Low Energy Experimental Astroparticle Physics

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1 Direct dark matter searches and experimental challenges

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This part of the course, "LE-EXP2" is held by Elisabetta Baracchini.

An archaic example of the search for something "dark" is given by Neptune and Vulcan.

The presence of Neptune was theorized by Le Verrier in the 1800s thanks to its influence on the orbit of Uranus. In this case, the observed anomalies were indeed caused by something "dark".

On the other hand, Le Verrier also attributed the anomalies in Mercury's orbit to a new inner solar system planet, Vulcan; however this was never observed, since the corrections were instead to be attributed to the precession induced by general-relativistic effects.

The idea behind these anecdotes is that, *a priori*, Dark Matter may very well exist, but it may also be an effect of an incomplete theory of gravity: both have happened in the past.

1.1 Evidence for dark matter

Galactic rotation curves The Keplerian velocity of test particles moving around a central mass (which is a good approximation for, say, the Solar system) looks like $v = \sqrt{GM/r}$.[1]

This is roughly what we would expect for the motion of stars at the edges of the galaxy, where little luminous mass is stored; instead of this $v \propto r^{-1/2}$ decay we observe flat rotation curves, indicating the presence of large amounts of mass even at the edges where the luminous mass fades.

This is, in a sense, the most "classic" and oldest indication of the presence of something we now call dark matter.

Galaxy clusters We can give an estimate for the mass of a galaxy cluster by measuring its *velocity dispersion* and applying the virial theorem, which can be simplified to

$$\left\langle v^2 \right\rangle \simeq GM \left\langle \frac{1}{r} \right\rangle . \tag{1.1}$$

[1] This can be easily computed, say, through the virial theorem: $2T + V = 0$, where $T = mv^2/2$ and $V = -GMm/r$.

This measurement of the mass can also be validated through other techniques: we can look at gravitational lensing, by which light is deflected by an angle

$$\Delta\phi = \frac{4GM}{bc^2} \tag{1.2}$$

to first perturbation order in GR, where b is the impact parameter.

Also, we can look at the X-ray emission by the gas in the cluster. This tells us that the average temperature is $T \sim 10\,\mathrm{keV}$. We can use this together with an assumption of hydrostatic equilibrium, which yields a relation in the form

$$k_B T \approx (1.3 \div 1.8)\mathrm{keV}\left(\frac{M_r}{10^{14}\,\mathrm{M}_\odot}\right)\left(\frac{1\,\mathrm{Mpc}}{r}\right), \tag{1.3}$$

to estimate the mass.

Invisible gas is not the culprit: its mass can be estimated to account for around 10 % of the total, while the observed ratio of mass-to-light ratio is on the order of $300 M_\odot / L_\odot$.

Types of gravitational lensing This is a quick aside:

1. *strong* lensing refers to the case in which a massive source deflects the light from a source behind it, which we can see as a distortion or as an Einstein ring or cross;
2. *weak* lensing refers to the combination of several minor lensing episodes in the path taken by the light from its source to us;
3. *micro* lensing refers to an episode of strong lensing in which the lens has a low mass, and there is relative motion which allows us to see a variation in the lensing. This has applications in the search for exoplanets.

Mergers of superclusters Superclusters are the largest gravitationally bound systems we observe, and we have been able to observe their mergers. Here, we can tell that the visible matter is not aligned with the gravitating matter.

Cosmic Microwave Background There are several effects impacting the multipolar decomposition of the CMB: the main ones are

1. the Sachs-Wolfe effect, in which radiation is red-shifted by coming out of an overdense region, so $-\Delta T / T \sim \Delta\rho / \rho$;
2. the Doppler effect, in which radiation is red-shifted depending on the velocity of the matter, so $-\Delta T / T \sim \Delta\rho / \rho$;
3. the Sunyaev-Zel'dovich effect, in which radiation is affected by scattering on hot electrons

4. the integrated Sachs-Wolfe effect, in which radiation goes in and out of a gravitational well, but because of the expansion of the universe it takes longer to get out than it does to get in, resulting in an overall red-shift.

We can model the dependence of the peaks in the CMB spectrum on the presence of baryonic and non-baryonic matter in the early universe, which is what allows us to get very tight constraints on these parameters.

Big Bang Nucleosynthesis BBN depends a lot on the balance between baryonic and non-baryonic matter. With it, we can look at the Universe *before* the CMB.

Still, the estimated amount of baryonic matter from BBN is much lower than the total mass.

1.1.1 Modified Newtonian Dynamics

The idea is that we have never tested Newtonian gravity in a very low-acceleration regime.

MOND was developed to explain galactic rotation curves, but other phenomena are not well-explained by it. Right now, no one has made a MOND theory which can explain all the data.

These lectures will focus on DM as a *particle* which we might be able to detect.

The proposal of DM as a WIMP has been strongly questioned, and also dark matter may:

1. not exist;
2. not be detectable, meaning that it only interacts gravitationally, or it has very suppressed non-gravitational interactions;
3. interact with the upper atmosphere and therefore never reach the ground;
4. be incredibly under-dense...

However, the WIMP hypothesis is not completely ruled out. There is a region in the parameter space we have not explored yet.

Also, developing the instruments used to search for DM is useful for other areas of physics as well.

1.2 Dark Matter candidates

The things we know about it (if it is a particle) are, roughly:

1. it is non-baryonic;
2. it is dark (does not interact with electromagnetic radiation) and neutral;
3. it is stable, or it has a lifetime which is long compared to the age of the universe;

4. it is, at most, weakly interacting (meaning that its interaction cross-section is at most at the weak scale);

5. it is either cold or warm, not hot;

6. we have data about its abundance.

Are there any SM candidates? The obvious candidate is the neutrino; however given the limits we have on their mass we have put limits on their relic density ($\Omega_\nu h^2 \lesssim 0.07$).

This is just one among the many known problems with the Standard Model.

Therefore, we look for candidates beyond the standard model. There is a whole "zoo" of candidates. A convenient way to plot these is on a cross-section versus mass log-log plot.

Some interesting candidates are those which come from other fields: for example, the axion emerged as a solution for the strong CP problem.

1.3 Weakly interacting massive particles

The assumption is that there was no dark matter asymmetry in the early Universe, but two DM particle can annihilate into two SM particles.

The freeze-out mechanism is crucial for the *WIMP miracle*: The decoupling happens when we start to have $\Gamma \lesssim H$.

In the hot, early Universe we have thermal equilibrium between SM and DM particles; then the Universe started to cool, and we only had decay of DM particles into SM ones; then finally both channels decoupled.

