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PARITY NONCONSERVATION IN ATOMIC CESIUM INDUCED BY NUCLEAR ANAPOLE MOMENT

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НОВОСИБИРСК

Parity Nonconservation in Atomic Cesium
Induced by Nuclear Anapole Moment

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ABSTRACT

Nuclear spin dependent P-odd effects in atomic cesium are calculated. The detection of these effects will allow to determine the nuclear anapole moment.

1. Up to now only parity nonconserving effects independent of nuclear spin have been observed in atomic experiments. The point is that in heavy atoms where the experiments are going on, P-odd correlations dependent on nuclear spin are smaller than those observed roughly by two orders of magnitude.

In heavy atoms the nuclear spin dependent parity nonconserving effects were shown [1—3] to be induced mainly by the so-called anapole moment of a nucleus, its P-odd electromagnetic characteristic. Therefore, the measurement of these effects would give extremely valuable information on parity nonconserving nuclear forces.

P-odd interaction with nuclear spin leads to some difference in the magnitude of P-odd effects at different hyperfine (hf) components of optical transitions [4]. The experiments that are going on now in this field are aimed at the search for such differences. In particular, in the experiments with cesium the first limits on the corresponding dimensionless constant $\varkappa_a$ of electron-nucleus interaction were obtained:

$$|\varkappa_a| < 100\,[5], \qquad \varkappa_a = -2 \pm 2\,[6]. \tag{1}$$

The theoretical prediction for this constant in the case of the nucleus ^{133}Cs is [2]

$$\varkappa_a = 0.25 - 0.33\,. \tag{2}$$

The first atomic calculations of the effects discussed were presented in [4]. In connection with the experiments actively carried out now, more careful calculations of these effects are relevant. In the present work such semiempirical calculation is performed for the highly forbidden transition $6s_{1/2} - 7s_{1/2}$ in cesium. Use of more accurate values for the radial integrals of E1 transitions, and correction of the values of wave functions at $r \to 0$ grounded on the hf-constants values, have led to results that for two of the four hf transitions differ considerably from the numbers obtained in [4].

2. We start from the considerations of the radial integrals of E1 transitions. For the transition $6s - 6p_{1/2}$ this integral is known experimentally with good accuracy and constitutes (in the units of the Bohr radius a) [7]

$$\rho(6s, 6p_{1/2}) = -5.535\,(14). \tag{3}$$

For two other transitions that give large contributions to the effect discussed, only the values of ρ averaged over the fine structure of p-level are known experimentally:

$$\rho(7s, 6p) = 5.45\,(3)\,[8]; \quad \rho(7s, 7p) = -12.30\,(3)\,[9]. \tag{4}$$

To obtain the values $\rho(7s, np_{1/2})$ of interest to us, we take into account following [10] the admixtures to the nonrelativistic radial wave function of a $p_{1/2}$ electron from other $p_{1/2}$ states due to the spin-orbit interaction.

In this way we get

$$\rho(7s, 6p_{1/2}) = \rho(7s, 6p) + \frac{2}{3} \sum_{n \geqslant 7} \frac{\sqrt{\Delta(6p)\,\Delta(np)}}{E(np_{1/2}) - E(6p_{1/2})}\,\rho(7s, np) \tag{5}$$

where $\Delta(np)$ is the fine-structure interval of an np level. Due to rapid decrease of $\rho(7s, np)$ with n, the lion's share of the sum in (5) is given by the term with $n=7$. The contribution of the term with $n=8$ constitutes about -0.01. The total contribution of other terms of the sum is estimated not to exceed 0.01 and is included into the error of the final answer which constitutes

$$\rho(7s, 6p_{1/2}) = 5.19\,(4). \tag{6}$$

Analogously we get

$$\rho(7s, 7p_{1/2}) = -12.42\,(4). \tag{7}$$

These numbers agree with the careful Hartree—Fock calculations [11] and with the results of a phenomenological analysis presented in [12].

