy resolution ever documented, making direct checks of our proposal difficult. However we find that much better detector resolution has long been routine in x-ray physics. In x-ray experiments a rise that appears to be CoGENT’s signal has been observed (Fig. III Section II B). If it is not the same signal, it appears to be the same signal, and we can’t find any previous discussion.

To check our proposal we suggest a duplicate of the CoGENT experimental elements be set-up and exposed to a wide-band neutron and x-ray sources. It has not been done before. It will undoubtedly involve sacrificing some detector components to activation. It is hard to know how one would ever know for sure the signals were not the same without a direct experimental exposure. It seems remarkable that experiments whose entire value is determined by uncompromising background studies would not have planned sacrificial “scorched-earth” calibration from the start.

- We propose that events from the CDMS experiment are consistent with resonant neutron absorption and activation. CDMS reports that certain of its events cannot in principle be separated from neutrons, making the experiment dependent on background simulations. Scaling the backgrounds of neutrons in a more realistic (and experimentally more conservative) way than the extrapolations reported by CDMS appears to explain the signal.

To check this proposal we suggest the full range of neutron interactions be incorporated in numerical simulations, which as we show below, has not been done to this date.

- We propose that Auger electrons delivering about 3.1 KeV from activation and decay of Iodine-128 might explain the signal reported by DAMA/LIBRA. There is no record of previous consideration. The resonant features of neutron-induced backgrounds in Na(Tl)I also present channels for direct excitation of the 2-6 KeV signal region. A seasonal variation of underground neutron-induced neutrons is known to exist. We will show the time dependence reproduces DAMA’s annual modulation with no free parameters.

To check our proposal, we suggest that annual variation of Na(Tl)I be duplicated in the Southern Hemisphere, perhaps at ICECUBE. The experiment operates under thousands of water-equivalent meters of a low radioactivity, well understood substance, which is water. The backgrounds in ICECUBE are so radically different from Gran Sasso that discovery of seasonal variation in absolute
phase agreement with the DAMA/LIBRA signal would likely be a positive discovery of dark matter not explainable by any known background.

I. THREE OR MORE MISCONCEPTIONS

Direct detection experiments operate in challenging low energy, low background regions never measured before. There is a feature of calibrating old physics and detecting new physics in one and the same experiment. In reading the literature three important misconceptions were found repeatedly. The origin is unknown, but the most cited reference is probably the 1985 paper of Goodman and Witten (GW). The misconceptions are supported by textbooks, but textbooks about neutrons are sometimes wrong.

Misconception 1 amounts to transferring a model of dark matter signals to neutrons. Many years ago it was noticed that the elastic recoil of dark matter on nuclei could be imitated by elastic recoil of neutrons. Perhaps by subtle transfer of focus, we find an habitual transfer of the signal-model to the background-model has been used to effectively define neutrons. To be specific, GW state a rule for the $2 \rightarrow 2$ elastic scattering cross section of dark matter on nuclei:

$$\sigma_{GW} = \frac{|M|^2}{(m_1 + m_2)^2}.$$  \hspace{1cm} (1)

where $M$ is the invariant scattering amplitude. A perception has come that all low energy cross sections take the form very generally, perhaps because it is so simple, but the formula is wrong in general. As a corollary comes Misconception 2, which is the energy losses of elastic $2 \rightarrow 2$ scattering computed for dark matter signals as well as neutron backgrounds by one uniform method. Given a target of mass $m_2$ at rest, struck by a particle with mass $m_1$ and Newtonian kinetic energy $E$, the energy transfer $\Delta E$ is predicted as

$$\Delta E = 2E_1 \frac{m_1 m_2}{(m_1 + m_2)^2} (1 - \cos \theta_{CM}).$$  \hspace{1cm} (2)

GW actually cite the simpler upper limit. Then a 100-1000 GeV dark matter particle moving at speeds of order $10^{-3}c$ will produce recoil energy transfers at the 10-100 KeV scale. This is why direct dark matter detection has been driven into a challenging low energy region. Likewise, the formula predicts energy transfers to nuclei at the 10-100 KeV scale from MeV-energy neutrons in the lab by selecting $CM$-scattering angles $\cos \theta_{CM} \rightarrow 1$. This is very convenient for purposes of calibration, and used extensively. Indeed dozens of papers on “quenching,” which is the measure of elastic recoil energy, use Eq. 2 as a definition of their study. While experimental conditions can be arranged in the lab to measure elastic scattering, it is a poor model for all neutron interactions that might contribute backgrounds.

Textbooks reiterate the $2 \rightarrow 2$ elastic scattering model for neutrons with statements that “Elastic scattering from nuclei $n(A,n)A...$ is the principal mechanism of energy loss in the MeV Region...In order for the inelastic process to occur, the neutron must, of course, have sufficient energy to excite the nucleus, usually on the order of 1 MeV or more. Below this energy threshold only elastic scattering may occur.” Detecting dark matter by arranging inelastic nuclear transitions was discussed by GW, Ellis et al, as well as Engel and Vogel. Ref. describes a shell-model calculation, and Ref. describes an experimental search. It is true that exciting a stable nuclear level will be inelastic. Yet the condition the neutron must, of course, have sufficient energy to excite the nucleus is wrong and defines Misconception 3. We’ll see there is no lower limit on neutron energies to be inelastic, and much of what is roughly measured as “elastic” neutron scattering actually has an inelastic component depositing energy in the medium. The loophole exists in careful textbooks if buried under a qualifier “...unless there are resonances.” Nevertheless, a large body of work assumes neutron-induced inelastic events are taboo, and use a joint elastic billiard-ball framework where Eqs. 1 2 are the starting points of both signal and background estimates.

There is abundant evidence these issues affect dark matter searches:

2. Calibrating On the Signal

Every experiment calibrates dark matter signals using neutron scattering selected at the elastic point, and at a special neutron energy. None measure instrument response to the full range of neutron interactions, and none put the detectors into situations to actually measure the full range of background events neutron interactions can produce. Experiments should state up front that the energy deposited by neutrons has not been measured and is unknown. This single fact proves our point that experiments have not made their case of exhaustively eliminating backgrounds.

The neutron source $^{252}Cf$ has a spectrum sharply peaked around 1 MeV, and is used by every experimental group except CoGENT. Figure 3.9 of the 1996 dissertation of CDMS collaborator P. Barnes shows beautifully the famous 2-slope response in a 60 g CDMS prototype. The response is produced simply by recording events with $^{252}Cf$ (some neutrons, some gammas) compared to $^{241}Am$ (no neutrons, all gammas and alphas) while recording ionization and phonon energy. The ratio calibrated with MeV-scale neutrons remains a primary signal discriminator through generations of Ph.D. theses to this day. We can find no record of more general experiments, and even the use of another (MeV-scale) radioactive source is unusual. Note only is a single source, single calibration the rule, but even re-calibration with the a given source is done rarely, to avoid activating the
detector.

DAMA/LIBRA (DL) experiments use $^{252}Cf$ and also calibrate quenching using an MeV-scale neutron beam scattering at selected forward elastic scattering angles [13] [14]. There are many such experiments, but always selecting elastic scattering at energies far above most dark matter backgrounds. DAMA’s Ref. [15] explains why generic neutron sources are avoided - to reduce activation. DAMA has never calibrated across the full range of neutron energies. “Pay attention that the aim of these calibrations (and others) is to induce nuclear recoils with neutron energies. “Pay attention that the aim of these calibrations (and others) is to induce nuclear recoils with kinetic energy from few to several tenths keV in the detector, just to study the response of the detectors to recoils. Of course, to do that, neutrons of MeV energy are required [16].” It is consistent with the doctrine that neutrons only produce the recoil signals we use to calibrate.