Changing the annihilation strength changes the resulting abundance. As we increase the annihilation strength, we decrease the resulting abundance.

There is a quantitative way to discuss this with the Boltzmann equation; the abundance of dark matter, as measured with the density rescaled by the entropy $Y = n/s$, at infinity (so, now) reads

$$Y_\infty = \sqrt{\frac{45G}{\pi g_*}} \frac{1}{T_F} \frac{1}{\langle \sigma_{\text{ann}} v \rangle}, \tag{1.4}$$

where g_* is the effective number of degrees of freedom computed at freezeout, G is Newton's gravitational constant, T_F is the temperature at freezout, while σ_{ann} is the cross-section for the annihilation of these DM particles.

The resulting abundance, as measured with $\Omega_X = \rho_X / \rho_c$ (where $\rho_c = 3H^2/(8\pi G)$ is the critical density for the universe), is

$$\Omega_X \propto \frac{1}{|\sigma v|} \sim \frac{m_X^2}{g_X^4}. \tag{1.5}$$

The "miracle" is that to get the observed density we need to have an interaction on the order of the weak scale, on the order of $\sim 100\,\text{GeV}$.

The SM itself is an effective theory, and it needs new physics at the $\sim$ TeV scale. Supersymmetry provides DM candidates, as well as solving this problem.

Supersymmetric models are many, and they have many parameters.

We also have Universal Extra Dimensions theories. Here gravity propagates in $3+1+n$ dimensions, reconciling the difference between the electroweak and the Planck scale.

The compactification of these dimensions happens in "Kaluza-Klein towers". Here we also get DM candidates.

In the next lecture we will give a quick introduction to axion-like dark matter (Weakly Interacting Slim Particles), but a more complete overview will follow in the last lecture of the course.

Thursday 2021-11-11

The name "axion" comes from a brand of detergent.

$$\mathscr{L}_{\mathrm{QCD}} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \sum_q \overline{q} \Big(i \gamma_\mu D^\mu - \mathcal{M}_q \Big) q + \underbrace{\frac{\theta g^2}{32\pi^2} G^a_{\mu\nu} \widetilde{G}^{a\mu\nu}}_{\text{CP - violating}} . \tag{1.6}$$

This term would give an electric dipole moment to the neutron

$$|d_n| = \frac{e m_u m_d}{(m_u + m_d) m_n^2} \overline{\theta} , \tag{1.7}$$

where $\overline{\theta} = \theta + \arg\det \mathcal{M}$, $\mathcal{M}$ being the quark mass matrix.

The CP-violating term is allowed in the QCD Lagrangian, but we do not experimentally observe it: $\overline{\theta} < 5 \times 10^{-11}$ [CEM21] (see also Kolb and Turner [KT94]).

The neutron dipole moment is bounded at a 90 % CL by $|d_n| < 1.8 \times 10^{-26}\,\mathrm{cm}\; e$ [Gro+20] (as opposed to the older value $|d_n| < 2.9 \times 10^{-26}\,\mathrm{cm}\; e$ quoted in the lecture). Using the PDG values for the quark masses [Gro+20]: $m_u \approx 2.16\,\mathrm{MeV}$, $m_d \approx 4.67\,\mathrm{MeV}$, and the neutron mass $m_n \approx 939.57\,\mathrm{MeV}$, we get

$$\frac{m_u m_d}{(m_u + m_d) m_n^2} \approx 1.67\,\mathrm{MeV}^{-1} \approx 3.30 \times 10^{-17}\,\mathrm{cm} . \tag{1.8}$$

Computing this value does lead to the correct result: it is off by an order of magnitude. Chadha-Day, Ellis, and Marsh [CEM21] report $|d_n| = 3.6 \times 10^{-16} \overline{\theta} e\mathrm{cm}$, while this computation yields 3.3×10^{-17}!
Computing the ratio between the two, using the formula given in the slides, yields $\overline{\theta} \leq 5 \times 10^{-10}$.

Why is this CP-violating phase so ("unnaturally") small?

The Peccei-Quinn mechanism promotes this phase to a dynamical field a, with its own kinetic term $\partial_\mu a \partial^\mu a / 2$,

If we define the dimensionless parameter $\theta = a / f_a$, this is minimized for $\theta_{\mathrm{eff}} = \theta + \langle a \rangle / f_a$.

This field is driven to 0 under the spontaneous breaking of a new global $U(1)$ symmetry.

If we assume the SM gauge group, the mass of this axion will be on the order of the μeV.

This axion may couple to photons, or to gluons, or to fermions. The photon coupling would allow for a $a \to \gamma\gamma$ process.

2 WIMP-like DM experimental detection

What may DM couple to?

1. nuclear matter (quarks, gluons)?
2. leptons (electrons, muons, taus, neutrinos)?
3. photons, or other W, Z, h bosons?
4. other dark particles?

We don't know, so we try them all. We must do it in different contexts, both astrohysical and from particle physics.

Consider the Feynman diagram for a process $\chi\chi \leftrightarrow qq$, where q means "quark" but it could be substituted for any SM particle.

We can look at it from different angles:

1. efficient annihilation: $\chi\chi \to qq$, so indirect detection (in the sky);
2. efficient scattering: $\chi q \to \chi q$ (underground);
3. efficient production: $qq \to \chi\chi$ (in particle colliders).

In particle colliders a χ may be produced, but it would be among a huge amount of other things. There, the particle physics people also must do trigger selection, so they may easily miss DM even if they do produce it.

Particle detectors measure the energy of the final state particles with calorimeters, as well as their momentum and trajectory with a tracking detector equipped with a magnetic field. In detectors such as ATLAS or CMS, neutrinos are indirectly measured by the missing energy.

> The relative uncertainty in the energy measurement of calorimeters is typically proportional to $1/\sqrt{E}$, therefore the accuracy is reported as $\sigma(E)/E = x\%/\sqrt{E/\mathrm{GeV}}$, often shortened to $\sigma(E)/E = x\%/\sqrt{E}$.

Conservation of energy does not really apply, since the quarks are moving around inside the protons before the collision, while the conservation of transverse momentum can be used.

Search paradigms include:

1. mono-X searches: a SM particle recoiling against "nothing";
2. mediator searches: a DM particle acting as a mediator, so it yields a bump in the mass spectrum of SM particle pairs;
3. Higgs portal: if DM couples to it, a Higgs can decay into DM.

