ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

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ENHANCEMENT OF P- AND T-NONCONSERVING EFFECTS IN RARE-EARTH ATOMS

PREPRINT 85-82

НОВОСИБИРСК

ENHANCEMENT OF P- AND T-NONCONSERVING EFFECTS IN RARE-EARTH ATOMS

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Abstract

Small intervals between atomic levels of opposite parity in rare-earth atoms cause the enhancement of P- and T-nonconserving effects. It is of interest for the determination of the electroweak mixing parameter $\sin^2\theta$, and for study of anapole (P-odd) and magnetic quadrupole (P- and T-odd) nuclear moments.

Now the existence of parity nonconservation in atoms is firmly established, and "weak charges" of the bismuth, thallium, cesium and lead have been measured /1-7/. However, up to now nuclear spin dependent effects of parity nonconservation have not been observed. Their measurement in heavy atoms would allow one to determine a still unobserved P-odd characteristic of nucleus - its anapole moment /8,9/. It would be interesting also to measure the proton and neutron "weak charges" separately. And at last, in spite of searches going on for many years, the effects of T-invariance nonconservation in atoms and molecules have not been observed up to now.

In the present note we wish to attract attention to the advantages of such experiments with rare-earth atoms. They have sufficiently large Z, and anomalously close levels of opposite parity occur in them. Both circumstances are known to lead to the enhancement of parity nonconserving effects. It is important that the total electron angular momenta of these levels can differ by unity. In such a case the mixing of the levels is caused by the nuclear spin dependent interaction only. Then the effects of this interaction would be enhanced not only absolutely, but as well relatively to nuclear spin independent effects. Such an enhancement is possible both in normal M1 transitions and in strongly forbidden transitions.

Normal M1 transitions of this kind take place in samarium. Its vapour pressure at temperature ~1100°C is suffeciently high for study of the optical activity. The ground state of this atom is $4f^6\ 6s^2\ {}^7F_0$, and close to it there are six other levels of the same configuration ${}^7F_J$, $1 \leq J \leq 6$ /10/. All M1 transitions between these levels lie in far infrared region and are by themselves hardly convenient for the searches for optical activity. The location of next levels of the configuration $4f^6\ 6s^2$ is unknown experimentally. But according to the calculations /11/ carried out for the configuration $4f^6$ in the ion Sm^{+2}, one should expect that five levels $4f^6\ 6s^2\ {}^5D_J$, $0 \leq J \leq 4$, lie in the interval 14000 - 23000 cm^{-1}. Now M1 transitions from the levels ${}^7F_J$ to ${}^5D_J$ belong to convenient spectral region. Moreover, in the mentioned energy interval a lot of levels of the configuration $4f^6\ 6s6p$ exists. Therefore, there are the reasons to expect here anomalously small intervals between opposite parity levels. The situation is especially convenient due to the abundance of levels $4f^6\ 6s^2\ {}^7F_J$ with various angular momenta J and populations comparable at reasonable temperatures. Just from these states ${}^7F_J$ the trasitions of interest to us can go.

M.S.Zolotorev and D.A.Melik-Pashaev have turned attention to the presence in the samarium spectrum of three high levels with energies $\sim 30000\ \mathrm{cm}^{-1}$ that are tentatively identified in the tables /10/ as belonging to the configuration $4f^6\ 6s^2$. A lot of opposite parity levels exists in this region also.

Nuclear spin dependent parity nonconserving effects could be detected here by the measurement of optical activity at different hyperfine components of optical transitions /12/. However, the serious shortcoming of samarium from this point of view is the small hyperfine splitting of the levels of $4f^6\ 6s^2$ configuration.

One more peculiarity of samarium is the existence of stable isotopes with large difference of the neutron numbers, $\Delta N = 10$, so that the difference of their "weak charges" exceeds 10%. If the optical activity of samarium vapour, in accordance with the above arguments, were at least by an order of magnitude higher than in bismuth, then the absolute experimental accuracy reached already in Ref. /1/ would be quite sufficient to measure the neutron "weak charge". Moreover, this experiment would allow one to determine $\sin^2\theta$, the parameter of the standard theory of electroweak interactions, with the accuracy comparable with the world average one. It can be easily seen that the error of the atomic calculations enters here only through the dependence of the result on the nuclear radius r_o that changes from an isotope to isotope. This error is evidently small. Even the rough account for such dependence (the optical rotation $\psi \sim r_o^{2-2\gamma}$, $\gamma = \sqrt{1 - Z^2\alpha^2}$) allows one to reduce the theoretical error in the determination of the ratio of the isotopes charges to the value $< 1\%$.

Another example can be pointed out in erbium. There is in it a pair of close opposite parity levels /10/:

1. $4f^{11}({}^4I)\,5d6s6p$, $J = 5$, $E = 24991\ \mathrm{cm}^{-1}$
2. $4f^{11}({}^4I)\,5d6s^2$, $J = 4$, $E = 25001\ \mathrm{cm}^{-1}$

The transition from one of the low-lying excited states, belonging to the ground configuration $4f^{12}\ 6s^2$ (their population at $T \sim 1200 - 1700°\mathrm{C}$ is sufficiently high), to the state 1 is opened by external constant electric field, like in experiments on measurement of parity nonconserving effects in thallium and cesium. Expected magnitude of the P-odd correlations, caused by the mixing of the states 1 and 2 by the parity nonconserving interaction, is close here perhaps to that measured already in thallium. But here we mean the nuclear spin dependent effects that should be in thallium, roughly, by two orders of magnitude smaller and have never been observed at all. One more possibility here is the observation of P-odd correlations in the two-photon transition from the ground state to the state 2; in this transition the absorption amplitude for one quantum is E1, for another – M1.

