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ON THE P- AND T- NONCONSERVING NUCLEAR MOMENTS

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Abstract

The contribution of virtual excitations of paired nucleons to T- nonconserving nuclear moments caused by T-odd nuclear forces is shown to be comparable with the contribution of external nucleon. Taking into account the contribution of paired nucleons in the ^{129}Xe nucleus allows one to extract from atomic experiment the best limit on the P- and T- nonconserving nucleon-nucleon interactions. This limit approaches by its implications the limit on the neutron dipole moment. In the case of P-nonconserving, but T-invariant, anapole nuclear moment the external nucleon excitations dominate.

In ref. [1] we have shown that under reasonable assumptions there is a regular enhancement factor for nuclear electric dipole moment (edm) caused by T-odd nuclear forces in comparison with the neutron edm. This factor equals by order of magnitude

$$3\pi \left(m_\pi^2 \, |U| \, r_0^3 \right)^{-1} \approx 60 \qquad (1)$$

Here $m_\pi = 140$ MeV is the π-meson mass, $|U| \approx 45$ MeV is the characteristic depth of the nuclear potential, $r_0 \approx 1.15$ fm. In ref. [1] we have calculated edm, magnetic quadrupole moment (mqm) and the so called Schiff moment (sm) for some nuclei. The sm $\vec{Q}$ is defined by the relations

$$\vec{Q} = \sum_p \frac{e}{10} \left\{ \langle r_p^2 \vec{r}_p \rangle - R_0^2 \langle \vec{r}_p \rangle \right\},$$

$$\varphi = 4\pi \vec{Q} \vec{\nabla} \delta(\vec{r}) \qquad (2)$$

where φ is the scalar potential created by sm, e is the proton charge, $R_0 = r_0 \cdot A^{1/3}$ is the nuclear radius, the summation is carried out over all protons, the brackets $\langle \ldots \rangle$ denote the expectation value in the nuclear state. The sm and mqm induce atomic and molecular edm. The nuclear edm by itself is useless in this respect: in a stationary atomic or molecular state the average electric field on the nucleus vanishes, so that the interaction $-\vec{d}\vec{\mathcal{E}}$ is absent (the detailed discussion and relevant references see, e.g., in ref. [2]).

In ref. [1] T- odd nuclear characteristics were calculated in the approximation where the excitations of external, non-paired nucleon only were taken into account. In the present paper the contribution to these nuclear multipoles from the nucleons of the core is considered. This contribution is shown to be in general no smaller than that of the external nucleon. This conclusion seems to be interesting by itself*). It is im-

*) After this work was over we have found ref. [3] that contains the conclusion that the contribution from the paired nucleons excitations is important for usual P-odd effects in nuclear γ-transitions.

portant also by the following, applied reason. The most stringent limit on the T- violation in atomic physics was obtained in the experiment on the measurement of the edm of the ^{129}Xe atom in the ground state [4]:

$$d\left({}^{129}Xe\right) = (-0.3 \pm 1.1)\cdot 10^{-26}\, e\cdot cm. \tag{3}$$

In the same ref [4] the feasibility of further increase of the accuracy in the experiments with xenon and mercury is discussed. In the ground state of these atoms the electron shells are closed, so that the nuclear mqm does not induce the edm of atom [1]. Therefore, the nuclear sm is here the only nuclear multipole that leads to atomic edm. However, in the case of even-odd nuclei the contribution of the external nucleon, the neutron, to the nuclear sm vanishes. This conclusion is valid also when recoil effects are taken into account, at least within the shell model of nucleus [1].

In the present work we have calculated sm of the odd isotopes of xenon and mercury caused by virtual excitation of paired nucleons due to T- odd interaction with external one. Using the found value of the ^{129}Xe sm, which is of usual nuclear order of magnitude, the result (3) is shown to approach by its implications, as the source of information on the nature of CP-violation, the best limit on the neutron edm [5]:

$$|d_n/e| < 4\cdot 10^{-25}\ cm \tag{4}$$

In the case of P-odd, but T- even, so called nuclear anapole moment (am) the situation is different. Here the contribution of core nucleons excitations is numerically small so that the result of the calculation of nuclear am carried out in ref [6] with the account of the external nucleon excitations only is valid not only qualitatively, by an order of magnitude, but quantitatively as well*). We discuss here the cause of such a difference between T- and P- odd nuclear characteristics.

