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Abstract

One of the biggest unexplained phenomena in physics is the lack of antimatter particles present in the universe which should equal that of matter particles according to the Standard Model, among the most successful theories ever formulated. Given the Standard Model's failure to explain such phenomena physicists, both on the theoretical and the experimental side, have been investigating other possibilities.In many locations worldwide physicists have been searching for an electric dipole moment in neutrons (nEDM) which, if found, would provide proof of charge conjugation and parity symmetry violations (CP violation) thus giving clues on why the matter-antimatter imbalance exists.

Contents

1 The matter/antimatter asymmetry and CP violation

1.1 The Sakharov conditions

When we look around us, we see a universe containing mostly matter. But from particle physics, we know that there is an existence of antimatter. From current theories, it is expected that these will appear in an equal amount. This is not at all what we observe when we look around us. Because when it would be the case that the universe contains equal parts of matter and antimatter, then the whole universe would be a sea of electromagnetic radiation - because of the annihilation of matter and antimatter, with no more matter in it. We can conclude that there must be an imbalance in matter and antimatter.
To satisfy this imbalance, Andrei Sakharov proposed three conditions:

1. There must be a *baryon number violation*, because only when this number is not conserved, an unequally amount of baryons over anti-baryons can be created. Thus there must exist a process of the form:

$$X \to Y + B. \tag{1}$$

   In this process is X converted to Y (both with baryon number of zero) by excessing baryons ($B > 0$). Note that this condition is rather a minimum starting point.

2. If we would consider charge conjugation (C)-symmetry, then would every reaction of the form given in equation (1) have the same rate as its C-conjugate reaction $\overline{X} \to \overline{Y} + \overline{B}$, where $\overline{X}, \overline{Y}$ and $\overline{B}$ are charge conjugations of respectively X, Y and B. We can express this mathematically as followed:

$$\Gamma(X \to Y + B) = \Gamma(\overline{X} \to \overline{Y} + \overline{B})$$

   This would mean that the baryon number still would be symmetric - what ignores the previous condition. So we can say that *C-violation* is required. Only then we can make sure that the interactions that produce more baryons than anti-baryons dominates the interactions that create more anti-baryons.
   When we combine charge conjugation (C) with a parity transformation (P) - together called charge conjugation-parity (CP)-symmetry, then we can again say that its CP-conjugate process proceeds at the same rate. Mathematically, this is written as followed:

$$\Gamma(X \to q_L q_L) + \Gamma(X \to q_R q_R) = \Gamma(\overline{X} \to \overline{q_L}\ \overline{q_L}) + \Gamma(\overline{X} \to \overline{q_R}\ \overline{q_R}),$$

   with $X \to q_L q_L$ a hypothetical baryon number violating process and $\overline{X} \to \overline{q_R}\ \overline{q_R}$ the CP-conjugate of it. Again, this means that the baryon number again would be conserved, which is again against the previous condition. So also *CP-violation* is a must, because when not satisfied there would be produced a equal number of left-handed baryons and right-handed baryons as an same amount of left-handed anti-baryons and right-handed baryons.
   All together, we say that both charge conjugation (C) and its combination with a parity transformation (CP) may not be exact symmetries of nature. In other words, we have to make sure that the physical laws act different for matter and antimatter.

3. Because CPT-symmetry would compensate different processes by increasing and decreasing the baryon number, we must suppose interaction that are *out of thermal equilibrium*.

These are the so-called Sakharov conditions [1].

1.2 CP-violation & the Standard Model

During this paper, we will focus only on the CP-violation condition.
Our most successful theory in particle physics is the Standard Model. This model binds three of the four known fundamental forces in nature: all but gravity. All known elementary particles are classified in this theory. The Standard Model contains three sources that play a role to satisfy this condition.
The first source of CP-violation in the Standard Model involves the Cabibbo–Kobayashi–Maskawa (CKM) matrix δ_{CKM}, which mismatches the quantum states of quarks depending if they propagate freely or of they play a role in the weak interactions. This CP-violation source has already experimentally been

observed from which we could conclude that this matrix only contributes a small amount of the total CP-violation needed to have the matter-antimatter imbalance. With the CP-violation present in the Standard Model, only a dipole moment of $d_n = 10^{-32} e \cdot cm$ for the neutron is predicted.
A second source is adapted in the Standard Model by the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix, which - analogous to the CKM-matrix - mismatches the quantum states of neutrinos.
The last source says something about strong interaction in nuclei. But also this one is predicted to be too small to declare all the CP-violation that is needed for having matter-antimatter.
Although the Standard Model is one of the successful theories in the history of physics, it fails to satisfy all three Sakharov conditions. That is one of the main reasons we want to investigate in physics beyond the Standard Model. Some examples of the theoretical models that go beyond are the ones that employ Supersymmetry (SUSY), but also the famous String Theory. Which model turns out to be the correct one is something that only experiments can show. [2]

