Xenon TPCs for rare searches

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• Contrarily to what their name suggests and to popular belief (Dave Nygren dixit) the main purpose of Time Projection Chambers is NOT time travel.

• There are numerous other devices which can **project** stuff (including people) back and forth on time (see image).

• Unlike Nygren’s TPC, however, none of those devices is known to work yet…
The Time Projection Chamber

• The TPC was invented by Dave Nygren at the Lawrence Berkeley Laboratory (LBL) in the late 1970s. Its first major application was in the PEP-4 detector, which studied 29 GeV $e^+e^-$ collisions at the PEP storage ring at SLAC.

• Since then TPCs have been used to study $e^+e^-$ collisions at PEP, at the TRISTAN collider, at the KEK laboratory, and at the Large Electron Positron (LEP) collider at CERN.

• The device has also figured in heavy-ion experiments such at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven and the ALICE experiment at the Large Hadron Collider (LHC).
The PEP-4 TPC was built to combine charged-particle tracking with excellent particle identification by measuring the specific energy loss (dE/dx) of charged particles.

Charged particles from e+e– collisions in the centre of the TPC ionized molecules in a mixture of 80% argon and 20% methane gas. A central cathode produced a strong electric field. Under the influence of this field, ionization electrons drifted to one of the two end caps.

A solenoidal magnetic field minimized the transverse diffusion and bent the charged particles to allow momentum measurement.

The end caps were divided into six sectors, each one containing a 183-anode multiwire proportional chamber (MWPC). The wire data were used to measure particle energy loss. Because of the high gas pressure, the ionization could be measured accurately and the dE/dx resolution achieved was an unprecedented 3%. This meant that pions, kaons and protons could be identified over most of the kinematic range.

Charged particles were tracked using data from 15 rows of 7 x 7.5 mm2 metallic pads located under the wires.

- PEP-4 TPC was 2 m long and 2 m diameter
- Operational pressure was 8.5 bar
- Cathode voltage was -75 kV
TPCs can be used to track zillions of tracks

- TPCs have been essential tools in heavy-ion collisions experiments.
- The 3D picture of ionization is ideal for tracking particles in high-density environments – hundreds or thousands of particles from a single collision – in which other detectors are overwhelmed by the huge multiplicity.
- The example shows a picture of the tracks emanating from a typical heavy ion collision at 200 GeV per nucleon in the STAR experiment at RHIC.
But TPCs are also ideal for “electronic pictures” of rare events

- MC simulation of the topological signature in the NEXT detector.
- Left picture depicts the trajectory of the two electrons emitted in the decay Xe->Ba2+2e (+2v)
- Right picture depicts a background electron event emitted by cascade decay of Bi-214.
TPC’s have been central to major discoveries (Higgs)
And they may bring about new discoveries
Is the neutrino its own antiparticle?

Neutrinos have no electric charge

The neutrino could be the only known (elementary) particle that is also its antiparticle

If the primitive Universe had neutrinos which were matter and antimatter at the same time (Majorana neutrinos)

And there was CP violation (the primitive neutrino decays slightly more to matter than antimatter and introduces an asymmetry)

We could explain the cosmic asymmetry between matter and antimatter
Are neutrino Majorana particles? Play double or nothing
Searches for neutrinoless double beta decays

Earth is a very radioactive planet

The lifetime of Th-232 is of the order of the life of the universe (14 Gy~$10^{10}$ y)

We now that the lifetime of the $\beta\beta_{0}\nu$ process in xenon is larger than $10^{26}$ y and possibly as large as $(10^{28}$ y)

This means that the initial background beats the signal by 16 - 18 orders of magnitude.
How many grains of sand?


About 1.5 x 10^9 per square meter (to a depth of 3 m). A beach 70 km long and 10 km wide would have 10^{18} grains of sand.
Take a walk in the Dark Side

• The image, a composite of optical data, X-ray data, and a reconstructed mass map, is one of the most famous and informative ones in all of astronomy.

• Known as the Bullet Cluster, it showcases two galaxy clusters that have recently collided.

• The individual galaxies present within the clusters, like two guns filled with bird shot fired at one another, passed right through one another, as the odds of a collision were exceedingly low.

• However, the intergalactic gas within each cluster, largely diffuse and making up the majority of the normal matter, collided and heated up, emitting X-rays that we can see today.

• But when we used our knowledge of General Relativity and the bending of background light to reconstruct where the mass must be, we found it alongside the galaxies, not with the intra-cluster matter. Hence, dark matter must exist.
Xenon TPCs for rare event searches

Why Xenon?