Several model-dependent bounds have been given, most of which are below 1 TeV.[2]

Indirect DM searches involve DM particles annihilating into SM particles somewhere in the universe, which we can then detect. This is a good idea in principle, but many candidates have their own issues. Photons point to the source, but they lose energy in the ISM if they scatter, and we have a large background of them from astrophysical sources. Protons and positrons are deviated by magnetic fields therefore we cannot assign them a direction, and we don't accurately know their background level. Neutrinos have a very small cross-section, and while they do point back to the source their directions are hard to determine; also, there is a large neutrino background.

The inverse problem problem It is easy for new data to be modelled as a detection of DM, since we know very little about DM, even if it is actually just background.

2.1 Direct WIMP-like DM searches

The idea is to detect the dark matter particle "bumping into" something we can see, which is typically a nucleus.

The Solar System is moving through the galaxy, towards the Cygnus constellation. Therefore, we expect to see an apparent "wind of DM" in that direction.

Our signal is WIMPs bumping into nuclei, with recoil velocity $v/c \sim 7 \times 10^{-4}$, and recoil energy $E_R \sim 10\,\mathrm{keV}$.

Our background is both electromagnetic (photons bumping into nuclei) and neutral (neutrons or neutrinos bumping into nuclei).

The expected rate is

$$R = N_N \phi_0 \sigma_{WN} = \frac{N_A}{A} \frac{\rho_0}{m_W} \langle v \rangle \sigma_{WN} \,, \tag{2.1}$$

where $\rho_0 \approx 0.3\,\mathrm{GeV/cm^3}$ is the local DM density, the mean velocity is $\langle v \rangle \approx 220\,\mathrm{km/s} \approx 0.75 \times 10^{-3} c$, but the cross-section is $\sigma_{WN} \lesssim 10^{-38}\,\mathrm{cm}^2$.

Therefore, we get $R \sim 0.13$ events per kg per year.

The interaction rate is very low, while backgrounds are very high.

A single banana, on the other hand, yields $\sim 100\,\mathrm{events/kg/s}$, or about a billion times more.

Environmental natural radioactivity is a mess. At LNGS we have more γs than at Boulby in the UK, because that is a salt mine.

We need to shield the detector from all possible backgrounds.

The chain is α easier to block then β, then γ (where we need steel plates), then finally neutrons (for which we need a water tank).

This is because hydrogen has the best kinematic match: same-mass moderators for neutrons are the best.

Roman lead! the production process makes lead radioactive, but if it was produced 2000 years ago we are fine.

[2] One can find many of these plots at https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV.

Another approach is to have active shielding: have detectors which are sensitive to backgrounds around the detector, and then actively remove the background. Monday 2021-11-15

Using pure germanium spectrometers allows one to not have a radioactive detector.

The bigger the detector, the more radioactivity one has to worry about.

We see a PMT sample's spectrum from the XENON collaboration.

We can have radiogenic or cosmogenic activation of the detector. Even if we go under the mountain, some cosmic ray flux remains, which can produce neutrons by spallation (this is cosmogenic). We can also have radiogenic activation: if there is a radioisotope left in our detector it can produce some new neutrons and α particles.

The typical lifetime of a detector is mostly spent trying to minimize its radioactivity.

We also have RPRs, radon progeny recoils: radon has a decay chain producing both α and β particles. Radon is in the air, and the polonium it produces gets stuck to the detector.

If the α decay happens at the edge of the detector, the polonium can escape it, leaving only the α particle inside it, which mimicks a DM signal.

The way to avoid this problem is *fiducialization*: using only signals coming from far away from the wall of the detector (in a "fiducial region"). In order to do this, we need 3D localization of each event.

Another evil background is that given by neutrinos from the Sun. These typically come from the pp chain:

$$\mathrm{p} + \mathrm{p} \to {}^2\mathrm{H} + e^+ + \nu_e \tag{2.2}$$

$$\mathrm{p} + e^- + \mathrm{p} \to {}^2\mathrm{H} + \nu_e \,, \tag{2.3}$$

and more.

Neutrino interactions will look just like the ones we are looking for, and there is no way to shield from them. We also have a diffuse SN neutrino background, as well as atmospheric neutrinos.

Experiments are currently getting close to the sensitivity at which this becomes an irreducible background. This is called the **neutrino floor**.

At GeV to TeV WIMP masses, the main contributions are neutrinos from Boron or Beryllium.

One can look at the differences between the spectrum of energy from these neutrinos, but we need a lot of statistics for this.

Another approach is to look at the directionality: fortunately, Cygnus (from which we expect DM to be coming) never overlaps with the direction of the Sun.

The event rate per unit energy reads

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = N_N \frac{\rho_0}{m_W} \int [v_{\mathrm{min}} < |\vec{v}| < v_{\mathrm{max}}] \, \mathrm{d}\vec{v} \, f(\vec{v}) v \frac{\mathrm{d}\sigma}{\mathrm{d}E_R} \,, \tag{2.4}$$

where ρ_0 is the local DM density, while m_W is its mass; $\vec{v}$ is the velocity of the DM, and we can compute

$$v_{\mathrm{min}} = \sqrt{\frac{m_N E_R}{2\mu_N^2}} \,, \tag{2.5}$$

where μ_N is the reduced mass of the interaction. This is the minimum velocity needed to produce a recoil with energy $\geq E_R$.

The local DM density and its velocity distribution come from astrophysics. We expect the DM halo to extend much further than the galactic disk.

Exclusion limits are traditionally computed setting $\rho_0 = 0.3\,\mathrm{GeV/cm^3}$, which is roughly the mean of our estimates, which are however rather uncertain, ranging from 0.2 to 0.56.

On average the halo is stationary, not corotating with the galactic center. Its velocity distribution is typically modelled as a Maxwellian, with $\sigma \sim \sqrt{3/2}v_e$, where v_e is the escape velocity for the galaxy.

We must also account for the motion of the Sun around the galaxy (which is written in terms of a "local standard of rest"), and the Earth's motion around the Sun.

We have knowledge of large-scale DM distribution, but it could be non-smooth on the milliparsec scale! The Gaia survey suggested the presence of *streams*...

The DM-nucleus cross-section $\mathrm{d}\sigma/\mathrm{d}E_R$ is not known. The order of magnitude of the momentum transfer can be used to estimate it, through $\lambda \sim \hbar/p \gtrsim r_0 A^{1/3}$.

In an effective field theory approach, we can write a Lagrangian like

$$\mathscr{L}_{\text{eff}} = \frac{1}{\Lambda^2}(\widetilde{\chi}\Gamma_{\text{dark}}\chi)\left(\widetilde{\psi}\Gamma_{\text{vis}}\psi\right). \tag{2.6}$$

We will have scalar-scalar, vector-vector interactions which are spin-independent, and enhanced by a factor A^2...