2. We start from the consideration of nucleon-nucleon interaction that violates T- invariance and induces T-odd nuclear multipole moments. To the first order in velocities $\vec{p}/m$ this interaction can be presented as

$$W_{ab} = \frac{G}{\sqrt{2}}\frac{1}{2m}\Big[(\eta_{ab}\vec{\sigma}_a - \eta_{ba}\vec{\sigma}_b)\vec{\nabla}_a\,\delta(\vec{r}_a - \vec{r}_b) + \eta'_{ab}\,[\vec{\sigma}_a\times\vec{\sigma}_b]\{(\vec{p}_a - \vec{p}_b),\ \delta(\vec{r}_a - \vec{r}_b)\}\Big] \tag{5}$$

Here $\{\ ,\ \}$ is an anticommutator, m is the nucleon mass, $\vec{\sigma}$, $\vec{r}$ and $\vec{p}$ are the spins, coordinates and momenta of the nucleons a and b.

In the used approximate local description of the T- odd nucleon-nucleon interaction the exchange terms can be reduced by means of Fierz transformation to the form (5). Therefore, their role is reduced to the redefinition of the dimensionless constants η_{ab}, η'_{ab} characterizing the magnitude of the discussed T-odd interaction in the units of the Fermi constant G.

We demonstrate now our assertion about the importance of the internal nucleons excitations by an example of the lowest T-odd multipole, nuclear edm. It is known that when the recoil effects are taken into account, the nuclear dipole moment operator is

$$\vec{d} = \sum_a e_a \vec{r}_a \tag{6}$$

where $e_p = e(1-\frac{Z}{A}) = e\frac{N}{A}$, $e_n = -e\frac{Z}{A}$. The induced nuclear edm we write as

$$\vec{D} = \sum_n \frac{\langle 0|W|n\rangle\langle n|\vec{d}|0\rangle + \langle 0|\vec{d}|n\rangle\langle n|W|0\rangle}{E_0 - E_n} \tag{7}$$

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*) As it was shown in refs. [6,7], just the electromagnetic interaction of an electron with nuclear anapole moment is the main source of the P-odd effects in heavy atoms that depend on nuclear spin.

To estimate the sum (7) we use the simple oscillator model of a nucleus (previously such an estimate of the usual P-odd effects was carried out in ref. [3]). In this model the operator (6) can be transformed as

$$\vec{d} = \frac{i}{m\omega^2}\left[\sum_a e_a \vec{P}_a, H\right] \tag{8}$$

where H is the unperturbed nuclear Hamiltonian, and ω is the oscillator frequency. Substituting (8) into (7) we reduce the expression for $\vec{\mathcal{D}}$ to the form

$$\vec{\mathcal{D}} = -\frac{1}{m\omega^2}\langle 0|\sum_a e_a \vec{\nabla}_a W|0\rangle \tag{9}$$

Since for internal nucleons $\langle\vec{\sigma}\rangle = 0$, the terms in the operator W that depend on the spins of core nucleons are not operative in this case. We substitute further proton and neutron densities for the arising sums of δ-functions. These densities are proportional with reasonable accuracy to the nuclear total density ρ. Finally we find the following expression for the nuclear edm

$$\vec{\mathcal{D}} = \frac{G}{\sqrt{2}}\frac{1}{2m^2\omega^2} e\langle 0|\vec{\nabla}(\vec{\sigma}\vec{\nabla})\rho\rangle \eta_a$$

$$\eta_a = \begin{cases} -\frac{N}{A}\eta_{pn}, & a=p \\ \frac{Z}{A}\eta_{np}, & a=n \end{cases} \tag{10}$$

Here the expectation value is taken over the state of the external nucleon a. Meanwhile, if we took into account the external nucleon excitations only (one term in the sum (6) for the operator $\vec{d}$), the result would be quite different:

$$\eta_a = \begin{cases} -\frac{N}{A}\left(\eta_{pp}\frac{Z}{A} + \eta_{pn}\frac{N}{A}\right), & a=p \\ \frac{Z}{A}\left(\eta_{np}\frac{Z}{A} + \eta_{nn}\frac{N}{A}\right), & a=n \end{cases}$$

The analogous expressions can be obtained in the oscillator model for nuclear mqm and sm. And although the oscillator model cannot give the quantitative description of discussed effects, the presented example seems to be a convincing evidence for the importance of the internal nucleons contribution.

