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Enhancement of parity and time invariance violation in the radium atom

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There are several factors that lead to a huge enhancement of parity and time invariance violating effects in the Ra atom: very close electronic levels of opposite parity, the large nuclear charge Z, and the collective nature of T,P-odd nuclear moments. Experiments with radium may be used to measure its nuclear anapole, magnetic quadrupole, and Schiff moments. Such measurements provide information about parity and time invariance violating nuclear forces and electron-nucleon interactions. [S1050-2947(99)50610-0]

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Effects of time invariance (T) and parity (P) violation are inversely proportional to the distance between opposite parity energy levels. There is a pair of close opposite parity levels in the Ra atom, the state $|1\rangle=|7s6d\ J^P=2^+\rangle$, with $E=13993.97\,\mathrm{cm}^{-1}$ and the state $|2\rangle=|7s7p\ J^P=1^-\rangle$, with $E=13\,999.38\,\mathrm{cm}^{-1}$, which are separated by a very small interval ($5\,\mathrm{cm}^{-1}\sim10^{-3}\,\mathrm{eV}$). Note that there are also very close levels of opposite parity in rare-earth atoms (e.g., in the Dy atom [1,2]), which have been used to measure parity violation. The advantage of Ra is that the electron states here are simple. Therefore, the mixing of these states by the weak interactions is not suppressed and can be accurately calculated (contrary to the mixing in the rare-earth atoms where there is a strong suppression of the matrix elements due to the complexity and different structure of the close opposite parity electronic eigenstates). There are also extra factors of enhancement in Ra: the large value of the nuclear charge, $Z=88$ (the P and T odd effects increase with Z faster than Z^2) and the collective T,P-odd moments of deformed Ra nuclei that are much greater than the same moments in spherical nuclei [3,4]. This makes radium an attractive object for future experiments.

The close electron levels in Ra have different electron angular momenta, $J=1$ and $J=2$. The conservation of the total angular momentum $\mathbf{F}=\mathbf{J}+\mathbf{I}$ requires the involvement of the nuclear spin I for these states to be mixed. Parity-violating effects in this case can be produced by the nuclear anapole moment, which is directed along the nuclear spin. An atomic electric-dipole moment (EDM) appears due to the interaction between the atomic electrons and nuclear T,P-odd moments: magnetic quadrupole, Schiff, and electric octupole moments. These effects also can appear due to P,T-odd nuclear-spin-dependent electron-nucleus interactions.

Let us start from an estimate of the contribution of the nuclear magnetic quadrupole moment M. The atomic EDM in the metastable state $|1\rangle$ appears, due to mixing with the opposite parity state $|2\rangle$ by the Hamiltonian H_M of the magnetic interaction between the nuclear magnetic quadrupole moment and the atomic electrons. The atomic EDM is given by the following formula:

$$\mathbf{d}=2\,\frac{\langle 1|H_M|2\rangle\langle 2|-e\mathbf{r}|1\rangle}{E_1-E_2}. \tag{1}$$

The spin-orbit interaction in radium is very large; therefore the electronic states can be approximately described by jj coupling. In this case $|1\rangle\simeq|7s6d_{3/2},J=2\rangle$ and $|2\rangle\simeq|7s7p_{1/2},J=1\rangle$. An expression for the matrix elements of H_M between the electronic orbitals $6d_{3/2}$ and $7p_{1/2}$ can be found in [5]. Using this expression and a simple numerical estimate for the matrix element of the radius vector $\mathbf{r}$ between these orbitals, we obtain the following value for the Ra atomic EDM:

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$$d \simeq 0.5 \times 10^3 M m_e, \tag{2}$$

where m_e is the electron mass. The magnetic quadrupole moment M is not zero in those Ra isotopes that have nuclear spin $I \geqslant 1$; for example, in ^{223}Ra where $I = 3/2$. This nucleus is deformed; therefore, it has a collective magnetic quadrupole moment M, which was estimated in Ref. [3] to be $M \simeq (10^{-19}\,\mathrm{cm})\,\eta\, e/m_p$, where m_p is the proton mass and η is the dimensionless constant of the T,P-odd nucleon-nucleon interaction (the strength of the T,P-odd interaction is measured in units of the weak interaction Fermi constant). The final result for the atomic EDM produced by the T,P-odd nucleon-nucleon interaction is

$$d \simeq 2 \times 10^{-20}\,\eta\, e\ \mathrm{cm}. \tag{3}$$

The atomic EDM can also be produced by the nuclear Schiff moment (see, e.g., [5]). However, the Schiff moment produces a contact interaction only (an electric field inside the nucleus). The mixing of $6d_{3/2}$ and $7p_{1/2}$ states by this interaction is very small. However, one can take into account configuration mixing and use the maximal matrix element between the $7s$ and $7p_{1/2}$ states (for example, include mixing between the $7s6d$ and $7p7p$ configurations). Budker and DeMille turned my attention to the fact that there should be especially large mixing (about 0.27) between the configurations $7s7p$ and $6d7p$ similar to the analogous $6s6p$ and $5d6p$ mixing in barium [6–9]. Thus, we have a conservative estimate of the matrix elements of the Schiff moment interaction: it is about 0.1 times the matrix element between the $7s$ and $7p_{1/2}$ states. Also, there is theoretical and experimental evidence that the odd radium isotopes have octupole deformation, which leads to a huge 10^2 enhancement of the nuclear Schiff moment [4]. A rough estimate of the Schiff moment contribution that includes this enhancement gives a value of the atomic EDM

$$d \simeq 5 \times 10^{-20}\,\eta\, e\ \mathrm{cm} \tag{4}$$

comparable to the magnetic quadrupole contribution (3). The advantage of the Schiff moment is that it exists also for the isotopes with nuclear spin $I = 1/2$, such as ^{225}Ra (the magnetic quadrupole is equal to zero for such isotopes). This value is 10^5 times larger than the EDM of the Hg atom, which was measured in Ref. [6] and gives the present best limit on η.