With these assumptions, we can write an expression like

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_r} \sim \frac{2m_N A^2 (f^p)^2}{\pi v^2} F^2(E_R) \tag{2.7}$$

$$F^2(E_R) = \left(\frac{3j_R q R_S}{qR_1}\right)^2 \exp\left(-q^2 s^2\right) \tag{2.8}$$

for the spin-independent contribution.

The spin-dependent contribution is proportional to $J(J+1)$, which is nonzero only if there is an unpaired nucleon.

The important parameter is A^2 for the spin-dependent interaction.

The final term is the kinematic one. The scattering is very much nonrelativistic, since $m_W \sim 10\,\mathrm{GeV} \div 1\,\mathrm{TeV}$; the typical velocity of such a nucleus is $v \sim 220\,\mathrm{km/s} \sim c/1400$.

The recoil energy is therefore

$$E_R = \frac{p^2}{2m_N} = \dots . \tag{2.9}$$

The kinematics of the process means that heavier nuclei cross-sections are suppressed with respect to lighter ones as the energy rises, even though the curves are higher overall because of the A^2 enhancement.

This law would be a strong confirmation that what we are looking at is indeed a DM signal.

The signal is a decaying exponential; but the background is also a decaying exponential. This poses a large problem for identification.

A more robust signature would be the temporal dependence of the rate: our velocity with respect to the center of the galaxy is modulated as we go around the Sun. This will yield a law like

$$\frac{\mathrm{d}R}{\mathrm{d}E} = S_0(E) + S_m(E) \cos\left(\frac{2\pi(t - t_0)}{T}\right). \tag{2.10}$$

DAMA claimed to have seen this kind of signal, but there might be another explanation.

The rotation around the Earth's axis also changes the apparent direction of Cygnus.

We can write a distribution depending on the direction of nuclear recoil:

$$\frac{\mathrm{d}R}{\mathrm{d}E\,\mathrm{d}\cos\gamma}. \tag{2.11}$$

This directional asymmetry is a tool to have a true, positive identification of dark matter.

If we measure the event rate, we can give a plausible region of m_W and $\mathrm{d}\sigma/\mathrm{d}E_R$.

In order to go to low DM mass we need light nuclei and a low threshold, in order to go to high DN mass we need heavy nuclei and large exposure (integration time).

We can also use the material response to a signal to figure out what it is: we can detect *charge* (ionization), *light* (scintillation) and *heat* (phonons).

DM will scatter only once, neutrinos as well. Neutrons might scatter more than once, which allows one to throw them out.

The distribution of energy between the three channels is a possible path for event discrimination.

A nuclear recoil will mostly produce heat, while an electron will mostly yield ionization. The ratio between the visible energies is known as the Quenching Factor:

$$\mathrm{QF} = \frac{E_{\text{visible}}(\mathrm{keV}ee)}{E_{\text{visible}}(\mathrm{keV}r)}. \tag{2.12}$$

Experiments can be then classified in terms of the three detection channels.

2.1.1 Scintillation-based detectors

Tuesday 2021-11-16

DM experiments are classified by which signals they are sensitive to. We start with experiments able to detect light: scintillating crystals and liquid noble-gas detectors.

The idea is that the energy lost as $\mathrm{d}E/\mathrm{d}x$ is converted into visible light, which is then detected with photo sensors (such as photomultipliers). The human eye was also historically used.

Is the claim "the human eye is sensitive to a single photon" true?

We hope that our detector is efficient in the conversion of excitation energy to fluorescent radiation, that it is transparent enough to the emitted light (the Stokes shift is the one between the absorption peak and the emission peak, we'd like this to be large).

The decay time should also be short, so that we have a short response time.

Photo multipliers The photomultiplier includes a photo cathode, where light releases an electron through the photoelectric effect; this electron is then accelerated towards a dynode and moves forward to generate secondary emission on successive dynodes.

The quantum efficiency is not very large: typically on the order of 10 % to 30 %.

Silicon photomultipliers are arrays of avalanche photodiodes in Geiger-Muller regime: they include a p-n junction, which has a depletion region. In this depletion region charges are free and subjected to an electric field, therefore it can be used as a radiation detector.

PMTs can be quite large, while SiPMs are typically small — 1 cm of diameter is already on the large side.

A comparison of PMTs and SiPMs follows.

Include this from the slides.

SiPMs are quite noisy if they are not cooled.

We measure the quantity

$$\mathrm{PDE} = \mathrm{FF} \times \mathrm{QE} \times \mathrm{AP}\,, \tag{2.13}$$

the product of the Filling Factor, the Quantum Efficiency and the Avalanche Probability.

Scintillators There is *quenching*: highly ionizing particles create defects in the atoms or molecules in the medium, thus resulting in quenching.

The emitted light per unit length reads

$$\frac{\mathrm{d}L}{\mathrm{d}x} = \frac{S\, \mathrm{d}E/\mathrm{d}x}{1 + kB\, \mathrm{d}E/\mathrm{d}x}\,, \tag{2.14}$$

where k is the quenched fraction, while B is called the Birks constant. This is called Birks' law.

In certain scintillators we have a two-exponential decay:

$$N(t) = A \exp\left(-\frac{t}{\tau_f}\right) + B \exp\left(-\frac{t}{\tau_s}\right)\,. \tag{2.15}$$

In principle we can do particle identification through *pulse shape analysis*, figuring out A and B in the aforementioned formula.

For DM searches, we typically use either liquefied noble gases or inorganic crystals. Liquefied noble gases have a high yield, a fast response. We can do pulse shape discrimination with them.

However, the light they emit is typically UV. We need ways to shift their wavelengths to detectable ones.

They are very sensitive to impurities, even at the order of 10^{-6}. The best ones (like Xenon) emit several tens of photons per keV.

Electron recoils have sparse ionization, ion recoils have dense ones. The response to highly ionizing particles, such as alphas, is different from the one to minimum ionizing particles such as electrons: they can also be discriminated through PSD, since they excite triplet and singlet states in different proportions.

We compare α particles to electrons — these are the things we can reliably make in a lab setting, ideally we would like to measure the recoils of heavy nuclei, but it's very hard to make these with reproducible, low energies.

Still, the idea is that the response to these αs is roughly similar to that from nuclei.

The difference between triplet and singlet decays is the difference between fluorescence and phosphorescence.

What one can do is then just integrate the starting part of the signal and the end part: this ratio approximates the ratio of the exponential fit components, and allows for the discrimination of nuclear to electron recoils.

These detectors are typically spherical, in order to have 4π coverage. Examples are XMASS at Kamioka, and DEAP-3600 at SNOLAB.