1.3 Neutron electric dipole moment

Another way to look beyond the Standard Model is to search a electric dipole moment of a neutron (nEDM) experimentally. It can be shown that a non-zero nEDM value is in violation with CP-symmetry. Like mentioned before, the Standard Model predict a dipole moment of only $d_n = 10^{-32} e \cdot cm$. Theories SUSY predict more CP-violation, and as such a larger nEDM-value in the range of $d_n < 10^{-25} - 10^{-28} e \cdot cm$.
Facilities all over the globe try to find where this dipole moment actually lies, in order to find more evidence (or disprove) theories like SUSY. One of these facilities to do this investigation is set up at the Paul Scherrer Institute in Switzerland. [2]

2 The nEDM experiment at PSI

The nEDM experiment at Paul Scherrer Institut (PSI) uses Ultra Cold Neutrons (UCNs) to measure the Electrical Dipole Moment (EDM) of the neutron. UCNs are neutrons with an energy of less than 350 neV. Due to this low energy the neutrons undergo a total reflection from many surfaces [4]. Because of this the experiment can use contained neutrons, and has no need to work on an on-beam set up.

The neutrons used in the nEDM experiment originate from proton-induced spallation of a neutron rich lead target. These neutrons have however an energy much higher than 350 neV. To cool the neutrons down they are first thermalized in a heavy water (D_2O) bath. Deuterium is used rather than hydrogen because normal hydrogen may absorb some neutrons. After the bath the neutrons are further cooled down by a solid D_2 crystal kept at 5 K [5].

To actually determine the EDM of the neutron, the Larmor precession frequency of the neutrons in an electromagnetic field is measured. This is done via a magnetic field with an additional electrical field which can be parallel or antiparallel to the magnetic field. The Larmor frequency can in this case be written as

$$\omega = \frac{2}{\hbar} |\vec{\mu_n} \cdot \vec{B} \pm \vec{d_n} \cdot \vec{E}|, \tag{2}$$

with $\vec{\mu_n}$ the magnetic dipole moment and $\vec{d_n}$ the electric dipole moment [6]. (+) is for the case when the fields are parallel, and (−) when both fields are antiparallel. The experiment measures the Larmor frequency in both the parallel and the antiparallel case. From the difference in frequency the EDM can be calculated. If the fields have the same strength in the parallel case as in the antiparallel case, the EDM can be written as

$$d_n = \frac{\hbar \Delta\omega}{4E}, \tag{3}$$

with $\Delta\omega$ the difference in frequency between the parallel and antiparallel case [2]. One of the flaws of the nEDM experiment at PSI is that there are two different measurements needed, namely one in the parallel case and one in the antiparallel case. Any time dependent systematic fluxtuations may have an effect on the experiment, and this reduces the sensitivity. Figure 1 gives the design of the nEDM experiment at PSI.

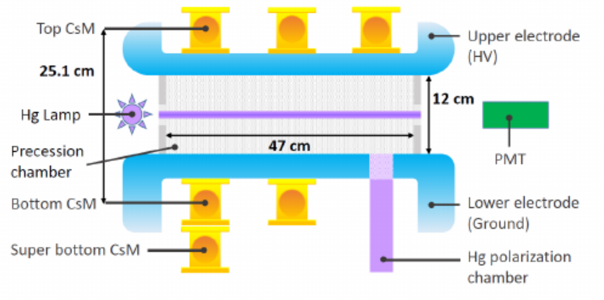


Figure 1: Design of the nEDM experiment at PSI.