CoGENT avoids $^{252}Cf$ and calibrates on a monochromatic 24 ± 2 KeV neutron beam using an ancient trick known as an “iron filter.” P. Barbeau [12] states that just three scattering angles were selected, to avoid damaging the crystal, and no other neutron exposure was arranged, to avoid activation.

The XENON experiment [12] [17] also uses $^{241}AmBe$, a source of MeV-scale neutrons. Its neutron beam calibrations use 2-4 MeV neutrons and time of flight to select elastic neutron scattering for calibration. Regions outside the elastic point are rejected.

Once detectors have not been put into neutron beams of all energies to know the response, we cannot agree that the response to neutrons is known.

The exception to single-energy calibration was an experimental accident. It is the sole record found published among dark matter experiments actually exposed to moderated neutrons. The 2006 dissertation of CDMS-collaborator Michael Attisha [12] made the discovery with the SOuden LOw Background Counting Facility (SOLO). SOLO was counting several blocks of low-radioactivity polyethylene for the CDMS experiment. A gross unruly response covering the whole detectable region of 0-700 KeV was observed. The “signals” were traced to a photon cascade from a distant neutron calibration source moderated by the polyethylene bricks. Unfortunately the phonon signal from the moderated neutrons was not described.

To repeat: The experiments on dark matter generally do not measure or report the response of the detectors to low energy neutrons. Response outside the region measured is based on modeling and theoretical extrapolations.

3. What Happens at Resonances?

Dark matter experiments tend to adopt a kinematic framework, the “rigid elastic billiard ball model,” in one uniform way both for dark matter and to define known neutron backgrounds. On that basis neutrons are operationally “defined” by the class of events found in “quenching” measurements. Anyone reading the experimental reports will find the elastic scattering formulas repeated again and again for backgrounds. It substitutes a kinematic model (Eq. 2) for a dynamical question.

Dynamics makes a difference. Even in a classical molecule made of balls and springs, the energy and momentum transferred depend on the time scale of interaction and the dynamics. For example, Eq. 2 predicts a neutron energy loss $\Delta E_n \sim (m_n/m_T)E_n$ when the neutron mass $m_n$ is small compared to the target mass $m_T$. This predicts that $\Delta E_T/E_n \sim 1.3\%$ (for Germanium) and $\Delta E_T/E_n \sim 0.8\%$ (for Xenon). Conversely, if one believes the model, and observes an event with energy $\Delta E_T$, one is led to focus on neutrons from a particular narrow energy range, (or excluding them) declare a “signal.” Yet $\Delta E_n/E_n = 1$ is allowed by conservation laws when a neutron hits a single nucleon inside a nucleus, which is very typical. (In pool, the cue ball (neutron) stops dead when elastically scattering on an equal mass ball (nucleon), while conserving kinetic energy and momentum. ) After the event the reaction of the struck nucleus as molecule will be whatever dynamics determines. It may re-emit the same neutron, or a different neutron, conserving total energy and momentum with an almost arbitrary amount of radiation. Such reactions may still be called “elastic” in neutron-physics parlance not overly concerned with radiation as a “small effect.”

For comparison with rigid billiard-ball theory, Figure 1 shows neutron capture cross sections in Germanium and Silicon. (When cross sections and decays are cited here, they come ndc[15], unless otherwise noted.) The wild energy dependence and sheer magnitude of cross sections defy the simplistic calibration procedures reported in the literature. (Note the log scale, with cross sections exceeding 10,000 barns).

We naturally ask, what is happening to the energy dissipated at all those resonances? Each resonance has a width, which is the inverse time to decay. Energy is going into the medium; the energy in “ionization”, or “phonons,” which are two names for quantum electrodynamic processes, will be spread around. The problem comes to why we can’t find a mention. Every standard detector element, including Sodium, Iodine and Xenon have similar resonant behavior, in some cases even more dramatic (Fig. 2 shows Xenon). The thermal neutron capture cross section of $^{135}Xe$ (not shown, being produced by activation) exceeds 2.6 million barns. This is 50 times larger than the famous 49,000 barn cross section of Gadolinium. The same effective cross section on $^{252}Cf$ (MeV neutrons) is only about 5.8 barns. Obviously the statistical fluctuations of events under such variable rates is a serious complication. The gross discrepancy between calibrating on one physics model and having backgrounds from different physics makes it fair to question whether backgrounds are known.

Table 1 shows a small collection of numerical values of cross sections. It is not even clear which kind of cross section to use for an order of magnitude estimate. The
nominal “elastic” cross sections compiled for neutrons are [18] (in general) the difference between the total cross section and the cross section to other channels that were measured. It is perfectly possible to distribute a few KeV of energy into the medium that was unobservable in old-fashioned neutron reaction experiments. We’ll return to the question of “what is meant by elastic?” shortly.

4. **What Compound Nucleus Theory Does Not Predict**

Neutron physics has certain fundamentals. The theory called the “compound nucleus” explains the thicket of resonances. In inclusive neutron capture, denoted \( A(n, \gamma) \), there is as much as 6-8 MeV of binding energy to dissipate, even when the neutron has zero kinetic energy. Normally one (or a few) MeV-scale gamma rays will account for most of the energy. Note that “most of the energy” is not “all of the energy.”

Neutron physics would be much easier if dark matter experiments operated on MeV-scale signals. Notice that resonances start becoming important at neutron energies as low as 1 eV. There is no exact theory of the resonances, and they cannot be predicted on the basis of established low-lying nuclear excited states. The compound nucleus concept imagines interaction with highly excited, densely packed levels 6-8 MeV above a bound state the neutron wants to make. This is strong interaction physics: it can be estimated in some statistical sense, but not predicted line by line.

Two different interpretations of the same words makes compound nucleus theory always correct by definition. According to tables the first excited state of \(^{23}\text{Na}\) occurs at 439.990 KeV. Under interpretation-1 neutrons with energies less than 440 KeV (plus a bit for momentum) cannot possibly scatter except elastically. This kind of interpretation has been used in dark matter physics to ignore low energy neutrons. Yet data (Fig. 3) for neutrons on Sodium shows a whopping resonance at neutron energy close to 3 KeV. Interpretation-2 says the resonance comes when the neutron energy is close to an excited state of the “compound nucleus.” Since the compound nucleus is defined by inspecting the data, the always-correct explanation is circular, and it means that whatever resonances are observed, are just the ones that occur. To repeat, it is completely wrong to think kinematics prevents a inelastic interaction below the energy to excite a stable nucleus. The correct rendition is that nuclear theory might hope to predict a resonance will occur when the theory of low-lying levels happens to apply. All the other resonances are a gift.
5. Does the Energy Dependence of Neutrons Matter?

To discover how neutrons affect experiments we look for evidence resonant processes were ever considered. Thousands of pages of PhD dissertations and journal articles have been searched, and do not yield a single occurrence of the word “resonance” in the context of neutron-induced backgrounds.

We also look for evidence that slightly different calibrations (despite the consistent agreement never to explore the full range) might have led to experimental inconsistencies. The dissertation of CDMS collaborator S. Kamat finds considerable inconsistencies between data and modeling that we can’t find were resolved. The calibrations of quenching factors in xenon by different groups using different methods do not agree: see Fig. 1 of Ref. [4], and also Fig. 8 of Ref. [20].