- **DARK MATTER** (in particular for Weak Interacting Massive Particles, or WIMPs) searches need:
  
- **A target of high A**, since the interaction cross section of WIMPs are (in the simplest case) proportional to $A^2$.
  
- **A low detection threshold**, since the energy of the recoiling nuclear fragment is very small.
  
- An experimental technique that provides **ultra-low radioactive background**. In particular, target material must not have long-lived radioactive isotopes.
  
- A possibility to **distinguish** signal (**nuclear recoils**) from backgrounds (**electromagnetic recoils**).
  
- **Detectors should be scalable** to large masses (in the vicinity of 100 ton), so that signal can be explored until reaching irreducible backgrounds (**neutrino floor**).

Principle of operation of a two-phase Liquid Xenon (LXe) TPC, the battle horse of a whole family of dark matter experiments. S1 provides the trigger, S2 the energy, PMT array provides (x,y), time between S1 and S2 translated into a Z coordinate.
The Xenon family has, so far, spawned four children
All of them based in the same principle: Xenon-10, Xenon-100, Xenon-1t and Xenon-nt. Close cousins LUX, LZ and PANDA-X, are also dual phase Xenon TPCs.

Do we need so many different experiments based in the same principle?
(Answer in the next two transparencies. Spoiler: yes)
Searching for DM. The known unknown…

- The search for WIMPs in XENON1t yields results consistent with the expectation from background, and place stringent limit on spin-independent interactions of WIMPs with ordinary matter for a WIMP mass higher than $6\text{ GeV/c}^2$.

- Even though about a billion WIMPs are expected to cross a surface of one square meter per second on Earth, this search shows that WIMPs, if they indeed comprise the Dark Matter in our galaxy, will result in signal, so rare that even the largest detector built so far can not see it directly.

- The sensitivity achieved with XENON1T is almost four orders of magnitude better than that of XENON10, the first detector of the XENON Dark Matter project, which has been hosted at LNGS since 2005.

- Over ~15 years the technology has scaled by $> x 200$ (5 kg to 1300 kg), while simultaneously decreasing the background rate by a factor 5000.
Searching for DM. The unknown unknown…

- One explanation could be the presence of tiny amounts of tritium in the detector. Only a few tritium atoms for every $10^{25}$ xenon atoms would be needed to explain the excess.

- Another explanation could be the existence of a new particle. The excess observed has an energy spectrum similar to that expected from axions produced in the Sun. Axions are hypothetical particles that were proposed to preserve a time-reversal symmetry of the nuclear force, and the Sun may be a strong source of them. Their detection would mark the first observation of a well-motivated but never observed class of new particles, with a large impact on our understanding of fundamental physics, but also on astrophysical phenomena.

- Alternatively, the excess could also be due to neutrinos, if their magnetic moment is larger than predicted by the Standard Model. This would be a strong hint to some other new physics needed to explain it.

- The figure shows the excess observed in XENON1T in the electronic recoil background at low energies, compared to the level expected from known backgrounds indicated as the red line.
The ultimate (so far) version of the DM LXe TPCs is the propose Darwin experiment, which scales the initial detector (5 kg) by 4 orders of magnitude. LXe should be able to resolve issues such as the low excess of electronic recoil (unknowns unknowns turning known unknowns) and hopefully finding new unknown unknowns.
Double beta decay

• Some nuclei, otherwise quasi stable can decay by emitting two electrons and two neutrinos by a second order process mediated by the weak interaction.

• This process exists due to nuclear pairing interaction that favours energetically the even-even isobars over the odd-odd ones.
Two protons decay simultaneously in a heavy isotope. Nuclear physics results in proportionality constants between period and the inverse of the Majorana mass squared.

\[ (T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q, Z) |M^{0\nu}|^2 m_{\beta\beta}^2 \]

- **Phase-space**
- **Nuclear matrix**
- **Majorana neutrino**

\[ \beta\beta 0\nu \]
Why Xenon?

- Neutrinoless double beta decay ($\beta\beta0\nu$) searches require a target material where double beta decay occurs. There are only a handful of such isotopes with sufficiently high $Q_{bb}$, including Xe-136.

- The target element must have reasonably high $Q$ and NME.

- The target element must provide good energy resolution, since a key signature of the NLDBD process is the fact that the sum of the kinetic energy of the two electrons is constant.

- The experimental technique must provide a way to suppress radioactive backgrounds. Expect about 1 event per ton and year for a lifetime of $10^{28}$ years. Backgrounds must be surpassed below that level.
Xenon TPCs for NLDBD. LXe or HPXe?