This is the DEAP-CLEAN family. As the mass scale of these detectors grows above the ton, experimental efforts tend to merge.

We look at DEAP-3600. In order to have a fiducial region, we go from 3.6×10^3 kg to 10^3 kg.

The argon used is radioactive! Contaminated with ^{39}Ar. Thanks to pulse shape, they can suppress electron recoils by a factor 10^{10}.

What is the wavelength shifter made of?

The prompt fraction of the light is used as a discriminator. Nuclear recoils have a larger F_{prompt}, of the order of 70 %, while electron recoils have something like 30 %.

Typical efficiency values selected for nuclear recoils is of the order of 50 %.

Fiducialization is the process of reconstructing the direction the signal was coming from. It can be time-based (measuring the arrival delays), or charge-based (measuring the signal amount).

Surface background, such as radon and polonium decays, also populate the signal region for F_{prompt}, however there are other methods.

The effect of the sphere's neck is also relevant, and modelled by current detectors.

The number of photoelectrons detected can be directly mapped to the number of keV in the recoil.

They didn't find dark matter, sadly.

2.1.2 Charge + light: double-phase detectors

The scheme for the ionization of the noble gas is the same, but now we also look at the electron which is ejected when the xenon is ionized. The light signal in the slow and fast channels is called S1, while the electron is called S2.

The ratio of S1 to S2 allows for further discrimination.

The light and charge contributions to the total energy are anti-correlated: if we add them together we reduce the fluctuation in energy by a lot.

We get energy resolutions of the order of $\sigma / E \sim 2$ %.

These detectors are typically shaped like cylinders, as opposed to spheres. It's very difficult to make a uniform, radial $\vec{E}$-field in a sphere.

Even in a cylinder geometry, a "field cage" is used, which prevents the field lines from exiting the cylinder. Instead of a single big voltage, we get a ladder of small voltages.

The first signal, S1, is detected early and after a certain time the charge drifts and allows us to measure the stronger S2 signal.

Electric charge does electroluminsescence and is detected by the same PMTs which detected S1.

2.1.3 Dual-phase noble-liquid detectors

Thursday 2021-11-25

There is a liquid and a gaseous part: the charges are extracted from the liquid with an electric field and then scintillate in the gas part.

The time difference from the initial scintillation pulse in the liquid region and the electron signal in the gas allows us to measure the z coordinate; combined with the measurement from all the sensors we can achieve a 3D localization.

If we use a field of only a few kV/cm, as opposed to several tens of kV/cm, instead of ionizing the atoms the electron just excites them.

We do not get an avalanche then, and we can get a better energy resolution.

We can plot the number of scintillating photons produced per primary event as a function of the electric field divided by the gas pressure. There is a linear regime, and then a dramatic rise. Between 4 and 8 kV/cm there is a minimum in the energy resolution.

We can discriminate electron recoils and nuclear recoils. We make a bivariate plot: the energy deposited in S_2 over that deposited in S_1.

Argon detectors have better discrimination between electron recoils and nuclear recoils than Xenon-based detectors.

With Xenon1T they reached less than $100\,\text{events/ton/yr/keV}_{\text{ee}}$.

The quenching factor is around 20 %: $5\,\text{keV}_{\text{nr}}$ corresponds to $1\,\text{keV}_{\text{ee}}$. Typically, higher atomic numbers correspond to higher quenching.

The detector must be kept very clean: even ppm-scale impurities would absorb the light. The detector is also surrounded by a water Cerenkov muon veto.

Measuring both light and charge provides an absolute energy calibration: we can add them together.

There is a background of radiogenic neutrons: an α decay induces an α-neutron event. The radon decay chain keeps creating problems.

Those events are spatially located at the border of the detector.

They get very stringent limits in the high-mass region (100 GeV range). They did see a few candidate WIMP events.

S_2 only analyses: give up the non-amplified S_1 signal. Do only radial analysis, without considering the depth. The gain is the ability to lower the energy threshold.

Electron recoil analyses: there seemed to be an excess of electron recoil. The idea is to not look at nuclear recoil at all! DM may scatter on electrons as well.

They just look at the energy spectrum of electron recoils. There is a $\sim 3.5\sigma$ excess at low ($\sim$ keV) energies. Is it tritium?

The **Migdal effect** could be a way to move to the low-energy region.

The electron cloud takes some time to follow the nucleus which was hit by something. If this causes the emission of an electron, it is the Migdal effect.

This works for WIMP masses which are below the target masses. However, there is a big penalty factor.

This effect has never been independently experimentally detected! There are proposals to test this effect at higher energies with a neutron beam.

What does looking at this effect mean in the data analysis?

DarkSide is a similar concept, but Argon-based. ^{39}Ar is radioactive, which means a lot of background.

They also saw the low energy excess for electron recoils.

They do need a wavelength shifter since the UV light produced directly is hard to measure.

3 Neutrinoless double beta decay

Thursday 2021-11-18

This part of the course is given by Fernando Ferroni.

In the seventies and eighties the Standard Models was created, putting quarks and leptons in separate families.

We know why the photon is massless, in that it mediates an r^{-2} force. Neutrinos were thought to be massless (by very strong people, such as Glashow!).

When Pauli postulated the neutrino, he thought it was massive! When they were making the SM, instead, they had moved to thinking that the neutrino was massless.

Majorana's idea does not apply is the neutrino was massless. In this course we will see how we might in principle prove or disprove Majorana's hypothesis.

For the examination, he will do it jointly with Elisabetta: a presentation about some technique discussed in each of the two courses.

3.1 History of the neutrino

In 1930, Pauli introduces an "invisible" neutral particle to resolve the issue of energy non-conservation in beta decay.

A two-body process imposes a definite energy to both products! So, with the observed energy spectrum there needed to be a light, neutral particle which did not interact with the detector.

A different hypothesis, by Bohr, was that energy conservation might not hold for each single process, but only on average.

Pauli had a strong social life.

Copy letter by Pauli

He called these particles neutrons!

The true neutron was discovered in 1932, two years later, by Chadwick. He had α particles hit beryllium atoms, which sent neutrons out, which then hit the low-Z paraffin, emitting protons. This would not have worked with no paraffin, nor with a high-Z element.

Chadwick did publish his results. Majorana said "Idiots: they discovered a particle that they didn't understand".

Fermi put these facts all together in 1934. After him, we know how to compute the decay time:

$$\lambda = \frac{2\pi}{\hbar} \left| M_{ij} \right|^2 p_f \,. \tag{3.1}$$

The decay time depends on the "form factor". The matrix element is basically the overlap of the parent and daughter wavefunctions.