In Ref. /13/ we have noted already the possibility to use metastable states of rare-earth atoms for the investigation of T - nonconserving effects. We have estimated there also the electric dipole moment (edm) of the samarium state with energy $E = 14920\ \mathrm{cm}^{-1}$ enhanced due to close opposite parity level with $E = 14916\ \mathrm{cm}^{-1}$. Here we wish to consider from this point of view the metastable state

$$4f^{10}({}^5I_8)\,5d6s({}^3D)\,{}^3[8],\ J = 9,\ E = 17514.50\ \mathrm{cm}^{-1}$$

in disprosium where the effect is larger. The close opposite parity level is

$$4f^{10}({}^5I_8)\,6s6p({}^3P_2)(8,2),\ J = 10,\ E = 17513.33\ \mathrm{cm}^{-1}$$

In the most natural models, T - invariance violation takes place in hadronic sector of the theory. Therefore, we are interested first of all in the atomic edm induced by T-odd nuclear multipoles. The most effective source of these multipoles is the T-odd nucleon-nucleon interaction /13/, but not the external nucleon edm. It is known that in a stationary atomic state the nuclear edm is completely screened, so that the atomic dipole moment is induced by higher T-odd multipoles. In the case of a heavy atom with non - zero electron angular momentum, the nuclear magnetic quadrupole moment (mqm) is the most effective source of atomic edm /13,14/. In this respect the isotope ${}^{161}\mathrm{Dy}$ is of special interest /15/ since, due to close nuclear opposite parity levels, its mqm is enhanced by about an order of magnitude and constitutes /13/

$$M = 3\cdot 10^{-19}\ \frac{e}{m_p}\cdot cm\cdot \eta \qquad (1)$$

where m_p is the proton mass, η is the dimensionless parameter that characterizes the magnitude of T-odd nucleon-nucleon interaction in the units of the Fermi constant G.

The matrix element of the mixing of one - electron opposite parity states, caused by nuclear mqm, is presented in Ref. /13/. The effective quantum numbers, on which it depends, constitute here $\nu_{6p}\approx 1.9$, $\nu_{5d}\approx 1.9$. The radial integral $\rho = \int_0^\infty dr\, r^3 R_{5d}R_{6p}$ is found by the Hartree - Fock - Slater method: $\rho \approx 2a_B$. The final answer for the edm in the state with the largest total atomic angular momentum F = 23/2 equals

$$d = 2.7\cdot 10^{-3}\ m_p M \qquad (2)$$

or, taking into account (1),

$$d/e = 8\cdot 10^{-22}\ cm\cdot \eta \qquad (3)$$

This value by more than two orders of magnitude exceeds the cesium ground state edm induced by the nuclear mqm. In the Kobayashi - Maskawa model where $\eta \sim 10^{-8}$ /13/, the dipole moment (3) exceeds by two orders of magnitude the neutron edm which equals according to Ref. /16/ $d_{n/e} \sim 10^{-31}$ cm.

It is curious that in disprosium there are atomic opposite parity levels with the interval that with the experimental accuracy turns to zero at all /10/:

$$4f^{10}(^5I_8)\,5d\,6s(^3D)\ ^3[10],\ J=10,\ E=19797.96\ cm^{-1}$$

$$4f^{9}(^6H)\,5d^2(^3F)(^8K)6s,\ J=10,\ E=19797.96\ cm^{-1}$$

In fact the distance between opposite parity levels is determined here by the hyperfine structure intervals and external fields. In such a situation the quantitative estimate of the effect in general form is rather difficult.

Clearly, the detailed investigation of the atomic levels structure in rare-earth elements would be extremely useful from the point of view of the search for the discussed P- and T-odd effects.

The authors thank L.M.Barkov, D.A.Melik-Pashaev, O.P.Sushkov and M.S.Zolotorev for useful discussions. I.B.Khriplovich is grateful to E.N.Fortson who in 1981 turned his attention to the existence of close opposite parity levels in rare-earth atoms.

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УСИЛЕНИЕ ЭФФЕКТОВ НАРУШЕНИЯ ПРОСТРАНСТВЕННОЙ И ВРЕМЕННОЙ ЧЕТНОСТИ В РЕДКОЗЕМЕЛЬНЫХ АТОМАХ

Препринт
№ 85-82

Работа поступила - 5 мая 1985 г.

Ответственный за выпуск - С.Г.Попов
Подписано к печати 21.6.85г. МН 05790
Формат бумаги 60x90 1/16 Усл.0,8 печ.л., 0,7 учетно-изд.л.
Тираж 290 экз. Бесплатно. Заказ № 82.

Ротапринт ИЯФ СО АН СССР, г.Новосибирск, 90