3. The real calculation of sm for the nuclei $^{129,131}Xe$, $^{199,201}Hg$ and $^{203,205}Tl$, which are now of experimental interest, was performed by us using wave functions and Green functions in the Woods-Saxon potential with spin-orbit correction. The results are presented in table. Note that all the found values are of the order of magnitude natural for heavy nuclei [1]:

$$Q \sim \frac{e}{10}\lambda R_0^2 \sim e\eta\cdot 10^{-9}\, fm^3 A^{2/3} \sim e\eta\cdot 10^{-8}\, fm^3 \tag{11}$$

Here

$$\lambda = \frac{G}{\sqrt{2}}\frac{1}{2m}\frac{\rho}{|U|} = 2\cdot 10^{-8}\, fm \tag{12}$$

is the dimensional parameter characterizing T-odd nuclear multipoles. The nuclear edm and mqm are expressed through it as follows:

$$\begin{aligned} \mathcal{D} &\sim \lambda e\eta \\ M &\sim \mu\frac{e}{m}(2I-1)\lambda\eta \end{aligned} \tag{13}$$

where $\mu\frac{e}{2m}$ is the nucleon magnetic moment, I is the nuclear spin.

In the first four nuclei the non-paired nucleon is neutron, therefore the sm is caused by the internal protons excitations and is expressed through the constant η_{np}. In thallium the internal nucleons contribution to the sm (1.23 η_{pp} in the units 10^{-8} e·fm^3) is comparable by an order of magnitude with the external proton contribution ($-1.4\eta_{pn} - 0.04\eta_{pp}$ in the same units). The last number is somewhat different from that presented in ref [1] since there the empirical density parametrization was used, and here the density was expressed through the wave functions in the Woods-Saxon potential.

All these results were obtained in the nuclear shell model. It is known however that in some cases the residual internucleon interaction renormalizes a result strongly. This phenomenon arises in particular in the case of E1-transitions where the residual interaction leads to the formation of the giant resonance. The influence of the collectivization of the E1-transition on the magnitude of nuclear edm and sm can be estimated in the following way. Assume that the sum over intermediate states in formula (7) for edm is saturated by the giant resonance with the frequency $\omega_\gamma = E_n - E_0$. Then this formula can be transformed as follows

$$\mathcal{D} = -\frac{1}{\omega_\gamma^2}\sum_n (E_n - E_0)\left(\langle 0|W|n\rangle\langle n|\vec{D}|0\rangle + \langle 0|\vec{D}|n\rangle\langle n|W|0\rangle\right) =$$

$$= -\frac{1}{\omega_\gamma^2}\langle 0|[W,[H,d]]|0\rangle = -\frac{1}{m\omega_\gamma^2}\langle 0|\sum_a e_a \vec{\nabla}_a W|0\rangle \qquad (14)$$

we have taken into account here that $(E_n - E_0)\langle n|\vec{d}|0\rangle = \langle n|[H,\vec{d}]|0\rangle$. Expression (14) differs from (9) obtained in the oscillator model only since, instead of the shell frequency ω, it contains the giant resonance frequency ω_γ that equals approximately 2ω. Therefore, the total collectivization of the matrix elements in sum (7) would lead to the suppression of nuclear edm by $\omega_\gamma^2/\omega^2 = 4$ times in comparison with the shell estimate. But contrary to the case of the sum rule for the oscillator strengths which is saturated by the giant resonance, the sum (7) contains the frequency in denominator rather than in numerator, besides, in one of the matrix elements, $\langle 0|W|n\rangle$, the transition to the giant resonance is not enhanced. Therefore, the characteristic frequency ω_c at which the sum (7) converges is perhaps smaller than ω_γ. In the following discussion we shall assume for estimates that the suppression factor $\xi \equiv \omega^2/\omega_c^2$ is equal to $1/2$.