Of course, this huge enhancement does not mean that the sensitivity to the CP-violating interaction will be 10^5 times higher than in the Hg experiment. The lifetime of the metastable level $|1\rangle$ is ~ 1 s. Also, it decreases after application of an external electric field, due to the Stark mixing with the level $|2\rangle$, which has a lifetime of about 300 ns (see [10,11]). A simple estimate shows that application of the electric field 10 kV/cm reduces the lifetime of the level $|1\rangle$ to 0.1 ms.

Recently I received a communication from Budker and DeMille, who had performed unpublished estimates for another radium metastable state $|3\rangle = 7s6d, J=1$ with $E = 13\,715.85\,\mathrm{cm}^{-1}$. They estimated the natural lifetime of this state: $\tau_3 = 0.8$ ms. (They found it by scaling from the known rate of a similar transition in ytterbium.) Then, using the calculated lifetime of the state $|2\rangle = 7s7p$ (in [10] $\tau_2 = 420$ ns and in [11] $\tau_2 = 250$ ns), they demonstrated that the lifetime of the state $|3\rangle = 7s6d$ is not sensitive to the applied electric field. Even in a very strong field, 100 kV/cm, the Stark-induced decay rate is about 1 ms^{-1} (note that a similar estimate for the state $|1\rangle$ considered in the present work gives a 10^3 times higher rate due to the smaller energy interval between the states $|1\rangle$ and $|2\rangle$). They also estimated an enhancement of the electron electric-dipole moment d_e in the state $|3\rangle = 7s6d$. The atomic electric-dipole moment in this state is $d_3 \simeq 1 \times 10^4 d_e$. This enhancement is an order of magnitude larger than the enhancement coefficients in Tl (500) and Fr (900). The enhancement of the electron EDM requires the mixing of atomic levels with the same electron angular momentum. Therefore, Budker and DeMille considered mixing the state $|3\rangle = 7s6d, J=1$ with the state $|2\rangle = 7s7p, J=1$. The interval between these states is $258.53\,\mathrm{cm}^{-1}$, which is 50 times larger than the interval between the states $|1\rangle$ and $|2\rangle$. This information may be considered as an additional argument to start experiments with the radium atom.

Finally, the radium atom can be used to measure the nuclear anapole moment. In principle, there are several possibilities. One can measure, for example, the interference between the $E2$ or Stark amplitudes and parity-violating amplitude in the transition between the ground state $|0\rangle = |7s^2, J=0\rangle$ and excited state $|1\rangle = |7s6d\ \ J^P = 2^+\rangle$, $E = 13\,993.97\,\mathrm{cm}^{-1}$. The parity-violating amplitude $E1_{pv}$ appears due to the weak mixing between the state $|1\rangle$ and the opposite parity state $|2\rangle = |7s7p\ \ J^P = 1^-\rangle$, $E = 13\,999.38\,\mathrm{cm}^{-1}$. Again, one has to take into account the configuration mixing since the direct matrix element $\langle 6d_{3/2}|H_a|7p_{1/2}\rangle$ of the interaction H_a between the atomic electrons and the anapole magnetic field, which is localized inside the nucleus, is very small. A rough numerical estimate shows that due to the closeness of the opposite parity levels and the large nuclear charge Z the amplitude $E1_{pv}$ in Ra is about $10^{-9} e a_B$, that is, $\sim 3 \times 10^3$ times larger than a similar amplitude (induced by the anapole) in Cs; the latter amplitude was recently measured in Ref. [12].

We stress that in Ra the anapole-induced amplitude makes the dominant contribution to the total parity-violating amplitude. This may be an advantage, since in Cs and Ba^+ [7] the anapole contribution has to be separated from the weak charge contribution (due to Z-boson exchange between electrons and nucleus), which is two orders of magnitude larger than the anapole contribution. We may neglect the weak charge contribution in Ra since the states $|1\rangle$ and $|2\rangle$ have different electron angular momenta $J=2$ and $J=1$ and cannot be mixed by the weak nuclear-spin-independent interaction. Note that a proposal of the trap experiment to measure parity violation in the Ba^+ ion [7] (see also [8]) may also be useful for designing of the trap experiment with Ra (the pattern of $E2$, $E1_{pv}$, and $E1$ electromagnetic transitions is similar).

In conclusion, we have considered strongly enhanced parity and time invariance violating effects in the Ra atom. Unfortunately, all odd Radium isotopes are unstable. However,

recent progress in the trapping of unstable elements makes such experiments feasible. For example, an experiment on parity violation in the short-lived Fr atom is in progress [13]. An experiment with ^{225}Ra, motivated by the work [4], has been discussed by Lamoreaux [14] and Young [15]. The Los Alamos National Laboratory has a source of this isotope. Note also that the electronic structure of the radium atom is relatively simple (two electrons above closed shells). Our experience has shown that the accuracy of atomic calculations for such systems can be about 1% (see, e.g. [16]).

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