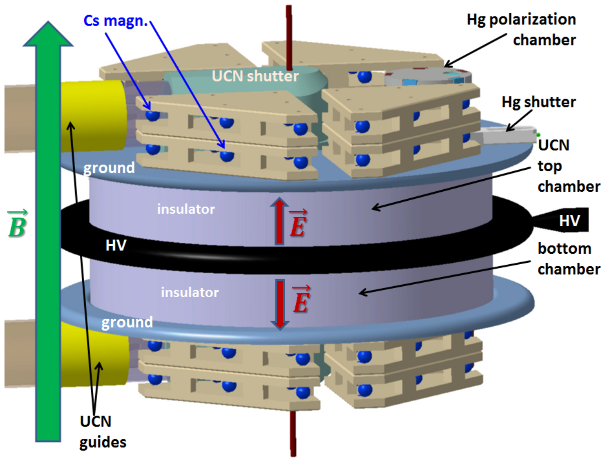


Figure 2: The design of the n2EDM. The two neutron chambers are separated by a high voltage electrode.

So far there has not been any nEDM observed, and all that the experiments can provide is a upper limit to the electrical dipole moment of the neutron. The nEDM experiment at PSI has a sensitivity of $9.8 \times 10^{-27}e$ cm. Nowadays a plan for a n2EDM experiment is on the table at PSI, with an even greater sensitivity. The n2EDM has two different neutron chambers on top of each other, separated by a high voltage electrode which provides the electric field. The design of the n2EDM experiment is shown in figure 2. Because the electrode separates the two chambers, both the parallel frequency as the antiparallel frequency can be measured simultaniously. This reduces any time dependent effects on the system. The n2EDM should be able to detect a neutron electric dipole moment of only $1.1 \times 10^{-27}e$ cm, almost a magnitude better than the nEDM experiment. With some improvements to the n2EDM set-up, the experiment can maybe even get up to a sensitivity in the range of $10^{-28}e$ cm [3].

3 Cesium magnetometers

In order to make dipole measurements of the neutron possible a high resolution magnetic field sensor is necessary to fulfill the magnetic field stability requirement. The experiment is performed with an magnetic field in the order of $1\mu T$ and should be controlled in the order of pT. This results in a very sensitive measurement which is easy disturbed. The purpose of this magnetometer is not to contribute in the neutron dipole moment measurement itself, more to provide a very accurate measurement of the magnetic field on multiple position at each time. This is crucial information during the experiment.

The Cesium magnetometer used is based on the concept of optically detected magnetic resonance (ODMR) spectroscopy. Cesium is an alkali metal, which means there is one valence electron in an sorbital. More specifically the electronic configuration of cesium can be described as $[Xe]6s^1$.Therefore the interaction of Cesium with an external magnetic field is governed by the magnetic moment of its unpaired electron, aligned with the electron spin. Since the absorption of resonant polarized light also depends on the electron spin it is possible to link it to magnetic interactions via light dependent properties.

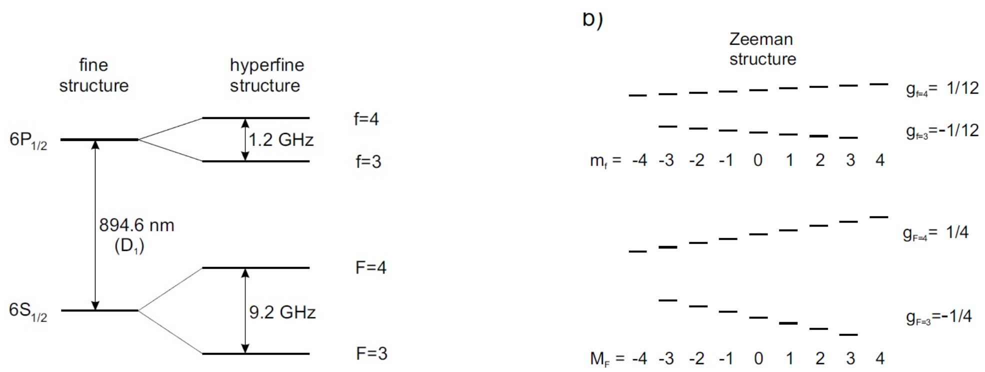
3.1 The cesium hyperfine and Zeeman structure