In ref. [1] the recoil effects in sm were shown within the shell model to cancel out so that formula (2) is valid literally, even if we mean in it by r_p the proton coordinates reckoned off the nuclear center of masses. Just due to this

reason the sm of even-odd nuclei of xenon and mercury depend on the constant η_{np} only. However, if the collectivization is taken into account, the value of $\mathcal{D}$ diminishes and there is no exact cancellation of the internal neutrons contributions. E.g., in ^{129}Xe the sm becomes

$$\frac{Q}{e\cdot fm^3\cdot 10^{-8}} = 1.75\,\eta_{np} + (1-\xi)(0.14\,\eta_{np} - 0.88\,\eta_{nn}) =$$

$$= 1.82\,\eta_{np} - 0.44\,\eta_{nn} \qquad (15)$$

Comparable corrections ($\sim$30%) arise also in the sm of ^{131}Xe and ^{201}Hg. In the nuclei ^{199}Hg and ^{203,205}Tl the corrections can reach 100%.

4. We shall get now the limit on the parameter η_{np} of the T-odd potential (5) that follows from the experimental result (3). The Hartree-Fock calculation carried out in ref [8] has shown that the xenon atom edm is connected with the nuclear sm as

$$d(Xe) = 2.7\cdot 10^{-18}\left(\frac{Q}{e\cdot fm^3}\right) e\cdot cm \qquad (16)$$

From (3), (16) and the value of Q (^{129}Xe) presented in table we get the following limit on the constant η_{np}

$$\eta_{np} = -0.07 \pm 0.24 \qquad (17)$$

From the experiments with the TlF molecule [9,10] and the calculations [11] the following limit on Q (^{203,205}Tl) arises:

$$Q(^{203,205}Tl) = (0.8 \pm 1.2)\cdot 10^{-8}\, e\cdot fm^3 \qquad (18)$$

Unfortunately, the calculation of Q(Tl) contains large uncertainties connected with the estimate of the giant resonance contribution. Therefore, the limit following from (18) and the value of Q(Tl) from table,

$$1.2\,\eta_{pp} - 1.4\,\eta_{pn} = 0.8 \pm 1.2 \tag{19}$$

is an order of magnitude estimate only.

The natural question arises: what are the physical implications of these limits? We shall try to answer this question grounding for definiteness on the Kobayashi-Maskawa model [12]. Now it seems to be the most natural gauge scheme of CP-invariance violation. The theoretical prediction for the neutron edm in this model [13,14]

$$d_n \sim 10^{-31}\ e\cdot cm \tag{20}$$

is about seven orders of magnitude smaller than the experimental limit (4). As to the T-odd nucleon-nucleon interaction, the corresponding dimensionless constants in the Kobayashi-Maskawa model constitute [1]

$$\eta_{ab} \sim 10^{-8} \tag{21}$$

The gap between this theoretical prediction and the limit (17) is only some times larger than in the case of the neutron edm. Therefore, the result (3) by its physical implications approaches indeed the limit (4) on the neutron edm. As to the tremendous gap between the experimental limits and theoretical predictions for both quantities compared, one should note that the Kobayashi-Maskawa model is now only the most simple scheme of CP-violation and that the true magnitude of T-odd effects can be much larger.

One can try to compare the results of the measurements of

the neutron and xenon edm purely phenomenologically, grounding on the one-boson exchange model popular in the calculations of the usual weak interactions. The lowest intermediate state contributing to the constant η_{np} is π^0 -meson. Its contribution is given by the relation

$$\frac{G}{\sqrt{2}}\,\eta_0 = -\,\frac{g\bar{g}_0}{m_\pi^2} \tag{22}$$

where g and $\bar{g}$ are the constants of the strong and T-odd π -meson-nucleon interaction:

$$\begin{aligned} &(g\,i\,\bar{\psi}_n\gamma_5\psi_n + \bar{g}_0\,\bar{\psi}_p\psi_p)\,\varphi_{\pi^0} + \\ &+\sqrt{2}\,(g\,i\,\bar{\psi}_p\gamma_5\psi_n + \bar{g}_-\,\bar{\psi}_p\psi_n)\,\varphi^+_{\pi^-} \end{aligned} \tag{23}$$

From (17), (22) the limit follows

$$g\bar{g}_0 = (1.0 \pm 3.7)\cdot 10^{-8} \tag{24}$$

The virtual π^--meson creation leads also to the neutron edm [15]

$$d_n = \frac{e\,g\bar{g}_-}{4\pi^2 m}\,\ln\frac{M}{m_\pi} = 0.9\cdot 10^{-15}\,e\cdot cm\ g\bar{g}_- \tag{25}$$

Here $M \sim m_\rho$ is the scale at which π -meson loop converges. From the limit on the neutron edm (4) it follows

$$|\,g\bar{g}_-\,| < 4.5\cdot 10^{-10} \tag{26}$$

The limits (24) and (26) refer generally speaking to different quantities. But, e.g., in the model of T-invariance violation with the θ -term*) $|\,g\bar{g}_0\,| = |\,g\bar{g}_-\,| = 0.36\,|\theta|$ [15].