We also discover that journal publications from dark matter experiments seldom if ever cite neutron cross sections, or do so only superficially. DAMA/LIBRA cites a single thermal neutron cross section of 0.53 barns for a $^{23}Na(n, \gamma)_{24}Na$ triple-coincidence used as a neutron tracer. No CoGENT publication found cites a neutron cross section. CDMS writes: “while Ge and Si have similar scattering rates per nucleon for neutrons, Ge is 5 - 7 times more efficient than Si for coherently scattering WIMPs.” The dissertations of CDMS collaborators A. J. Reisetter, R. Hennings-Yeomans, and C. N. Bai-
ley, repeat the “similar scattering rates per nucleon for neutrons” statement for Ge and Si almost verbatim. On the basis of repetition in dark matter literature the claim seems direct and well-documented fact.

Compare the claim with Table 1, which shows that Germanium and Silicon cross sections vary from 0.08 barn to 63 barns, depending on how one chooses them. Fig. 1 shows variations by factors of thousands. It is hard to see how Ge and Si are “similar”. Comparing many other over-simplistic statements in dark matter papers with Figure 1 and Table 1 suggest to us that dark matter collaborations are either not consulting the full range of information available about neutrons, or when they consult it, the facts become insider “secrets.” No discovery of dark matter is going to be based on secrets! Consider the consequences: If there is more energy deposited than calibrated as neutron energies decrease, the current practice may count neutrons as dark matter. Conversely, if the neutron energy is overestimated by calibrations, than by miscounting neutrons the experiments may state false limits rejecting dark matter. When there are two types of energy measured, such as ionization and phonon energy, then there are at least four (4) ways to go wrong with incomplete calibration.

| Nucleus  | %   | $\sigma_{\text{thermal}}(\text{tot})$ | $\sigma_{\text{thermal}}(n, \gamma)$ (barns) | $\sigma_{\text{epithermal}}(n, \gamma)$ (barns) | $\sigma_{\text{elastic}}$ (barns) |
|---------|-----|--------------------------------------|-----------------------------------------------|-----------------------------------------------|----------------------------------|
| 23Na    | ∼ 100 | 3.84 | 0.53 | $\rightarrow$ 0.32 | 1.6: (2.45 MeV) |
| 28Si    | 92.23 | 2.13 | 0.16 | $\rightarrow$ 0.084 | $\sim$ 3? (MeV) |
| 29Si    | 4.67 | 2.70 | 0.12 | 0.08 | " |
| 30Si    | 3.1 | 2.56 | 0.11 | 0.54 | " |
| 70Ge    | 21.23 | 16.9 | 3.10 | 2.60 | $\sim$ 6? (MeV) |
| 72Ge    | 27.66 | 9.75 | 0.89 | 0.90 | " |
| 73Ge    | 7.73 | 19.5 | 14.7 | $\rightarrow$ 62.9 |
| 74Ge    | 35.94 | 7.69 | 0.52 | 0.65 |
| 76Ge    | 7.44 | 8.52 | 0.15 | 1.35 |
| 124Xe   | 0.09 | 150 | 150 | 3190 |
| 126Xe   | 0.089 | 8.53 | 3.46 | 66.5 |
| 128Xe   | 1.90 | 12.0 | 5.19 | 12.66 |
| 129Xe   | 26.4 | 24.6 | 21.0 | 245 |
| 130Xe   | 4.07 | 11.0 | 4.78 | 4.91 |
| 131Xe   | 21.2 | 91.2 | 90.0 | $\rightarrow$ 882 |
| 132Xe   | 26.9 | 4.21 | 0.45 | 5.27 | $\sim$ 2? (2-4 MeV) |
| 134Xe   | 10.4 | 4.76 | 0.26 | 0.47 |
| 136Xe   | 8.86 | 8.48 | 0.26 | 0.14 |
| 127I    | ∼ 100 | 9.86 | 6.14 | $\rightarrow$ 159.6 | 3.2; (2.45 MeV) |

TABLE I: A small survey of neutron cross sections. Natural abundance indicated by %. The “thermal neutron cross sections” $\sigma_{\text{thermal}}$ are evaluated at the exact thermal energy 0.024 eV. The “epithermal” $\sigma_{\text{epithermal}}$ is the “resonance integral”; arrows show largest abundance $\times \sigma_{\text{epithermal}}$ for each element. Question marks indicates theory extrapolations at typical energies of elastic quenching experiments.

6. Reliance on Unverified Simulations

Lacking the data-versus data calibrations we first assumed was the core of backgrounds, we’d still hope numerical simulations took complete physics into account.

Unfortunately, numerical simulations do not incorporate even the fraction of neutron-inucleus-atomic processes that are known. Without being privileged to all simulation details, we can verify that some simulations are based on using high energy physics codes upon which the elastic $2 \rightarrow 2$ scattering of neutrons is tacked on at the end. Considerable attention has been given to generating neutrons from muons, which is a standard high energy physics task. For all the rest the coarse-graining of high energy codes customized for many-GeV events ought to be a concern. Propagation and interaction of neutrons through the resonance region ought to be a major complication, but it is another “undiscussed problem.”

In the December 2009 paper[3] Results from the Fi-
We think this discovery gives reasons for concern. Experiments have wisely tried to minimize reliance on simulations. However, it has actually encouraged an impression that neutrons don’t need to be modeled due to their inability to cause inelastic reactions. The 1996 UC-Berkeley dissertation of CDMS collaborator P. Barnes writes that “One line of defense against the muon-induced (underground) neutrons is to moderate the neutrons below detector threshold before they reach the detector. Note than an 18 KeV neutron has a maximum energy deposition on germanium of 1 KeV.” The same statements appear everywhere. If there is reason to hope that signals consistent with elastic recoil at MeV scales would still apply to multi-KeV neutrons, we don’t understand how it is claimed to be known.

A. A Short List of Undiscussed Processes

The problem of energy losses is intimidating because Nature tends to find every channel possible. The Lindhard theory describes the stopping power of atoms and ions in materials. It is based on non-relativistic particle interactions with a free-electron gas, assumptions that the interactions are a small perturbation, and applications of screened Coulomb collisions between two colliding atoms. Every dark-matter quenching experiment cites the Lindhard theory. Citation tends to be self-consistent because the experiments have been arranged to reproduce the theory’s assumptions.

None of the interesting neutron energy losses are included in the theory. Let us try to imagine a few alternative processes that may occur:

- Earlier we found the kinematics of neutrons and nuclei actually allows a neutron to stop dead, $\Delta E_n = E_n$, breaking all the rules of dark matter neutrons.
- After that, if the energy is ignored, the momentum transfer $\Delta p_n = p_n$ might appear in recoil kinetic energy, $\Delta E_T = p_n^2 / 2m_T \sim E_n m_n / m_T$, for which the elastic recoil estimate is ok. This depends on the time scale.
- However, if the time scale of the collision is very slow, the nucleus can be effectively pinned in the crystal lattice. A neutron at rest can fall in to be bound by negative energy $E_B$. The neutron accelerates to get momentum $\Delta p_n \sim \sqrt{2m_n E_B} \sim 10^4 K eV / c$, and spreads this momentum among the other nucleons. The “pinned” nucleus absorbs $\Delta p_n$ and recoils with $\Delta E_T \sim 8 MeV / m_T \sim 80 K eV$. This calculation is completely different from the last, potentially yielding a signal.
- Nucleons typically have Fermi momentum of order 200 MeV simply from being bound. When a neutron arrives, it must fit itself into the wave function, by finding a way to distribute its momentum and
energy in the face of Pauli blocking. However if the neutron is not captured, but merely scatters in a compound nucleus, it interacts (in theory) with excited states not subject to Pauli blocking. During that process the unstable system is radiating to develop the widths observed for resonances.