The decay from which one computes the Fermi constant is muon decay:

$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3} \left(1 + \Delta q\right) , \tag{3.2}$$

where one finds $G_F \approx 1.1 \times 10^{-5}\,\mathrm{GeV}^{-2}$.

However, all the cross-sections will scale like $\sigma \approx G_F^2 E^2$: this diverges at high energies! This is a problem since it violates unitarity. Therefore, Fermi's theory was known to be incomplete.

The paper was initially rejected, as a "solution to an irrelevant problem".

The solution to that issue was in the Standard Model: unifying EM and weak interactions, mixing photons with the other vector bosons.

In 1935, it was hypothesized that two β decays would occur for the same nucleus: it is known that odd Z nuclei have more energy. So, it is possible that from an even nucleus we can go to another even one, passing through an odd one with a higher energy.

This can happen, but it cannot be frequent: the second Fermi constant heavily suppresses the process.

There are 35 isotopes which can undergo this process. This has a lifetime $T_{1/2}(2\nu\beta\beta) \sim (10^{18} \div 10^{21})$yr, however we can use many nuclei!

In one mole, roughly A grams, of the nuclide we will have N_A isotopes, meaning $10^2 \div 10^6$ decays per year.

The process ${}^Z\mathrm{A} \to^{Z+2} \mathrm{A} + 2e^-$ is often energetically allowed, while ${}^Z\mathrm{A} \to^{Z+2} \mathrm{A} + 2e^- + 2\overline{\nu}_e$ is observed.

Majorana wrote a new fundamental paper, "Teoria simmetrica dell'elettrone e del positrone". He didn't like Dirac's interpretation of a sea of negative energy states. He wanted to avoid the negative energy states. In reality, his theory only apply to neutral particles.

His theory, he said, allowed one to not require the existence of antineutrons and antineutrinos. (He was wrong about neutrons, since they are not fundamental particles).

This would allow one to use the same neutrino for $\beta^\pm$ decay.

Racah replied quickly with "Sulla simmetria tra particelle e antiparticelle" (in Italian!). A Majorana field could describe the situation in which particles and antiparticles coincide, leading however to different physical predictions!

When theorists know that something cannot be tested they do not pay it so much attention. In 1939 W. Furry said that it can be shown that Majorana theory does not make different predictions from Dirac theory in the case of regular β decay, while the prediction do differ in the case of double β decay!

This is through the fact that in the process ${}^{Z}\mathrm{A} \to^{Z+2} \mathrm{A} + 2e^-$ the neutrino/(anti)neutrino pair is only virtual.

Add a loop diagram for $0\nu 2\beta$! Through a W^+ boson.

The issue here is that the neutrino must act as its own antiparticle.

Dirac would say that ν_R^0 is mapped by a CPT transformation to a $\overline{\nu}_L^0$.

Again the story of the decay of the pion into electron being suppressed.

After Furry's paper there was complete silence until the 90s. In all those times it was inconceivable that $0\nu 2\beta$ would be measured.

A massless particle cannot flip its helicity, and the SM was built with massless neutrinos.

However, neutrinos are massive, albeit with a very small mass. This was discovered by the Kamioka experiments, which found neutrino oscillations.

At LNGS they saw some τs from a beam of muon neutrinos! This is also evidence of flavor mixing.

The differences of the masses were thus measured: $\Delta m^2 \sim \mathrm{eV}$. There is an impressive mass gap between these and all the other SM particles!

If we have an experiment looking for proton decay, a significant background will be given by atmospheric electron neutrinos.

The processes will be $\pi \to \mu \nu_\mu$, and then $\mu \to e \nu_e \nu_\mu$. The ratio of muon to electron neutrinos will be 2 to 1. But we do not measure 2! Also, the number changes if we look in different directions.

This can be fit with a model including oscillations. Trying to do this for the purpose of removing the background for proton decay was the reason why people measured this stuff.

One can write a Dirac mass term for the neutrinos. This term preserves lepton number.

In a Majorana mass term, that symmetry is no longer enforced.

A hybrid mass term is also allowed.

A see-saw mechanism allows for three energy scales: m_D at the electroweak scale, m_L is approximately 0 (since we have $2\nu\beta\beta$), and m_R is determined as m_D^2/m_ν, so if $m_\nu \sim 50\,\mathrm{meV}$ we get $m_R \sim 10^{15}\,\mathrm{GeV}$.

Friday 2021-11-19

How do we tell whether a neutrino is Dirac or Majorana? The SM has been built assuming a massless neutrino, and in it (anti)neutrinos are always (right)left-handed; however, since they have mass this cannot be exactly true.

Majorana's hypothesis is as follows: in their rest frame, the only distinction between neutrinos and antineutrinos is their spin, not a Lorentz invariant concept.

This would imply a violation of L at the order m_ν / p_ν. In most cases we observe ultra-relativistic neutrinos, for which this value is tiny.

The weak interaction is $V - A$, while Dirac conserves L.

How do we test this? we need a neutrino beam from the decay of, say, π^+ or Kaons. We would like to have a pure neutrino beam without antineutrinos. We can deflect the charged particles away, but we have an issue: antineutrinos will pollute our beam coming from neutral particles.

The suppression of the $\pi^- \to e^- \overline{\nu}_e$ over the muon decay because of the necessity of a spin flip is quantified by the matrix element $M_{fi} \approx m/(m_\pi + m)$.

For the difference between massive and massless neutrinos, we get

$$\frac{\Gamma_{m_\nu=0}}{\Gamma_{m_\nu\neq 0}} \sim 1 + \frac{m_\nu^2}{m_e^2} \dots . \tag{3.3}$$

For the expected $m_\nu \sim 10\,\text{meV}$ values we get an order 10^{-12} suppression.

Another possibility would be measuring the magnetic dipole moment of the neutrino. This is due to the interaction $\nu + \gamma\nu$ with a $W^+ + e^-$ loop; for a Dirac neutrino we get a nonzero moment, while for a Majorana the prediction is exactly zero.

The prediction is

$$\mu_\nu^D \approx 3.2 \times 10^{-19} \frac{m_\nu}{1\,\text{eV}} \mu_B\,, \tag{3.4}$$

but the current experimental limits are $\mu_\nu < 2.9 \times 10^{-11} \mu_B$ at a 90 %.

Make diagram!

Even measuring this very precisely, if we still measure zero, means that we do not know anything yet.

Since the neutrino mass is very small it is very hard to tell whether they are Dirac or Majorana.