*) The nuclear T-invariance nonconservation was considered within this model in ref. [16].

Unlike Kobayashi-Maskawa model, in this case the limit on the parameter θ following from the neutron edm measurements is considerably stronger than those from the xenon edm. However, even the most optimistic of the modern projects of the neutron edm measurements do not plan the accuracy in the determination of d_n/e better than 10^{-26} cm. And the authors of ref. [4] plan to increase the accuracy of atomic experiments by four orders of magnitude. Note that only by transition from xenon to mercury one could gain, due to larger Z, an order of magnitude in the value of atomic edm. Using the atomic calculation [17] one can show that the edm of mercury atom is

$$d(H_g) = -4\cdot 10^{-17} \left(\frac{Q}{e\cdot fm^3}\right) e\cdot cm \tag{27}$$

Therefore, the prognoses in atomic physics look more optimistic than in neutron one, especially since the transition to other heavy atoms, as well as molecules, with larger edm is possible (see, e.g. ref [1]).

5. We pass now to the estimate of the internal nucleons contribution to the P-odd but CP-even nuclear anapole moment (am) $\vec{a}$. We define it by the relation[7]

$$\vec{a} = -\frac{\pi}{2} \left\langle \sum_b \left(r_b^2 \vec{j}_b + \vec{j}_b r_b^2 \right) \right\rangle \tag{28}$$

where $\vec{j}_b$ is the current density of the nucleon b. The contribution of am to the vector-potential equals

$$\vec{A}(\vec{r}) = \vec{a}\, \delta(\vec{r})$$

We present the P-odd nucleon-nucleon interaction in a local form analogous to (5):

$$W_{ab}^{p} = \frac{G}{\sqrt{2}} \frac{1}{2m} \Big[\left(g_{ab} \vec{\sigma}_a - g_{ba} \vec{\sigma}_b \right) \left\{ (\vec{p}_a - \vec{p}_b), \delta(\vec{r}_a - \vec{r}_b) \right\} + g'_{ab} \left[\vec{\sigma}_a \times \vec{\sigma}_b \right] \vec{\nabla}_a \delta(\vec{r}_a - \vec{r}_b) \Big] \tag{29}$$

The nuclear anapole was calculated in ref [6] taking into account the external nucleon excitations only. The calculation was carried out both numerically, using the Woods-Saxon potential with the spin-orbit correction, and analitically in the approximation of the constant core nucleons density $\rho(\vec{r})$. The agreement of the approximate analitical calculation with the numerical one is quite satisfactory. The analytical result looks as follows:

$$\vec{a} = \frac{G}{\sqrt{2}} \frac{9}{10} g_a \frac{e\mu_a}{m r_0} A^{2/3} \frac{K}{I(I+1)} \vec{I} \tag{30}$$

Here

$$g_a = g_{ap}\frac{Z}{A} + g_{an}\frac{N}{A}, \qquad K = (-1)^{I+\frac{1}{2}-l} \left(I+\tfrac{1}{2}\right),$$

l is the orbital angular momentum of the external nucleon, the index $a=p$ or $a=n$ refers to the external nucleon.