- A neutron with 1eV-10 MeV of energy might go into a nucleus and be directly captured. Since no detector is 100% efficient, there is a finite probability not to detect the hard photon(s) radiated. The detector reacts to whatever energy it detects, in any form of recoil or resonance radiation, potentially making a signal.

- In electron capture a nucleus with too many protons may also convert an atomic electron to a neutrino of energy in the MeV range. Let \( E_n \) be the energy emitted with a massless particle. The nucleus recoils with energy

\[
\Delta E_T = 0.85 \text{KeV} \sqrt{\frac{m_T}{72 \text{GeV}}} \frac{E_n}{10 \text{MeV}}.
\]

The energy range below 1 KeV happens to be the “signal region” of the CoGENT experiment, and it produces a signal.

Do experiments with neutrons see anomalies not explained by the Lindhard theory? The work of Jones and Kraner\cite{24,25} devised a rather ingenious method to measure atomic stopping power in Germanium. The experiments sought to detect recoil from MeV-scale photons emitted in neutron capture. A precise capture photon (915 KeV) was known to be associated with a decay pathway producing a particular tracer photon (68.5 KeV). The tracer photon was detected in coincidence with the Germanium crystal response. However foolproof the method might seem, the results of \(^{74}\text{Ge}\) compared to \(^{72}\text{Ge}\) did not agree, essentially contradicting the Lindhard theory. (See Fig. 2 of Ref. \cite{24}. Note that \(^{74}\text{Ge}\) is de-emphasized on the plot.) Some plausible excuses were constructed without really explaining the discrepancy. When the “good case” of \(^{72}\text{Ge}\) was pursued in subsequent papers\cite{25} its energy deposition was found to be in discrepancy with theory by about 35%.

Note these discrepancies occur in experiments done with cleverly selected, precise lines predicted from first principles in order to make clean measurements. In using thermal neutrons they also avoid the dangerously resonant region entirely. It is unfortunate that information on the whole gamut of energy deposited in crystals of such experiments does not seem to be available.

II. OUR PROPOSALS

A. DAMA/LIBRA

DAMA/LIBRA is a 250 Kg \(\text{Na}(Tl)I\) detector designed to exploit a strategy of overdetermination, internal-consistency and background rejection regardless of background origin\cite{1,14,28}. “Overdetermination” means using multiple consistency conditions set up to be robust under revision of background estimates. DAMA does not use pulse-shape discrimination to separate recoils, and does minimal processing of raw data. Simulations and accounting for the overall rate and spectrum seen in the detector are sketchy. Kudryavtsev, Robinson, and Spooner\cite{29} give a rather thorough overview of previous criticisms, stating that features of the reported spectrum are difficult to explain and that DAMA’s divulging the measured energy spectrum up to MeV energies is necessary. We will also find that a lack of published information about the spectrum weakens DAMA’s claims.

From DAMA’s documents:

1. The experiment seeks a time-dependent signal. Annual variation of high statistical significance has been found. The phase of the signal is consistent with dark matter flux models.

2. Accepted events must be detected in coincidence, by two independent phototubes connected to each crystal, which controls phototube noise. Multiple-hit events are excluded.

3. Environmental factors including temperature, electronics thresholds, air conditioning, and radon levels are continuously monitored with great care. Contamination with Radon, \(^{238}\text{U}, \, ^{232}\text{Th}, \, ^{40}\text{K}\), etc. are acknowledged, with adequate documentation.

4. The signal region in which annual variation is observed is limited to detected energy \(2\text{keV} < E_d < 6\text{keV}\).

5. Any conventional background producing annual variation in the signal region should produce annual variation in the regions \(E_d > 6\text{KeV}\), which is not observed.

The crucial element, which is more critical and more ambitious than the procedures of other groups, is the concept that any background producing a variation in the signal region should produce a variation over the full energy range above the signal region. This is the extra structure to define a background hypothesis cited in the Introduction. The most important null regions of DAMA/LIBRA are the range \(6\text{KeV} < E_d < 20\text{KeV}\), binned in Fig. 6 of Ref. \cite{1}, and the measured rate integrated above 90 keV, denoted \(R90\).

The energy dependence of neutron reactions falsifies the crucial assumption. It is perfectly consistent for resonant processes to affect one energy region more than others.

What are the important neutron-induced processes? DAMA/LIBRA cites a thermal neutron cross section of 0.53 barns for a \(^{23}\text{Na}(n, \gamma)24\text{Na}\) triple-coincidence used as a neutron tracer. We agree with this particular cross section, listed in Table 1. Yet the rates for triple-coincidence are a strong function of detector acceptance,
and also a tiny fraction of the total rate. Based on the number of coincidences detected, the group cites \cite{14} 28, "An upper limit on the thermal neutron flux surviving the multicomponent DAMA/LIBRA shield has been derived as [110]: <2.2 × 10^{-7} cm^{-2} s^{-1}(90\% C.L.). The corresponding capture rate is: <0.022 captures/day/kg." For reference, the DAMA/LIBRA signal modulation amplitude is about 0.02 cpdf/kg/KeV, or 0.08 cpdf/kg. A simple calculation confirms the flux and thermal cross section gives the rate of captures (counts) per day (cpd) cited. The context of DAMA’s flux estimate is a consistency check designed to be an overestimate. For comparison Ref. [30] cites total fluxes (no shielding) in the Gran Sasso lab of order 1 - 4 × 10^{-7}/cm^{2}/s/MeV at the lowest (MeV) range measured.

Total fluxes from rock are expected to be orders of magnitude larger than muon-induced fluxes. But DAMA has a Lead brick shield inside the concrete, and Lead is an excellent source of neutrons. The production of neutrons from muons has been extensively studied by Kudryavtsev et al, including Ref. [21]. Mei and Hime’s study of muon-induced backgrounds \cite{32} note that neutrons bounce around in caves, while stating “We have seen a large increase (a factor 10-20, depending on the thickness of lead) in the neutron flux due to the additional and efficient production of neutrons in lead...” Ref. [33] actually observed $^{127}$I($n,\gamma$) in a 6.9 MeV line inadvertently induced in Na(Tl)I by adding a Lead shield.

Why do groups emphasize thermal neutrons? It is because they are simple. Yet we have no reason to believe that muon-generated neutrons produced from the Lead or Copper (placed inside the concrete/polyethylene shielding) would be thermalized. Suppose they are epithermal: The resonance integral for Sodium is $\sigma_{res}(23)Na(n;\gamma) = 0.316$ barns, and the estimate decreases. However the resonance integral [15] for Iodine activation $\sigma_{res}(127)I(n,\gamma) = 160$ barns, about 300 times the figure used by DAMA/LIBRA. Iodine activation is not mentioned by DAMA/LIBRA other than a 1998 paper \cite{15} considering a triple-coincidence decay channel less distinctive than Sodium, and papers citing it [16].

Investigation finds that the $^{128}$I isotope produced by capture has a half-life of 24.99 minutes. The NNDC \cite{18} lists decays to $^{128}$Xe (93.0\% ) and $^{128}$Te (6.9\%) predominantly by emission of $\beta^-$ and $\gamma$'s \cite{18}. Beta-decays to $^{128}$Xe are distributed with a mean energy of 801 KeV, and with $5.8 \times 10^{-4}$% in the region 67 - 242 KeV. There is no surprise this would produce no detectable annual variation in R90, the integrated rate above 90 KeV. DAMA’s claims that any events in this region would cause a variation are too broad to be well-defined and hinge on the parts of the spectra that apparently have not been published.