- Compact detectors which can achieve “large” masses (O(1 ton)) in a single module of moderate size (~1 m³). On the other hand, while scaling is “easier”, staging is difficult. One must pay all the enriched xenon upfront.

- LXe is self-shielding. If sufficiently large, detector’s core is very quiet. This advantage is also exploited by DM detectors, but the energy regime of NLDBD is higher.

- Energy resolution is good to modest (~2-3 % FWHM). Topological information of 2 e- is not available.

- Ba²⁺ tagging may be possible.

- Detectors are less compact, about 100-300 kg (m³) depending on operating pressure. “Harder” to scale, but staging possible.

- Excellent energy resolution (< 1 % FWM). Topological signature is available (Identification of 2 electrons). Requires EL amplification (and most likely pure xenon)

- EL TPCs (NEXT, XENON, LZ, LUX, DARWIN) detect only light (S2 converted via electroluminescence in photons)

- Ba²⁺ tagging may be possible
**LXe TPCs for NLDBD: EXO-200**

- Demonstrated LXe technology
- Searched for $\beta\beta 0\nu$: sensitivity $T \simeq 3.7 \times 10^{25}$ y. Limit $T > 1.8 \times 10^{25}$ y at 90% CL.
- $BQ: (1.5 \pm 0.3) \times 10^{-3} \text{ kg}^{-1} \text{ yr}^{-1} \text{ kev}^{-1}$
• Monolithic detector with 5 ton total mass (2 ton fiducial mass). Principle of operation like EXO-200, modern technology

• S2 measured from charge (no amplification, tiles at the anode).

• S1 measured covering the barrel with SiPMs.

• Combines low background budget, self-shielding, good energy resolution.

<table>
<thead>
<tr>
<th>LXe mass (kg)</th>
<th>Diameter or length (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000</td>
<td>130</td>
</tr>
<tr>
<td>150</td>
<td>40</td>
</tr>
<tr>
<td>5</td>
<td>13</td>
</tr>
</tbody>
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This works best for a monolithic detector
nEXO performance

Lifetime required for good ionisation measurement: 10 ms (EXO 3ms)

In inner 2 ton: \[ B(\text{nEXO}) \sim 3.6 \times 10^{-4}/(\text{FWHM} \cdot \text{kg} \cdot \text{year}) = 5.3 \times 10^{-6}/(\text{keV} \cdot \text{kg} \cdot \text{year}) \]

\[ B(\text{EXO}) \sim = 1.5 \times 10^{-3}/(\text{keV} \cdot \text{kg} \cdot \text{year}) \]

Reach: \( T \sim 10^{28} \) year for 50 ton \cdot year
Darwin for $\beta\beta$0ν

Rate versus fiducial mass

Rate in 5 tonnes fiducial region (0.45 t $^{136}$Xe)

Signal: $T_{1/2} = 2 \times 10^{27}$ y

Lifetime: 10 ms (XENON-1t 1ms), Energy resolution = 1.8 % (XENON-1t 1.8%) FWHM at $Q_{\beta\beta}$

Reach: $T \sim 2.4 \times 10^{27}$ year for 5 ton \cdot year similar to nEXO

$2.4 \times 10^{27}$ y for 5 t \times 10 y exposure (90% CL)
• HPXeEL TPC

• Good energy resolution (measured < 1 % FWHM, feasible 0.5 % FWHM).

• Topological signature (reconstruction of electrons in event). Measured 70 % efficiency for 95 % background suppression, expected 90-97 %

• Radiopure detector, along the lines of all other Xe TPCs

• Strong potential for barium tagging “in situ”.
The NEXT program

- Prototypes (~1 kg) [2009 - 2014]
  - Demonstration of detector concept
- NEXT-White (~5 kg) [2015 - 2018]
  - Underground and radio-pure operations, background, ββ2ν
- NEXT-100 (~100 kg) [2020 - 2020’s]
- NEXT-HD/BOLD [2020’s]
  - ββ0ν searches (10^{26} - 10^{28} y)
  - Show extrapolation to ton scale
• A full scale demonstrator of the NEXT technology (started in 2016)

• Energy resolution, topology, lifetime, measured $\beta\beta 2\nu$ mode
Energy resolution at $Q_{\beta\beta} \sim 0.8\%$ FWHM dominated by track corrections (0.5% FWHM for point-like tracks). Room for improvement.
Topological signature

Single and double electrons from $\beta\beta 2\nu$ analysis with energies near $Q_{\beta\beta}$
NEXT-100 (construction under way)
Detecting “tagging” the Ba++ signaling a $\beta\beta0\nu$ process has been a long sought holy grail of xenon chambers.
The NEXT Collaboration’s Big Idea:

Exploit *single molecule fluorescent imaging (SMFI)* to visualize a single barium ion as it arrives at the TPC cathode.