We pass now to the discussion of the mixing of the opposite parity levels caused by the interaction of electron with nuclear anapole moment. In the quasi-classical approximation for the wave function of external electron the matrix element of the mixing can be written as (see. e. g., [13]).

$$\langle s_{1/2} | H | p_{1/2} \rangle = i\,\frac{G m^2 \alpha^2 Z^2 R}{\sqrt{2}\;\pi (\nu_s \nu_p)^{3/2}}\, Ry\, \frac{2\gamma+1}{3}\, \varkappa_a\, \frac{K}{I(I+1)}\, 2\mathbf{jI}. \tag{8}$$

Here G is the Fermi weak interaction constant; m is the electron mass; $\alpha = \frac{1}{137}$; Z is the nuclear charge; $\gamma = \sqrt{1 - Z^2\alpha^2}$; ν_s, ν_p are the effective principal quantum numbers of the mixing states; R is a relativistic enhancement factor which equals 2.8 for cesium; I is the nuclear spin; $K = (-1)^{I+1/2-l}(I+1/2)$; l is the orbital angular momentum of the external nucleon; $\mathbf{j}$ is the operator of the electron total angular momentum. We shall supplement (8) with correcting factors that account for the deviation of the true value of $|\psi(0)|$ from the quasi-classical one. These factors are found from the comparison of the experimental values of the hf constants with their values found in the same quasi-classical approximation. Those factors constitute 1.024; 0.974; 0.877; 0.859 for $6s$, $7s$, $6p_{1/2}$, $7p_{1/2}$ states respectively.

As to the contribution to the effect from the admixtures of higher p-states, we use for them the results of numerical calculations of Ref. [4]. The error of the total contribution of the admixtures of the states $np_{1/2}$, $n \geqslant 8$, is estimated to be 10% for each of the levels, $6s$ and $7s$.

Table

F	F'	$[(\mathrm{E1})^a_{FF'}/(iea\varkappa_a)]\cdot 10^{12}$	$[(\mathrm{E1})^a_{FF'}/(\varkappa_a (\mathrm{E1})^Q_{FF'})]\,\%$
3	3	0.59 (3)	3,1
3	4	1.73 (4)	-5.2
4	3	1.96 (4)	5.9
4	4	0.68 (4)	-2.4

3. The results of the calculation of the reduced matrix elements $(\mathrm{E1})^a_{FF'}$ for the discussed P-odd E1 transition $6s_{1/2}$, $F \to 7s_{1/2}$, F' are presented in the Table. They differ considerably from those obtained in [4]. For the transitions with $F' = F$ the difference reaches 40%.

It should be noted that for the comparison the numbers from [4] obtained for the neutral current constant $\varkappa_{2p}$ should be multiplied by $K/(1/2-K)=-8/7$.

The indicated errors correspond to the direct addition of the errors in (6), (7) and the above mentioned error for the contributions of higher states. For the transitions with $F'\neq F$ where the latter contributions add up, their error constitutes 10%, but for the transitions with $F'=F$ where there is a considerable cancellation between them, their error reaches 60%. Such an estimate of the total accuracy seems reasonable in the situation when there is also an error from $|\psi(0)|$ that may constitute some percent.

Note that found in this way amplitude of the P-odd transition due to the weak charge Q of the cesium nucleus

$$(E1)_z^Q=-0.94(5)\,10^{-11}(-Q/N)\,iea\,, \qquad (9)$$

($N=78$ being the number of neutrons in ^{133}Cs nucleus) agrees with the results of the most accurate Hartree—Fock calculations that give for the coefficient in this amplitude the values

$$-0.886\,[14]; \qquad -0.89\,(2)\,[15]. \qquad (10)$$

The result (9) coincides with that of Ref. [12], the latter in the same units being

$$-0.935\pm0.02\pm0.03\,. \qquad (11)$$

This coincidence is quite natural since our approach by its spirit and in some details is close to that used in [12] for the calculation of $(E1)_z^Q$.

Note that the assumption is inherent in our approach that the mixing of levels is of one-particle nature and that the values of $|\psi(0)|$ both for P-odd effects dependent on nuclear spin and independent of it are effectively the same. Then the amplitudes $(E1)_{FF'}^a$ of interest to us can be obtained at $F'=F$ from $(E1)_z^Q$ directly by a trivial calculation. If more accurate value (10) is used for $(E1)_z^Q$, we get for $(E1)_{FF'}^a$ the coefficients:

$$\text{at } F=F'=3 \quad 0.56\,(2)\,,$$

$$\text{at } F=F'=4 \quad 0.64\,(2)\,,$$

instead of 0.59 (3) and 0.68 (4) in the Table correspondingly.

We indicate also in the Table the ratio in percent of the reduced matrix element $(E1)_{FF'}^a$ to the corresponding reduced amplitude $(E1)_{FF'}^Q$ the latter being calculated from (10) at $-Q/N=0.944$. The expected magnitude of the discussed effect at $\varkappa_a=0.25$ reaches 1%.

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