The decay to $^{128}$Te gives definite reason for concern. Almost all decays (5.7 per 100 $^{128}$I nuclei) produce Auger-L electrons with average energy of 3.19 KeV. At the rate of 0.6\% the decay also makes x-rays with average energy 3.77 KeV, which will be immediately absorbed. These energies fit perfectly the DAMA/LIBRA signal region.

Decay to $^{128}$Te also produces about 6\% rate to several Auger and x-ray lines over the region 22 KeV - 32 KeV. This energy lies above the 20 KeV region of Fig. 6 of Ref. [1], and so cannot affect it. The region is also absent from the region covered by R90.

What can be done with the numbers? Recalculating the background in terms of the 0.022 cpdf/kg value with the resonance integral method gives

$$rate\ (3\ KeV) \sim \frac{160\ barns}{0.316\ barns} \cdot 0.6\% \sim 0.7\ cpdf/kg.$$  

This is 10 times the DAMA/LIBRA signal. Assigning a 10\% annual variation gives a background well matched to the DL signal.

There is another way to make the estimate. Ref. [14] states: “Assuming cautiously a 10\% modulation (of whatever origin) of the thermal neutron flux, the corresponding modulation amplitude in the lowest energy region (our italics) has been calculated by Monte Carlo program to be <0.8 \times 10^{-6} cpdf/kg/KeV...the corresponding modulation amplitude is <10^{-4} cpdf/kg/KeV.”

Stating quantities in units of per-KeV without controlling their energy dependence will not do. It is hard enough to estimate the total fluxes of neutrons. DL presents a rough estimate of muon-induced neutron rates. It is based on 20 muons/m^{2}/day, times (1-7) \times 10^{-4} neutrons/muon/(gm/cm^{2}), times 15 tons of material. (That number of neutrons/muon comes from a measurement using liquid scintillator, a hydrocarbon with very low yield.) DL assume 1/16 of neutrons are detected, divided over 4 KeV, with a 2\% annual variation giving between (0.4 -3 ) \times 10^{-5} n/day/kg/KeV. We redd the calculation with the following corrections: (1) 1.1 muons/m^{2}/hour = 26.4/m^{2}/day, the actual Gran Sasso flux; drop four factors of 1/2 used for detection of elastic scattering; multiply by 4 KeV artificially divided; use 0.3 neutrons/muon produced in 200 gm/cm^{2} of Lead, cited for underground muons in Ref. [31]. The calculation gives

$$annual\ variation = \frac{26.4\ muons/0.3\ neutrons/m^{2}/day}{m^{2}/day/\muon} \cdot effective\ area \cdot \frac{0.3\ neutrons/day}{\muon},$$

with an area of 1 m^{2}. If 6\% of these neutrons give a 3 KeV signal the background from Lead-induced neutrons is 0.19 cpdf/250 kg = $7 \times 10^{-5}$ cpdf/kg.

Perhaps these calculations are naive. They use numbers cited by DAMA/LIBRA as straw-man overestimates made under the assumption that neutrons could not possibly matter. Similar complacency is observed in all elastic recoil-based estimates.

Our case has been made when the uncertainties exceed the certainties. Once an order of magnitude calculation matters, a number of other factors enter. DAMA has not published enough quantitative information to know
whether the relative rate of multiple scattering to capture processes makes the veto of multiple-hits informative. What a reader can find is denial that neutrons matter based on the over-simplified picture of neutron interactions endemic to the dark matter community. Our estimate using epithermal fluxes is not particularly reliable, while capture cross sections themselves vary by thousands. If there is a significant energy deposition from resonant radiative damping perhaps the total cross section should be used. The total epithermal cross section of 320 barns rather than the capture cross section of 160 barns, doubling the estimate. Fig. 3 shows that resonances become active in the DAMA/LIBRA signal region. Since it has not been published before, it represents work for the experimental groups using sodium iodide. What is known about how the the energy of those resonances is deposited?

1. Backgrounds Depend on Calculations

Are the Auger calculations of 3.19 KeV energy at a 5.7% rate reliable? Communications with the DAMA group indicate a disagreement about existence of the Auger L component. R. Bernabei responded there is β− decay “with end-point at 2 MeV. Again, no modulation has been observed at high energy, see for example the analysis of R90 in our papers. Therefore, the decay of 128I cannot play any role.”

We checked with experts[34, 35] that the 1252 KeV Q value of 128I → 128 Te is carried away almost entirely by the neutrino. The small recoil energy of the nucleon inside the nucleus translates to the small Auger energy listed. The experts also explained[34, 35] that the Auger calculations given on undc should be good to relative orders of percent, while in the process of being made better[34]. The absence of the 3.1 KeV process on the LBNL website is because those process are not intended to be complete.[35]

Auger energies are first of all a weighted average of many complicated processes with their own internal nomenclature (Auger processes, for those not expert in atomic physics, are first labeled K, L, M...from the inner shell-out.) They are then subdivided into multiple classes such as K − L2 − L3, etc. Different subdivisions and weightings cause small variations. Although sometimes obtained from measurements, the “art” of calculating Auger processes has been long established[34, 35]. Much of the Auger “data” appearing in compilations has been replaced by theoretical calculations said to be highly reliable.

When the DAMA collaboration was consulted[16], we also confirmed that the detectors have never been calibrated with neutrons other than the few-MeV elastic recoil setups used for imitating dark matter signals. Indeed exposure to radioactive sources has been avoided to minimize activation. Ordinary Na(Tl)/f detectors have been exposed to neutrons and show a lively response, unfortunately not studied much below 1 MeV. While acknowledging that DAMA/LIBRA’s multiple-detection strategy and background rejection have been set up to develop a “data versus data” comparison, we do not find it convincing. Evidently what is known about the detector’s response to low energy neutrons is based on extrapolations, Monte Carlo simulation, and rough estimates of Auger processes we hope might be improved in the future.

On the basis of the information publicly available an activation process might as well explain the rate of DAMA/LIBRA’s signals. What about the time modulation?

2. Seasonal Variation of Underground Neutrons

It seems not widely known that the ICARUS collaboration measured the seasonal variation of muons some years ago[36]. The data was recorded for about a year in Hall C of the Gran Sasso lab, using a 32 liter liquid scintillator detector. Events were classified as “alphas” or “neutrons” with energies below (above) 3 (3.5) MeV. The authors of the study report an overall shift of the starting date by as much as 10 days may be possible[37], which is within the error bars. While this experiment is tentative and needs to be confirmed, the data available may be an important key to the DAMA puzzle.

Fig. 4 shows the ICARUS data for the rate deviation (R− < R >)/R re-plotted on a cycle beginning with the calendar year. We fit the data to a constant plus cosine function,

\[
\frac{R-<R>}{R} = A \cos(2\pi(t-t_0)/\text{year}).
\]

The fit gives A = 0.059 ± 0.01, and t0 = 145.1 ± 5 days and \(\chi^2/dof = 1.1\). The peak of this data occurs on May 25, which is within one day of the peak observed previously for DAMA/LIBRA’s annual signal modulation[10].

FIG. 4: Time dependence of underground neutron rates (R− < R >)/R in Hall C of Gran Sasso. Data from ICARUS collaboration[36] re-plotted on yearly scale. The cosine fit has its peak at day 146.4 ± 5 , close to the peak of DAMA signals.
(More recently\[1\] the peak date cited is 152.5, which lies within the ±7 day error bars of previous estimates).