To illustrate the further arguments it is useful to show how expression (30) can be obtained in the oscillator model of nucleus. In this model the operator of am caused by spin current

$$\hat{\vec{a}}_s = \frac{\pi e}{m} \sum_b \mu_b \vec{r}_b \times \vec{\sigma}_b \tag{31}$$

can be presented as (cf. (8))

$$\hat{\vec{a}}_s = \frac{\pi e}{m} \frac{i}{m\omega^2} \left[\sum_b \mu_b \vec{p}_b \times \vec{\sigma}_b ,\, H \right] \tag{32}$$

Substituting this expression into the formula for nuclear am arising in the second order of perturbation theory (it is analogous to (7)), we get the following result:

$$\vec{a}_s = -\frac{\pi e i}{m^2\omega^2}\langle 0|\Big[\sum_b \mu_b \vec{p}_b\times\vec{\sigma}_b,\ W^p\Big]|0\rangle \qquad (33)$$

Now we start from the contribution due to the term in the sum $\sum_b \mu_b \vec{p}_b\times\vec{\sigma}_b$ corresponding to external nucleon. In this case all the terms in the operator W^p (29) dependent on the spins and momenta of internal nucleons drop out. Therefore, this contribution reduces to

$$\vec{a}_s^{\,ex} = -\frac{G}{\sqrt{2}}\frac{\pi e}{2m^3\omega^2}\mu_a i\langle 0|\Big[\vec{p}_a\times\vec{\sigma}_a,\Big\{\vec{\sigma}_a\vec{p}_a,\sum_b g_{ab}\,\delta(\vec{r}_a-\vec{r}_b)\Big\}\Big]|0\rangle =$$

$$= -\frac{G}{\sqrt{2}}\frac{\pi e}{2m^3\omega^2}\mu_a g_a i\langle 0|\Big[\vec{p}_a\times\vec{\sigma}_a,\big\{\vec{\sigma}_a\vec{p}_a,\rho(\vec{r}_a)\big\}\Big]|0\rangle \qquad (34)$$

Here $\{\ ,\ \}$ is an anticommutator, $[\ ,\ ]$ is a commutator. The expectation value in the second line is taken over the state of external nucleon marked by the index a. If one takes in (34) the internal nucleon density to be constant, averages over angles and makes the substitution $\langle p^2/m^2\omega^2\rangle = \langle r^2\rangle \approx \frac{3}{5} r_0^2 A^{2/3}$, expression (30) arises again.

Consider now the internal nucleons contribution from the sum $\sum_b \mu_b \vec{p}_b\times\vec{\sigma}_b$ in expression (33). It is clear that in this case only those terms in the potential (29) that depend on the spins of internal particles are operative. Here the terms of full commutator (33) remain that contain an anticommutator of spin variables (for internal nucleons $\langle[\sigma,\sigma]\rangle\sim\langle\sigma\rangle = 0$) and a commutator of coordinate variables. The last one contains $\nabla\rho$, and therefore the factor $\langle p^2/m^2\omega^2\rangle = \langle r^2\rangle \sim A^{2/3}$ cannot arise now in the answer. More detailed calculation shows that the contribution of the internal nucleons spin anapole moment is indeed suppressed by $A^{2/3}$ times in comparison with (30). Although this conclusion is obtained in the oscillator model, we believe that it is of general character*).

*) Note that by the analogous reason there is no enhancement factor $A^{2/3}$ in a nuclear mqm.

Pass now to the contribution to nuclear am of the orbital current in expression (28). Of course only protons are operative here. Start again from the external nucleon contribution. It is clear that here also those terms from the operator (29) survive that are independent of the spins and momenta of internal nucleons, so that

$$W^p \to \frac{G}{\sqrt{2}}\frac{1}{2m}\sum_b g_{ab}\big\{\vec{\sigma}_a\vec{p}_a,\ \delta(\vec{r}_a-\vec{r}_b)\big\} \to \frac{G}{\sqrt{2}}\frac{g_a}{2m}\big\{\vec{\sigma}_a\vec{p}_a,\ \rho(\vec{r})\big\} \qquad (35)$$

We understand now that the enhancement $\sim A^{2/3}$ is caused by those terms only that do not contain $\nabla\rho$. In other words, looking for the contribution $\sim A^{2/3}$ one can here also put $\rho(\vec{r}) = \rho_0 = const$. But then the interaction (35) is equivalent to the electromagnetic one with the constant vector-potential $\vec{A} = -\frac{G g \rho_0}{e\sqrt{2}}\vec{\sigma}$, which naturally does not lead at all to any observable effects for operators independent of spin. As to the spin anapole operator (31), it does not vanish to this approximation due to the non-commutativity of σ-matrices[6].