For $^{136}$Xe, in gas phase, the daughter is $\sim 100\%$ $^{136}$Ba$^{++}$, perfect for using SMFI techniques.

Goal: develop custom molecules that change luminous response after chelating Ba dications.

Molecules must (and do!) display high specificity to Ba$^{++}$

Common elements: crown ether + fluorophore + linker

Complementary approaches explored in US and Spain

Spain: molecule changes color strongly: green $\rightarrow$ blue

Texas: molecule changes from non-luminous to luminous

Molecular engineering: predictive computations too!
New Chemistry

• Conventional ion chemosensors are not suitable for solventless (dry) imaging.

• NEXT has developed selective, dry-phase imaging of barium ions using crown ether derivatives.

• Ring receptor can be tuned to bind efficiently and selectively to barium.

• Computational chemistry is predictive for molecular fluorescence and binding.

• Two types have been developed: on-off, and bi-color.

Nature 583, 48–54 (2020)
arXiv: 2006.09494 (submitted to JACS)
Ba$_2^+$ expected to chelated indicators in high pressure gas

_Nature 583, 48–54 (2020)_
First demonstration of Ba$^{2+}$ chelation in dry medium

**Fig. 3** Sublimation of Ba(ClO$_4$)$_2$ on the FBI. **a**, Experimental setup. Photograph of the interior of the UHV chamber used for sublimation. The positions of the pellet, evaporator, quartz microbalance and mass spectrometer are indicated. **b**, Photograph of the pellet before sublimation. **c**, Photograph of the pellet after the sublimation. In both cases, the excitation light is 365 nm. We note the characteristic green colour of unchelated FBI before the sublimation and the blue shift after the sublimation, which shows a large density of chelated molecules.

*Nature* 583, 48–54 (2020)
NEXT Steps

• Ion beams using $^{222}\text{Rn}^{2+}$ from thorium decay are under development for single ion test.
  (RITA/SABAT program, Spain)

• Beam tests also planned at ANL CARIBU with $^{144}\text{Ba}^{2+}$ mass-selected from $^{252}\text{Cf}$ fission.
  (GodXilla program, USA)

• The ultimate test-beam is $\beta\beta\nu$!

• Demonstrator phases at 10kg-scale are being planned for ~2024-2025.

• Multiple full system concepts under exploration, to be guided by ongoing R&D.

"SABAT" concept with fully active cathode, SiPM-based tracking and Energy Barrel Detector

"CRAB" concept with RF carpet concentrators and camera-based topology measurement
**NEXT-BOLD (SABAT) concept**

- Asymmetric detector.
- Energy measured by Barrel Detector (fibres).
- Topology reconstruction with SiPMs.
- High pressure to increase mass and decrease size of track (40 bars)
- Scanning region selected by predicted impact point.
- Cathode at V+ opens gate only on delayed bbonu trigger.
- Fast, high-pressure microscopy.
- Prototype: NEXT-White or NEXT-100

**Delayed trigger:**

- Single deposition with energy in ROI
- Opens gate at predicted arrival time
- Scans ~1cm around predicted arrival point

**Funding for SABAT program granted through an ERC Synergy Grant.**
• A detector similar in size to DARWIN, operating at high pressure (30-40 bar), deploying 2-3 tons of mass and instrumented for Ba$^{2+}$ (thus virtually background free) will have a very large discovery potential.
TPCs for rare searches

• At almost 50, the time projection machine invented by Dave Nygren has become an ubiquitous detector in particle physics experiments.

• Xenon TPCs have become mayor players in the searches for rare events. The field of Dark Matter appears dominated by the XENON large family, while xenon appears to be also very promising in the search for NLDBDs.

• LXe TPCs offer many advantages for both kind of searches, including scalability and self-shielding.

• HPXe TPCs may offer, in addition of excellent energy resolution and a topological signature, the possibility of Ba2+ tagging, leading to large-scale, background free experiments able to explore NLDBD lifetimes of $10^{28}$ year and beyond.
Fig. 3: Sublimation of Ba(ClO$_3$)$_2$ on the FEL. a, Experimental setup. Photograph of the interior of the UHV chamber used for sublimation. The positions of the pellet, evaporator, quartz microbalance and mass spectrometer are indicated. b, c, Photographs of the pellet before (b) and after (c) the sublimation. In both cases, the excitation light is 3.65 nm. We note the characteristic green colour of unchelated FEL before the sublimation and the blue shift after the sublimation, which shows a large density of chelated molecules.