Encouraged by this, we propose that a ratio \( f \) of the Gran Sasso neutrons are transmitted to the DL detector in the range \( 1\text{eV} - 100\text{KeV} \). It is probably impossible to estimate \( f \) from first principles. DAMA/LIBRA reports the apparatus is almost completely surrounded by 1 meter of concrete “which acts as a further neutron moderator.”

a. **About Moderation:** *Moderation* describes the process of slowing neutrons to room temperature by elastic scattering. Since the energy loss depends on the energy, it takes a surprising number of elastic collisions to bring neutrons to room temperature. Leo\[7\] cites an analytic calculation for a 1 MeV neutron needing an average of 111 collisions with Carbon, and 17.5 with Hydrogen. Neutrons actually evolve into an epithermal distribution phase\[38\] in which their energy distribution goes like \( 1/E \), rather than being Maxwellian. As a result, the nuclear physics and nuclear power industry compile *resonance integrals*, which are cross sections integrated over the resonances and weighted by \( 1/E_n \). Comparing resonance integrals with “thermal” cross sections is useful because it avoids the misconception that the thermal cross section (by definition evaluated at the single point \( E_n = 1/40 \text{eV} \) exactly) might be a universal predictor - see Table 1.

Note that moderation does not imply absorption. On the contrary, moderated neutrons are often assumed to be *transmitted*. The “moderating ratio” of nuclear reactor theory is a weighted average of elastic to absorption cross sections. High moderating ratios are desirable for nuclear power uses, and indicate poor absorbers. Polyethylene has a very high moderating ratio\[39\] of 122 in the 1 eV to 100 KeV range: it is a good neutron transmitter. Absorption is a different and specialized topic: there tend to be many channels, of which capture with \( \gamma \) release \( (A(n, \gamma)) \) tends to be important. It turns out that Lead is among the top-10 best *transmitters* of thermal neutrons, with a tiny absorption cross section of 0.17 barns. \( DL \) also has a 1.5 mm layer of Cadmium between the concrete (outside layer) and Lead/Copper (inner layer). Elemental Cadmium has an absorption cross section of 2450 barns, dominated by the cross section of \(^{113}\text{Cd} \) (7.7% abundance) exceeding 20,000 barns, an isotope that happens to be radioactive. Above 1 eV the Cadmium cross section drops precipitously and its resonance integral is only 392 barns. Thus DAMA/LIBRA’s envelope of 1.5mm of Cadmium is ineffective for epithermal neutrons.

b. **Continuing:** Now faced with the fraction \( f \), we note that conservation of neutrons over the energy range \( 1 \pm 1 \text{MeV} \), where Gran Sasso neutron fluxes are measured, translates to an *increase* in epithermal flux at \( 10 \pm 10 \text{KeV} \) by a factor of 100. Assuming this scaling and the known neutron normalization gives a prediction for the \( DL \) single-hit residuals \( A \),

\[
A = f \kappa \cos(2\pi(t - 145.1)/\text{day}).
\]

FIG. 5: Overlay of time dependence predicted by the Gran Sasso underground neutron rate of Fig. 4 (blue online) with time dependence of DAMA/LIBRA signal region 2-6 KeV (red online, Fig. 1 of Ref. [1]). There are no free parameters in the period or phase. Overall normalization is free, and slightly misadjusted for graphic purposes.

Here \( \kappa \) is the conversion factor to obtain DAMA’s definition of amplitude \( A \). From the previous estimate the uncertainties justify fitting \( \kappa \) to the data. Figure 5 shows the prediction from ICARUS time dependence for the DAMA/LIBRA signal in the range of 2-6 KeV. In order to retain information and avoid re-plotting errors, the prediction is overlain graphically with the original DAMA figure. Agreement is excellent. The normalization \( f \kappa = 0.15 \) was deliberately mistuned a bit to avoid a complete overlap.

Environmental neutrons from rock may not be the end of the story. It has long been known that underground muons show seasonal variation. MACRO\[40\] and MINOS\[41\] have measured variations at the few-percent level directly. MACRO’s variation peaks at the beginning of July. These studies used selected “high quality” muons of a particular energy range, and are not representative to measure all muons. Higher quality selection produces smaller variation: the LVD collaboration\[42\] signal is only 1.5%, but seems of very high quality. It peaks in July at day 185 ±15. ICECUBE has reported variations between 10%-15% in ice at the South Pole\[43\]. Once again this is high in South Pole summer, low in winter, exactly reversed in real time relative to the Northern Hemisphere.

The history of annual variations is actually quite extensive. According to Rocco\[44\] it was first observed by Forro\[45\] in 1947 before muons had been named. By 1952 Barret et al.\[45\] gave calculations based on temperature variations in the atmosphere. The history of this effect indicates is not inherently small, while the amplitude as a function of energy can be debated, especially at low energy. It is difficult to assess the relative importance of rock-generated neutrons compared to muon-generated ones. A combination of the two might produce the signals reported by DAMA. Numerical work shows that the fit we cited is degenerate to shifting to earlier dates the peak of the rock-generated muons (as measured by ICARUS) while adding a compensating fraction of muon-generated...
neutrons peaking at day 185. This is because the sum of two cosines with different amplitude and phases is another cosine. Quite a large effect can be tolerated: Letting “1” be the rock-generated amplitude peaked at day 146.4, then (0.72, 0.41) are the amplitudes of rock-and muon components giving an equally good fit when shifted by 3 weeks. The whole range of fit parameters varying linearly with the shift will fit as well in between. Thus DAMA’s can be gotten by a wide range of annual oscillation effects and is not overly dependent on the ICARUS data. [58]

B. CoGENT

Consider the CoGent experiment.[47] “Listing from innermost to outermost components, the shielding around the detector was: (i) a low-background NaI[Tl] anti-Compton veto, (ii) 5 cm of low-background lead, (iii) 15 cm of standard lead, (iv) 0.5 cm of borated neutron absorber, (v) a > 99% efficient muon veto, (vi) 30 cm of polyethylene, and (vii) a low-efficiency large-area external muon veto.”

Note the 0.5 cm of borated neutron absorber. Below 10 KeV Boron is an effective neutron absorber, with the reaction $^9\text{B}(n, \alpha)$ dominating to total. At $10^{-2}$ eV (thermal) energies the capture cross section (weighted by abundance) is about 800 barns, making the 0.5 cm shield about 40 $\mu$m interaction lengths, where $n_{23}$ is the number density in units of $10^{23}$ cm$^{-3}$. However at 1 MeV neutron energy the cross section has dropped to only about 5 barns, making the 0.5 cm shield only about 0.25 interaction length. Fig. 9 of Ref. [23] is concerned with constructing Boron shields and has a discussion on how Boron does not produce complete shielding. We simply do not know the rate of multi-MeV neutron punch-through of the polyethylene and boron shield. Once again the Lead is on the inside, in part to shield from gammas produced by the neutron capture in Boron. Lead makes a neutron source for unshielded cosmic muons for which we have no background rate. No discussion of runs made with the crude but simple step of varying the thickness of moderator and absorber suggest an under-reporting (or immense confidence) about neutron backgrounds.

CoGENT’s signal [2] is an unexplained rise in response below 1 KeV (Fig. 7). Somewhat above the signal is a sharp line at about 1.1 KeV attributed to $^{72}\text{Ge}$. The isotope is produced by knocking out alphas with rather high energy neutrons. The Barbeau dissertation[12] states “According to the background estimate, this would be the dominant contributor to the background.” That is partly on the basis of the isotope remaining in underground experiments with the somewhat long 271 day half-life after surface activation. The knock-out reaction has a cross section of about $10^{-2}$ barns at 10 MeV, (Fig. 6), which then shrinks to negligible values below that energy.

