Noise Proofing Molecules for New-Physics Searches

Certain molecules can be placed into states that are less sensitive to external noise, offering researchers a quiet system for probing fundamental physics.

By **Steven Hoekstra**

Molecules are like tiny sandboxes for exploring fundamental physics. Within the molecular environment, bound electrons and nucleons can be exposed to exceptionally strong fields, inducing effects that can't easily be observed elsewhere. By measuring transitions within these molecules, researchers can look for small deviations from theory, which could be signs of new physics beyond the standard model of particle physics. However, molecules are very sensitive to external fields, causing "noise" that can hide the small internally induced deviations. Yuiki Takahashi and colleagues at Caltech have come up with a potential solution, which counterintuitively uses external fields to make molecules immune to external fields [**1**]. By exposing small triatomic molecules to carefully tuned electromagnetic fields, the researchers have placed the molecules into special states where their sensitivity to noise is reduced by a factor of several hundred. With further experimental improvements, such noise-proofed molecules should be prime "locations" for precision tests of fundamental physics.

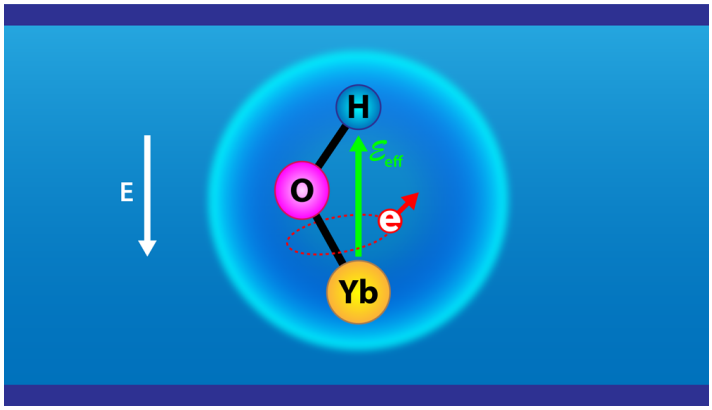

Figure 1: An ytterbium hydroxide (YbOH) molecule is placed in an electric field (E), causing a strong polarization field ($\mathcal{E}_{\text{eff}}$) to form with the molecule. Valence electrons interact with this field, potentially revealing a signature of the electron electric dipole moment. The challenge is that electromagnetic noise can also interact with the molecule. Researchers have devised a way to "shield" the molecule from this noise by taking advantage of so-called clock transitions.
Credit: APS/Alan Stonebraker

Atoms and molecules typically respond quite strongly to their electromagnetic environment. As early as 1896, physicist Pieter Zeeman noticed that the light emitted by a gas of sodium atoms spectrally broadened in the presence of a magnetic field. This sensitivity to the external field is practically unavoidable, as atoms consist of moving charges and spin degrees of freedom that are strongly coupled to magnetic fields. Electric fields can also have a strong effect, especially on molecules made up of different elements: Since their charge is unevenly distributed, these heteronuclear molecules become polarized and experience a force that depends on their orientation in the field.

The strong polarization of molecules can be exploited in searches for new physics. A molecule polarized by an external field exposes its valence electrons to an internal field that is amplified by as much as a million times compared with the external field. This amplified field offers a very sensitive probe of the electric dipole moment (EDM) of the electron. The standard model of particle physics predicts that the electron EDM is extremely small: around 10^{-35} e cm, where e is the electron charge [**2**]. But there are theories—in particular, those

aiming to explain the dominance of matter over antimatter—that expect a relatively large electron EDM, up to 10 orders of magnitude larger than the standard-model upper limit. Since the 1960s, researchers have searched for an EDM in electrons, as well as in other fundamental particles, but no signal has yet been seen [**3**]. Recent improvements in measurement techniques have increased the sensitivity, allowing experiments to probe lower EDM values, thereby severely restricting the parameter space of new theories.

There are, however, significant experimental challenges. To search for an EDM signal in a molecule, researchers typically need a strong external electric field, and they need to reverse it to see an asymmetry. But that reversal produces a magnetic field that can interact with the electron spin, generating an effect that is much stronger than the electron dipole interaction with the internal electric field of a polarized molecule.

Takahashi and colleagues have devised a way to effectively shield their molecules from external fields. To test their solution, they chose ytterbium hydroxide (YbOH), a triatomic molecule with reduced sensitivity to external noise [**4**]. In addition, the molecule's heavy Yb nucleus hosts highly relativistic valence electrons, which provide a strong probe of EDM effects. The team generated a beam of YbOH and exposed it to a combination of electric, magnetic, and optical fields, which allowed the internal structure of the molecules to be examined in great detail (Fig. **1**).

The main element of the measurement is called Ramsey interference. In this technique, a laser pulse first prepares the molecules in a quantum superposition of two internal states—in this case, rotational states of the molecule where the oxygen atom rotates around the molecular axis. The molecules then traverse a distance of 5 mm, over which their quantum superposition evolves under the applied electric and magnetic fields. This evolution ends with a second laser pulse that induces interference between the two parts of the superposition. The final state of the molecules (which is read out by a laser-spectroscopy measurement) depends on electric and magnetic interactions, among which is the sought-after interaction between the electron EDM and the polarization field of the molecule. The signature of this EDM interaction would be a correlation between the electric-field direction and the spin direction of the electron (which is set by the applied magnetic field).

Given this context, it is rather remarkable that Takahashi and colleagues have been able to reduce the sensitivity to electromagnetic noise while still probing the effect of an EDM. To understand this electromagnetic-noise cancellation, we need to take a closer look at the molecular quantum structure. In laser spectroscopy, a transition between two energy levels is driven by a laser—provided the light's frequency precisely matches the energy difference between the two levels. These levels can shift in the presence of an external field, causing a mismatch with the laser. However, Takahashi and colleagues targeted energy levels that shift up and down in the same way, keeping the energy difference the same. As a result, the laser driving frequency becomes less sensitive to electromagnetic noise, and one can measure subtle effects, such as those caused by the electron EDM.

Transitions that are practically insensitive to external fields are not new; they are a key ingredient of atomic clocks, where such transitions are called magic. What is new is that Takahashi and colleagues have shown that these clock transitions can suppress background in molecular EDM experiments while maintaining EDM sensitivity. This achievement thus opens new possibilities to probe for very faint effects of new physics, for which the chosen YbOH molecules are very well suited.

Whereas the experiment demonstrates all the elements of an EDM-type measurement, it is not yet optimized for maximum sensitivity. The interaction region with external fields is only 5 mm long. In typical EDM experiments, this region is about a meter long, allowing telltale effects more time to accumulate. Also lacking is laser cooling of the molecules, which would prevent the beam from spreading out. But by improving these and other factors, this experimental setup could become relevant not only for fundamental physics, but also for a range of exciting applications—from quantum simulation to ultracold chemistry—where molecules with controllable sensitivity to external fields would be useful.

Steven Hoekstra: Van Swinderen Institute, University of Groningen, Groningen, Netherlands; and National Institute for Subatomic Physics (Nikhef), Amsterdam, Netherlands

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