What about $0\nu2\beta$? What is the prediction for its lifetime? The nice thing is that this is a monochromatic process: the energies of the electrons add to the mass difference of the nuclei.

We do know $2\nu2\beta$ very well, it is an easy process to measure. We need a magnetic field, otherwise the two e^- would look the same as pair-production e^+e^-.

The values of $E_1 + E_2$ for the two electrons are binned with 100 keV bins. The end point for this should be where we see $0\nu2\beta$.

From the Nemo measurements, in the Frejus tunnel, we see that the ratio of the lifetimes needs to be at least a million.

And, ^{100}Mo is the fastest of the isotopes doing 2β!

The lifetimes are written in terms of certain terms which are not fully known

$$\Gamma^{2\nu} = G^{2\nu}(Q_{\beta\beta}, Z) \left| M^{2\nu} \right|^2 \tag{3.5}$$

$$\Gamma^{0\nu} = G^{0\nu}(Q, Z) \left| M^{0\nu} \right|^2 \frac{\left| m_{\beta\beta}^2 \right|}{m_e^2}\,. \tag{3.6}$$

What is $m_{\beta\beta}$ in the suppression term? We cannot write "neutrino mass", since we do not know which neutrinos appear. We need to figure out which masses appear in the process.

Also, even seeing this decay might also be an indication of new physics! (Tales we tell ourselves to have more hope)

Are the other terms beside the suppression factor in the lifetimes the same? The phase space term G is computable, it's a bunch of integrals. One must integrate over all possible energies.

The integral comes out to something that fluctuates a lot between isotopes, by several orders of magnitude, for the 2ν case. These are of the order of $G^{2\nu} \sim 10^{-21}\,\text{yr}^{-1}$.

The reason for this is that, to lowest order, the phase space term is $G^{2\nu} \propto Q_{\beta\beta}^{11}$, where Q is the Q-value of the decay.

For the 0ν case we have $G^{0\nu} \propto Q_{\beta\beta}^{5}$. These are typically of the order of $G^{0\nu} \sim 10^{-15}\,\text{yr}^{-1}$.

The nuclear matrix element is a mess. Nobody has ever done a proper *ab initio* calculation.

This must be done taking into account the possibility of passing by excited states. There are several models such as

1. the Nuclear Shell Model;
2. the Quasiparticle Random Phase Approximation;
3. the microscopic Interacting Boson Model (like Cooper pairs in superconductivity);
4. the Interacting Shell Model.

These are hard, there are only few people who do this.

These do not accurately reproduce the measured matrix elements: we should have accounted for the fact that the axial coupling constant g_A may be different from its value for a free neutron, $g_A = 1.269$.

Even normal β decay tells us that g_A varies. The coupling constant seems to scale like $g \sim g_A^{(0)} A^{-0.18}$. But what will g_A for $0\nu 2\beta$ be?

This will not be a pure Gamow-Teller transition, we might have a Fermi (vector) term or a tensor one.

We don't know what the g_A behaviour will be. The calculation methods do not really agree with each other, but they are all within a factor of $2 \div 3$.

Considering all these factors, we can make some estimates: they are typically of the order of $T_{1/2}^{0\nu} \sim 10^{24}\,\text{yr}$ for $m_\nu = 1\,\text{eV}$.

And this scales quadratically with $1/m_\nu$! For $m_\nu \sim 10\,\text{meV}$ we get $\sim 10^{28}\,\text{yr}\dots$

At least the predictions for these isotopes tell us which isotopes to use.

The last part, which is more well-known than the rest, are weak interactions.

We know the Δm^2 for different neutrino species, from atmospheric neutrinos and from solar neutrinos. One is on the order of $2 \times 10^{-3}\,\text{eV}^2$, the other $7 \times 10^{-5}\,\text{eV}^2$.

Specifically, we care about the electron neutrino mass. Is it on the "upper side" or not?

The crucial parameters for an oscillation are

$$1.267 \frac{\Delta m_{31}^2 L}{E_\nu} \,. \tag{3.7}$$

So, measuring the oscillation at LNGS for a 2 GeV beam or after only a km at CERN for a 3 MeV beam should be the same.

The neutrino hierarchy problem is a very big deal.

Pion decay at 3 GeV: the angle for neutrinos will be about $140\,\text{MeV}/(3\,\text{GeV}) \sim 2°$. Monday

The three coupling constants for electromagnetism, weak and strong theory are thought to reach similar values around $10^{15}\,\text{eV}$, which because of the seesaw mechanism corresponds to small energy scales. 2021-11-29

The three masses could be

$$m_1 = m \tag{3.8}$$

$$m_2 = \sqrt{m^2 + \Delta m^2} \tag{3.9}$$

$$m_3 = \sqrt{m^2 + \Delta m^2 + \delta m^2/2}\,, \tag{3.10}$$

or the inverse.

The CKM matrix, defining the mixing of quarks, is rather close to diagonal, while the neutrino mixing matrix is quite "democratic", with all components having rather large values.

The effective Majorana mass is

$$m_{ee} = \left| \sum_{i=1,2,3} U_{\beta e}^2 m_i \right|, \tag{3.11}$$

but due to the phase terms cancellations can occur.

We can make an exclusion plot, with the exclusion range varying the lightest neutrino mass. In the inverted hierarchy case the m_{ee} is around 20 meV, in the normal hierarchy case it could be around 2 meV or even less.

There is this corner we cannot really eliminate. But, we have cosmological bounds for the sum of the neutrino masses. In a ΛCDM model one can include $\sum_\nu m_\nu$ as a parameter.

The half-life for $0\nu 2\beta$ heavily depends on this m_{ee} mass. In the inverted hierarchy case, we have 40 meV which means $T_{1/2} \sim 2.5 \times 10^{26}$ yr. In the normal hierarchy case this is much worse, and we $T_{1/2} \sim 2.5 \times 10^{28}$ yr.

The normalized half-life for the $0\nu 2\beta$ of ^{100}Mo, instead, is $T_{1/2} \sim 4 \times 10^{23}$ yr.

One can look at the original papers from Majorana, Goeppert-Mayer, Furry; the kinematics and nuclear matrix elements for the ones by Iachello, for the weak part the ones by Francesco Vissani.

From a calorimetric point of view, the signal will look like a peak at $Q = 2.039$ MeV in the energy spectrum (that Q value refers to germanium). On the other hand, the $2\nu 2\beta$ decay spectrum is quite broad.

What is quite important to distinguish this peak is the energy resolution of the detector.

The risk of background from $2\nu 2\beta$ may be mitigated by using a tracking particle detector: thin foils of emitter and then tracking gas. The problem, though, is that then we cannot have a large mass of emitter.