We note that activation of $^{73}\text{Ge}$ and $^{75}\text{Ge}$ in the detector are not mentioned in any CoGENT document found.[48] Metastable $^{73}\text{Ge}$ is produced by activating $^{72}\text{Ge}$ (abundance 28%, epithermal $\sigma_{\text{epithermal}} \sim 130$ barns) and stable $^{73}\text{Ge}$ ($\sigma_{\text{epithermal}} \sim 63$ barns).

Metastable $^{73}\text{Ge}$ decays 198% of the time (per neutron) to 1.19 KeV Auger-L electrons, 47% of the time to 8.56 KeV Auger-K electrons, and there are about 50% x-rays emitted[64] at about 9.8 KeV. A nearly identical pattern of production and decay is seen for $^{75}\text{Ge}$. The half-lives of metastable $^{73}\text{Ge}$ and $^{75}\text{Ge}$ are 0.499 s, and 47.7 s, respectively. Since production and decay of these isotopes is too long delayed to veto with detector dead-times reported, the figures of high veto efficiencies do not translate into statements about neutron rejection. We then consider the activation processes as new candidates contributing to the background which contribute to the line at 1.1 KeV. It is a reasonable proposal, given the low energy capture $^{72}\text{Ge}(n, \gamma)$ cross section is orders of magnitude larger than the cross section of the $^{72}\text{Ge}(n, \alpha)$ reaction (Fig. 6).

Turn to the 8–9 KeV energy decay. The energy is so low it will seldom escape, but be converted inside the detector into other energy. We consulted the x-ray literature to find what happens. X-ray beams often have superb energy calibrations from coherent Bragg scattering, and they take data at tremendous signal to noise ratio. In fact Silicon and high-purity Germanium (HPGE) detectors have been resolving sub-fractions of KeV energies in the x-ray regime for more than 20 years. Some theory of the response function is given in Ref. [19]. In 2003 Papp[51] published a detector study in which individual energy levels of atoms are beautifully resolved. The stated detector resolution is 115 eV. Figure 7 (top) taken from that study is of great interest. Using an 8.4 KeV x-ray beam from CEA Saclay, the detector response reveals a low-energy ramp below 1 KeV. The paper reports this rise is just as expected from M-shell photoelectrons.
The low-energy rise is not noise and is absent at lower x-ray energies (see discussion and compare Figs. 4a and 4b of Ref. [51]). Just to make sure this is real, Fig. 1 and 2 of Ref. [22] show a similar rise. The x-ray response of the detectors is indistinguishable to our eyes from the CoGENT signal.

Why didn’t CoGENT make the same proposal? After we inquired, a collaborator [50] expressed no concern for neutrons after “shielding.” An order of magnitude counting rule for Auger-M was cited. However the estimate and discussion do not appear in publications. It is not consistent with the data of Fig. 7. Rather than quench the question, we find it is the burden of proof of groups such as CoGENT to show that this and other backgrounds have been considered and eliminated.

Fig. 7 also shows that an 8.4 KeV x-ray beam excites some processes filling a region above 1 KeV not filled in the CoGENT data. Papp [51] identifies the increasing component and peak around 6 KeV with the KLL Auger electron spectrum produced by a Nickel electrode. The electrode is absent in CoGENT. There is also no reason to expect external x-ray irradiation to be restricted to the same effects as internal nuclear radiation, as we now explain.

c. Problems of Internal Conversion: First, the CoGENT group is exploring a new technology of P-type point contact detectors for many applications, including double-beta decay. Their detector is designed to be more quiet than an ordinary HPGE crystal detector by arranging very low capacitance, and corresponding low electronic noise (P. Barbeau, Ref[12]). Since CoGENT’s low-energy noise is small, it should be less than the noise of the first-quality HPGE crystals of Ref. [51], which already (to repeat) resolve the M-shell photoelectrons below 1 KeV. So both detectors see the same thing. Second, one of the main reasons that gamma-ray spectra from neutrons stop being tabulated below the 10-100 KeV region is internal conversion. The “internal conversion coefficient” (ic) of gamma rays is the ratio emitted to those absorbed by atomic electrons. Once gotten from data and hand-made calculations, ic are now calculated on websites (“Hager-Seltzer ” coefficients). At energies below 10 KeV calculations may be unstable. That is because ic factors tend to explode as energies decrease: little to none of the energy escapes the atom. Clumsy efforts to generate and measure gamma-rays below 50 KeV escaping a substance may be an exercise in destroying the target.

The coincidence of shape and strength of Auger-M lines makes us believe it may explain CoGENT’s sig-
nal. There does not seem to be enough information published to verify whether rates from neutron-induced processes are consistent. Credible rate estimates will need a higher standard of simulation and a more complete reporting than CoGENT has published. Regarding neutron interactions inside the detector, T. Perrera [12] of CDMS makes a remark not seen elsewhere: “...most high-energy neutrons will penetrate the polyethylene (moderator)...due to reflection by the lead shield, these neutrons will pass through the near-detector region many times before escaping, which greatly increases the interaction probability.” (Italics ours.) Reflection seems plausible since Lead has little absorption and healthy (10-100 barn) estimated elastic cross sections. We believe if more were done or reported about neutrons and healthy (10-100 barn) estimated elastic cross sections. We believe if more were done or reported about neutrons and healthy (10-100 barn) estimated elastic cross sections. But the undeveloped comment is the only case we have seen.

Given the slim reporting and absence of direct calibrations with neutrons, we find every reason to propose that CoGENT has observed a neutron-induced background.

C. CDMS and XENON

Every experiment has an activation process we can’t find discussed in the dark matter detection literature. We find them by going to neutron physics data, and seeking big cross sections with decay in dangerous regions.

The December 2009 paper [13] “Results from the Final Exposure...”, CDMS states that the cosmogenic background is estimated by a simulation. The observed number of vetoed single nuclear recoils in the data is multiplied by the ratio of unvetoed to vetoed events from the simulation. Note: *observed recoils are once again those events consistent with elastic recoil calibrations... as opposed to all neutrons. Unvetoed events will be underestimated if they are simply absent from the code recognizing them.*

We then consider events from activation. Metastable $^{125}\text{Xe}$ is produced by activation of $^{124}\text{Xe}$, with cross sections $\sigma_{\text{thermal}} = 150$ barns, $\sigma_{\text{epithermal}} = 3190$ barns. It decays to itself (“isomeric transition”) with 56.9 s half-life. Potential signals mimicking dark matter might be produced by Auger-L (3.43 KeV, 88.7%), Auger-K (24.6 KeV, 7.7%), CE K (76.7 KeV, 33%) processes. $^{135}\text{Xe}$ is also neutron activated and decays on 15.3 minute half life. Once again the delay is too long for a muon veto to be effective. Apparently the most effective abundance-weighted cross section comes with $^{131}\text{Xe}$ (Table 1). It produces metastable $^{132}\text{Xe}$ with 8.4 ms half-life, decaying to 10-130 KeV Auger and x-ray processes about 50% of the time. We are at a loss to explain why we’ve not found reports from the XENON experiment or associated dissertations about the resonant cross sections or backgrounds. As with the other information in this paper, we can do out best to read everything, but if a crucial basis of the experiment has been missed, it is really the collaboration’s responsibility to publicize it.