The first step in understanding ODMR is to better understand the hyperfine and Zeeman structure in cesium. The only stable isotope of cesium is $^{133}_{55}$Cs, which is used in all applications. It has a nuclear spin of $\frac{7}{2}$. The interaction of this nuclear spin with the $J = \frac{1}{2}$ angular momentum provided by the valence electron results in a splitting of the ground state $6S_{\frac{1}{2}}$ into two hyperfine states $F = |I \pm J| = 3, 4$. These two hyperfine states are separated by an energy difference corresponding to a frequency of $9.2GHz$. An energy scheme of Cs is shown in figure 3a. The transition D_1 to the first excited state lies in the near-infrared (894.6 nm). The hyperfine interaction also splits this first excited state $6P_{\frac{1}{2}}$ into two hyperfine states corresponding with $f = 3, 4$ separated by an energy difference corresponding to $1.2GHz$. The Zeeman splitting observed when a magnetic field is applied causes a further splitting of the hyperfine states into $2F + 1$ degenerate sublevels, as shown in figure 3b. More formal we say state $|F\rangle$ splits into $|F, m_f\rangle$ with $m_f = -F, -F + 1, ..., F - 1, F$. The energy difference between those degenerate sublevels can be quantified with the Breit-Rabi4 formula. Where μ_b is the Bohr magneton and g_f is the Landé g-factor for the hyperfine level.

$$\Delta E\,(M_F) = g_f \mu_b B_0 M_f \tag{4}$$

From equation 4 it's easy to calculate the energy difference between two consecutive states and therefore the corresponding frequency, the Larmor frequency ω_L. From equation 5 we get an expression for ω_L, where γ is the gyromagnetic ratio $\gamma = \frac{g_f \mu_b}{\hbar}$. Equation 5 is our first equation which relates a frequency to the applied magnetic field resulting in Zeeman splitting. From a very accurate knowledge of the gyromagnetic ratio, information concerning the magnetic field can be obtained resulting from frequency measurements. Which in physics is a very desired tool as frequency is the quantity which can be most precisely measured. In the cesium ground state $\gamma = 2\pi \cdot 3.5Hz/nT$, a magnetic field in the order of μT results in a (Larmor) frequency of some kHz, which can be measured very precisely.

$$\omega_L = \frac{1}{\hbar}\left[\Delta E(M_{F+1} - \Delta E(M_F))\right] = \gamma B_0 \tag{5}$$



(a) Energy scheme of ^{133}Cs. D_1 transition with hyperfine structure.

(b) Linear Zeeman effect in a small magnetic field (not to scale). The Zeeman levels presented are sublevels of the hyperfine levels presented in 3a

The general idea from which we want to determine the magnetic field is based on equation 5 and an exact knowledge of γ for a certain transition. The component missing is an exact measurement of the energy difference and thereby the frequency between two neighboring Zeeman states. This magnetic resonance frequency will be determined using the optical properties linked with the spin state. To be able to use these optical properties a preparation of cesium gas done with the technique of optical pumping is required, which is discussed next.

3.2 Optical pumping

The energy difference between the two ground state hyperfine levels is around $38\mu eV$, which is smaller than the thermal energy at room temperature. The two hyperfine states $F = 4$ and $F = 3$ are therefore equally populated. In order to observe magnetic resonance between Zeeman states a population imbalance is necessary. This imbalance is generated using optical pumping, which is basically done by illuminating a sample initiating the transition to higher energy states. This can be done using a Cs discharge lamp with the disadvantage that their emission spectrum is very broad. As a consequence multiple possible transition are excited all at once. To avoid this we make us of a tunable laser which makes it possible to focus on the excitation of just one hyperfine transition. Moreover the laser has the advantage of providing a higher light intensity. In the literature consulted the laser is focused on the D_1 hyperfine transition: $6S_{\frac{1}{2}}, F = 4 \rightarrow 6P_{\frac{1}{2}}, f = 3$, as shown in figure 3a. We consider a laser producing right circularly polarized light (σ^+), this beam consists of a photon carrying one unit of angular momentum. When absorbed by the atom the angular momentum of the atom increases by one. Mathematically speaking the laser excites transition from $|4, M\rangle$ states to $|3, M+1\rangle$ states. The atom is in an excited state which spontaneously decays back into the ground state level, following the selection rules $\Delta F = \pm 1, 0$ and $\Delta M = \pm 1, 0$. The photon emitted during this decay can posses an angular momentum of 0 (linearly polarized) or ± 1 (circularly polarized) due to the selection rules. The possible transitions induced by circularly polarized light and possible decay channels are shown on the left hand side of figure 4.