This, on the other hand, is a rather good technique to measure $2\nu 2\beta$ itself.

The energy spectrum of a single electron is not very informative in the $0\nu 2\beta$ case. In the $2\nu 2\beta$ case, though, it can tell us about nuclear transitions.

The tracking detectors do not really have good energy resolution.

If the electrons' energy is too low, then they are not detected.

The factors going into the number of detections are the half-life $T^{0\nu}_{1/2}$, the number of available nuclei N_{nuclei}, the duration of the experiment t, and the efficiency of the detector

ϵ:

$$N_{\text{detections}} \approx \epsilon N_{\text{nuclei}}(1 - 2^{-t/T^{0\nu}_{1/2}}) \approx \epsilon N_{\text{nuclei}} \left(\frac{t \log 2}{T^{0\nu}_{1/2}} \right) . \tag{3.12}$$

The time for which we can run the experiment is limited by the human factor; but also the background increases nonlinearly with the time. Therefore, the SNR increases with $\sqrt{t}$, as opposed to linearly with t.

If the calorimeter were to coincide with the emitter, it could allow us to reach a very high efficiency.

We can assume that the number of nuclei scales with the mass, but that is not necessarily true! We will often have different isotopes in the same sample; actually, it is often the case that the interesting $0\nu 2\beta$ isotope is not even the majority of the sample.

The solution to this problem is *isotopic enrichment*. How does that work?

There are two methods (let us discuss it for Uranium): the very painful one is to take the Uranium and put it in a cyclotron; since $\vec{B}$ is constant particles with different energies are separated.

The painful one is to make a Uranium gas (by making the chemical compound Uranium Hexafluoride), put it in a centrifuge which will separate by mass density.

The centrifuge will spin at a few thousand turns per second. Each centrifuge has an awful efficiency, and the process must be repeated many times. The cost in terms of electricity is very high.

The cost is about 100€/g. This is due to both the electricity and the chemistry.

There are cases in which we can easily make a molecule: Xenon is already a gas! Therefore, the chemistry cost for Xenon is zero.

The case in which we save on electricity, on the other hand, is when we have a better isotopic abundance initially.

Suppose we have bought some 95 % enriched germanium. Now we have about 10^{27} atoms within only 125 kg. It will take a while: there are not that many centrifuges for scientific isotope enrichment.

Germanium has a very good energy resolution. However, the phase space for germanium is very bad.

Tellurium oxide, TeO_2, has a quite good isotopic abundance.

Isotopically pure detectors, however, are much better in terms of background.

$\beta^+\beta^+$ decay does not have many good candidates, but it would be nice since it produces 4γ through annihilation. These are an interesting signature. The best candidate seems so be Rutenium, but its transition energy is quite low.

The three things we'd want are an abundance of $\gtrsim 15\,\%$, a $Q_{\beta\beta} \gtrsim 2.7\,\text{MeV}$, a long lifetime of $2\nu 2\beta$.

There seems to be a bit of a correlation between the $\mathcal{M}^2_{0\nu}$ and the specific $\mathcal{G}_{0\nu}$.

Isotopes basically have the same decay rate per unit mass, at any given value of $m_{\beta\beta}$.

The "black line" for $Q_{\beta\beta}$ at around 2.6 MeV marks the end of Earth's radioactivity. The decay of Uranium and Thorium, in the background, yields two decay chains. There is a photon at 2.6 MeV from ^{208}Tl, and below it there are a lot of other things. So, we try to find $0\nu 2\beta$ candidates which decay at above these energies.

In a calorimeter the signature from a single photon and two βs is the same. Tuesday 2021-11-30

Radioactivity is unavoidable as a whole, but some element concentrations can be reduced.

The strongest lines: 2.6 MeV is Thallium, 1.5 MeV is Potassium, 511 keV is β^+ decay.

The 208Thallium line is a strong separator. Near a strong line we have a very taxing requirement in terms of energy resolution.

The number of background events is typically $N_B = n_B t M \Delta E$. It heavily depends on the isotopic makeup of our detector.

We need to choose a window around our expected energy with which to select "signal" events.

The relevant quantity is n_B: the number of background events per unit time, per unit mass, per unit energy. It is typically expressed in $\mathrm{kg}^{-1}\mathrm{keV}^{-1}\mathrm{yr}^{-1}$.

In order to make proper estimates for this parameter we need to select a "background-only" region. Ideally, we would want to also be able to compute it with some *ab initio* calculation.

The sensitivity is

$$\frac{S}{\sqrt{B}} = \frac{n_{\beta\beta}}{\sqrt{N_B}}\,, \tag{3.13}$$

which comes out to be

$$\mathrm{SNR}_{0\nu} \propto x\eta\epsilon\sqrt{\frac{Mt}{n_B \Delta E}}\,, \tag{3.14}$$

where x is the stoichiometric abundance, ϵ is the detector efficiency, ΔE is the detector energy resolution, η is the isotopic abundance.

Germanium is efficient for calorimetry because it is cheap energetically to excite one of its electrons.

One could try to use a calorimeter as a calorimeter, measuring the actual heat.

The thermal capacity tends to zero as $T \to 0\,\mathrm{K}$ (ideally, for dielectric elements). Therefore, we may have a very sensitive calorimetric detector working in that regime. Also, even very small temperature changes (of order nK) can be measured by looking at the change in resistivity of a conductor.

The scaling with time $\sim \sqrt{t}$ is terrible, as well as the one with mass, $\sqrt{M}$.

Also, we have

$$\Gamma^{0\nu} = \frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q, Z)\left|M^{0\nu}\right|^2 \frac{\left|m_{\beta\beta}\right|^2}{m_e^2}\,, \tag{3.15}$$

so the effective neutrino mass we are able to measure scales like $m_{\beta\beta} \propto 1/\sqrt{T^{0\nu}_{1/2}}$.

So, there is a power 1/4 in the scaling of the measured effective $m_{\beta\beta}$ with the time. A factor 10 difference is required to distinguish between normal and inverted hierarchy — it corresponds to a factor 10000 more Mt.

No experiment done so far has even touched the $\sim 50\,\text{meV}$ mass at the upper limit of the inverted hierarchy.

There is a way to escape this problem if we are able to limit the number of background events to $N_B \lesssim 1$.

Given the background index n_B, we can choose the duration of the experiment such that $\langle N_B \rangle \lesssim 1$.

The goals are clear:

1. maximize the mass with the right isotopic composition;
2. minimize the background index;
3. get the best energy resolution possible;
4. get the efficiency as close to 1 as possible.

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