Earlier we mentioned that XENON calibrates its quenching factors with elastic scattering by neutron beams of MeV energies, selecting data from the elastic point. Fig. 7 of the paper by Manzur *et al* Ref. [17] is typical of the other studies. It shows that a slice of about 5 ns width was selected from a time of flight distribution over 90 ns wide. The cut selects the first half of particular bump in the data, under the assumption that the contribution from scatters other than single elastic ones is negligible, as supported by Monte Carlo simulations. Cutting to retain the data most purely suited to detect dark matter is done. Commitment to the elastic recoil model for neutron backgrounds is evident: “In order to establish the background rejection efficiency of LXe for a dark matter search, the absolute ionization and scintillation yields from nuclear recoils has to be precisely known [20].” We commented earlier that different quenching experiments of Xenon do not agree. It is probably significant that the points of largest quenching and largest disagreement [22] were taken at higher energies of 6-8 MeV. Comparing Fig 3 (top) of Ref. [22] with Fig. 7 (top) of Ref. [17] finds entirely different structures identified as “elastic scattering”. If the different measurements can be reconciled, the consistent focus on elastic recoil is complemented by a possible lack of curiosity in actually finding out what the more general interactions of neutrons might be.

We propose there is work to do in calibrating Xenon with every possible background. Paying the price of activating a Xenon sample ought to help experiments calibrate the interactions of neutrons in order to support the case backgrounds are understood. For one thing, measurements would support simulations of the XENON active shield, which due to the complicated resonant interactions in conjunction with multiple scattering is not a simple affair. The “First Dark Matter Results” of XENON100 [4] report little more than “GEANT4 Monte Carlo simulation of the entire detector”, while GEANT4 is high energy physics code not designed to emulate the low energy interactions and propagation of neutrons.

If what has been published is true and complete, so that the response to neutrons is based on extrapolations rather than direct calibration, then it may also happen that events misidentified as neutrons and rejected could be due to dark matter.

1. Is More Neutron Data Needed?

The body of knowledge of neutrons experiments themselves give relatively little information about the resonant states of neutron scattering. It is not clear whether new experiments are needed.

The *Atlas of Neutron Resonances* [54] compiles thousands of experimentally determined resonance parameters collected over the past 75 years. Nevertheless, cross section data may not be sufficiently complete or reliable. Much of the data is old. According to the author of
Ref. [55], many experiments were done by transmission methods. They did not actually report cross sections, but fit data directly to multiple Breit-Wigner parameters, which were more convenient to report. Thus one will find gaps and possible discrepancies comparing actual cross sections reported, versus the detail shown by resonance parameters. And then, a cross section measurement does not necessarily disagree with a resonance parameter measurement, because different things were measured....Fig 9 shows 127I(n, γ) cross section data and evaluated data on the a finer scale. (On the nndc website SIGMA, one clicks “Plot experimental data (EXFOR)” and unclicks “ENDF/B-VII.0 Library” to get rid of the resonance parameters. In some cases this leaves a blank plot !) We are assured[55] by the author of the Atlas that resonance parameters “are not based on any theory, but all come from experiment.”

As mentioned earlier, neutron elastic scattering seems to have relatively scant data. It is sometimes assigned by models. The optical theorem relates the total cross section to the forward elastic scattering amplitude:

\[ \text{Im}(M(s, t = 0)) = 4\pi k\sigma_{\text{tot}}(s) \]

As a consequence, rapid variations in total cross sections from thresholds and resonances also tend to be reflected in rapid variations in elastic cross sections. Total and elastic cross sections don’t predict each other, but models exist; they are used when needed on the website.

While “based on experiments”, we find the actual data on neutron cross sections and energy losses (not discussed enough in direct dark matter detection) may not be sufficiently reliable for background calculations. Recalling the claims that Ge and Si cross sections are “similar”, we reviewed the elastic data. The actual set of data for Germanium elastic neutron scattering at nndc consists of one (1) experimental point at 0.02 eV neutron energy that was reported at a 1970 Helsinki conference. [56].

But at least the theoretical extrapolations for Ge and Si to the special kinematic calibration points of neutron quenching studies are “similar.”

Error bars on the energy deposition are not easy to find out. We reiterate the historical reasons for the lack of detail at low energies. Much of the data is quite old. The old technology focused early on energies of 1 MeV and above where the detectors were efficient. MeV-scale detection complemented old nuclear theories focused on the excited levels of stable nuclei. The needs of nuclear power and weapons research focused early on the net flow of energy, as dominated by sufficiently energetic processes. Resonances extending through the KeV region and below were historically hard to measure, and lacked a predictive theory. The “Hauser-Feshbach” statistical model came to be accepted as “good enough” for most nuclear physics, and remains state- of-the-art. Information on more sophisticated neutron energy losses is remarkably hard to find, and possibly classified secrets. This is underscored by the segregation of neutron experts and experiments at weapons labs.

The information found falls short of the incredibly refined ambitions of dark matter experiments to know all background energy below 50 KeV and seeking cross sections below $10^{-44}\text{cm}^2$.

III. SUMMARY

A review of the literature finds a variety of neutron background processes have been under-recognized or perhaps under-documented in the reports of major experimental groups. Since the premises of the experiments rely on quantifying backgrounds above and beyond theoretical extrapolations, neutron backgrounds cannot be dismissed.

It is sometimes thought that direct detection of dark matter is so exciting that the drive for discovery is guaranteed to dominate. However the hypothesis of particle dark matter is defined very loosely in its magnitude and rate. No experiment can falsify the hypothesis. The proposal can only be “truthified” by a dramatic contradiction to conventional physics. But if truthification had top priority, the procedures of DAMA/LIBRA might have been repeated already in the Southern Hemisphere. This indicates there are other forces at work. Nobody wants the field of dark matter detection to follow the slippery slope of unprogressive conservatism where higher and higher status will be achieved by developing better and better technology to discover nothing.

In seeking one consistent explanation of everything known, it came as a complete surprise that the backgrounds, not the signals, are the actual hypotheses of the dark matter detection experiments. The experimentals have to prove their case for backgrounds, not for signals. That is why discussion is appropriate. The situation is rather different from discovering new physics at the LHC (for example), where certain signals of new
physics might stand out. In contrast, the dark matter experiments have already granted that nothing stands out in direct detection and nothing matters until all backgrounds have been exhaustively characterized.

This is why backgrounds have become everyone’s business, and sitting back to accept casual assurance can only harm progress. There are many cases in physics history where discoveries were late because backgrounds of conventional physics became the domain of technical specialists. For example, Leverrier discovered the precession of the perihelion of Mercury in 1859, contrary to rumors that Einstein predicted it in 1915. Leverrier’s proposals failed, and the topic was left to backgrounds of classical celestial mechanics. More and more terms in perturbation theory kept pace with more precise measurements, and for 50 years the inherent profit of validating the status quo, fiddling with parameters, and never taking risks, blindly confirmed Newton’s Laws to higher and higher accuracy. This might have continued forever, so that the opportunity to question the law of gravity itself might have never been born.

Not every experimental group queried showed a willingness to discuss anything about backgrounds. This is something to ponder. We showed here that the existing literature contains many lapses in the treatment of neutrons. The phenomena observed so far appear to be consistent with backgrounds amended to include known neutron physics. We think this is progress.

It would be also progress for experiments to begin clarifying and publishing their neutron backgrounds as a matter of course. For many years collider experiments have published and released their continuum backgrounds, which are fit by thriving communities of higher-order QCD and numerical simulations. In both collider physics and dark matter, the backgrounds are the bulk of the data measured, are interesting in their own right, and cannot possibly be kept as proprietary secrets. Engaging everyone with complete transparency and openness will be how new physics might come to be discovered.

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