The magnitude of the orbital contribution can be estimated by the substitution $\rho\to\rho-\rho_0$ in (35). The contribution to the matrix elements of the operator $\rho-\rho_0$ is given by the nuclear surface with the relative volume $\sim A^{-1/3}$. Moreover, the orbital contribution does not contain the relatively large factor μ_p, the proton magnetic moment. Therefore, orbital contribution of external proton is $\mu_p A^{1/3}$ smaller than the spin one (30). This estimate is confirmed by the calculation in the oscillator model, as well as numerical calculations in the Woods-Saxon potential [6].

Note that from the same arguments it follows that the accuracy of the constant density approximation for the spin contribution of external nucleon to nuclear am (30) is $A^{-1/3}$.

And finally consider the contribution of the internal protons orbital current. Generally speaking, it can contain the large factor $A^{2/3}$. Here one should retain in (29) only those terms that depend on the external nucleon spin and internal nucleons momenta. Write down this interaction as

$$W^p \to -\frac{G}{\sqrt{2}}\frac{1}{2m}\, g_{ap}\sum_p \{\vec{p}_p, \vec{\sigma}_a(\vec{r}_p)\} \tag{36}$$

where

$$\vec{\sigma}_a(\vec{r}_p) = \int d\vec{r}_a\, \psi_a^+ \vec{\sigma}_a \psi_a\, \delta(\vec{r}_a - \vec{r}_p) = \psi_a^+(\vec{r}_p)\,\vec{\sigma}_a\, \psi_a(\vec{r}_p)$$

is the spin density of external nucleon a taken at the point $\vec{r}_p$ where an internal proton p is located. It is convenient to transform the contribution of orbital current to am as follows [7]:

$$\vec{a}_l = -\frac{2\pi}{3}\frac{ie}{2m}\sum_k \frac{\langle 0|W^p|k\rangle\langle k|\sum_p[\vec{l}_p^{\,2}, \vec{r}_p]|0\rangle + \langle 0|\sum_p[\vec{l}_p^{\,2}, \vec{r}_p]|k\rangle\langle k|W^p|0\rangle}{E_0 - E_k}$$

$$= -\frac{2\pi}{3}\langle 0|\sum_p r_p^2\, \vec{j}_p - \vec{r}_p(\vec{r}_p \vec{j}_p)|0\rangle \tag{37}$$

where $\vec{j}_p$ is a contact current defined by the relation

$$\vec{j}_p = ie\,[W^p, \vec{r}_p] \tag{38}$$

One can estimate the contact current contribution substituting for the spin density $\vec{\sigma}_a(\vec{r}_p)$ its average value $\vec{\sigma}_a \frac{\rho_0}{A}$. Under this assumption the contact contribution equals:

$$-\frac{G}{\sqrt{2}}\frac{3}{10}\, g_{ap}\,\frac{Z}{A}\,\frac{e}{m r_0}\, A^{2/3}\,\frac{K\vec{I}}{I(I+1)} \tag{39}$$

The obtained value differs from the result (30) by the factor

$$-\frac{1}{3\mu_a}\,\frac{Z}{A}\,\frac{g_{ap}}{g_a} \tag{40}$$

which is numerically small. Moreover, in the approximation of constant spin density $\vec{\sigma}_a(\vec{r}_p)$ the terms in expression (37) that depend on the contact current $\vec{j}_p$, according to the above arguments, should cancel out exactly other terms. This cancellation can be checked also by the direct calculation. On the other hand, the constant spin density approximation allows one to get a reasonable estimate for every of these contributions taken separately. Therefore, one can consider the small quantity (40) as a sufficiently generous estimate of the internal nucleons contribution to the nuclear am. The calculation without the assumption $\vec{\sigma}_a(\vec{r}_p) = const$ can be carried out in the oscillator model. It confirms the estimate (40).

Thus the formula (30) obtained by us previously in ref. [6] is indeed a reasonable approximation for nuclear anapole moments.

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T a b l e

Values of Schiff moments $\frac{Q}{e \cdot fm^3} \cdot 10^8$.
Constants η are the parameters of T-odd interaction (5).

^{129}Xe	^{131}Xe	^{199}Hg	^{201}Hg	$^{203,205}Tl$
$1.75\,\eta_{np}$	$-2.6\,\eta_{np}$	$-1.4\,\eta_{np}$	$2.4\,\eta_{np}$	$1.2\,\eta_{pp}\;\; -1.4\,\eta_{pn}$

R e f e r e n c e s

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