During the absorption-emission pumping cycle an atom originally in a $|4, M\rangle$ state gets excited to an $|3, M+1\rangle$ state by absorption of a σ^+ photon. After decay following the selection rules the original $|4, M\rangle$ state can end up in a $|4, M\rangle$, $|4, M+1\rangle$ or $|4, M+2\rangle$ state. Depending on the angular momentum of the emitted photon. This means that a state cannot lose angular momentum during an absorption-emission single, but it can only earn angular momentum. When σ^+ light is applied to the sample the $F = 4$ Zeeman level population is driven towards the $M = 3, 4$ states. This result in the increase of population of those states as shown on the right hand side of figure 4. These specific states cannot absorb σ^+ photons anymore and are called dark states. At this configuration the sample is completely polarized and it is completely transparent for σ^+ light. A major problem is the depolarization because of spin-exchange collisions and collisions with the walls of the container.This depolarization caused by collisions with the walls can be strongly reduced by coating the inner walls of the cell with paraffin. [7, 2]

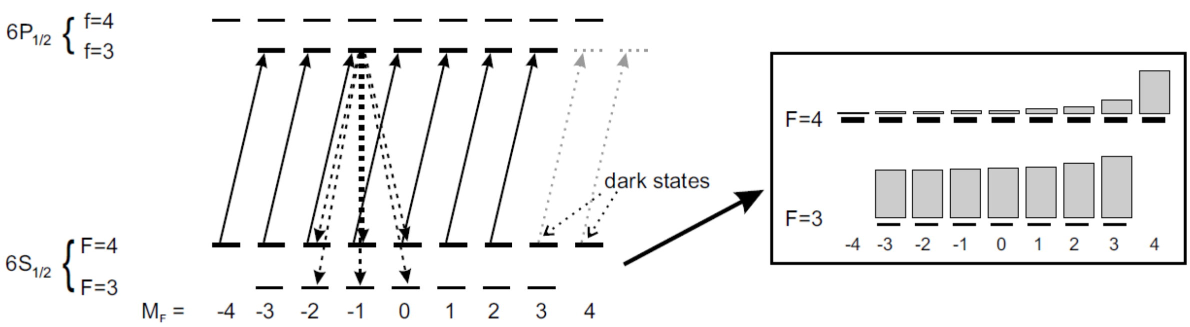


Figure 4: Transitions induced by right circularly polarized light are shown by the solid lines. The decay channels of the level $6P_{\frac{1}{2}}|f = 3, m = -1\rangle$ are indicated by the dashed lines.

3.3 Optically detected magnetic resonance

When all atoms are in dark states and the sample is highly polarized, then our sample is highly polarized and transparent. At this point we reach a maximum in transmitted light intensity. We assume our sample is subject to a weak magnetic field B_0 resulting in a non degenerate Zeeman structure. By optical pumping with σ^+ light we assured all atoms are in dark states, which we can measure from the transmitted light intensity reaching a maximum. An additional applied resonance radio-frequency field can drive the transition between neighboring Zeeman states. Due to this r.f. field atoms escape from the dark states to ones where excitation by σ^+ is possible again. This results in a decrease in polarization because of the redistribution of spin states, which leads to the decrease of transmitted light intensity, and we can measure it. For one frequency for which a maximum change in transmitted light intensity is observed corresponds to ω_L.

From measurements of the transmitted light intensity we are now able to determine the frequency corresponding with ω_L. This information combined with the knowledge of the gyromagnetic ratio result through equation 5 in an exact value for B_0.

Conclusion

So far there have been no results that confirm the existence of an nEDM. This may have been due to experimental limitations. The experiment at the PSI for example can be considered flawed as the the necessity to take two measurements greatly reduces the sensitivity of the result. The n2EDM currently being planned at PSI should improve on the sensitivity.

Few other nEDM experiments worldwide are also undergoing construction and the use of the Cesium magnetometer may provide further magnetic stability increasing the precision of the results. Overall it's still too early to tell whether the nEDM exists. However if more precise experiments fail to deliver relevant results it may not depend on the sensitivity of the measurements but on the theory behind it and the solution to the matter-antimatter imbalance may not depend on CP violation at all.

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