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The discovery of the nuclear anapole moment

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The anapole moment (AM) of the nucleus ^{133}Cs has been experimentally discovered [1]. Searches for nuclear AM have been carried out for many years by several groups. So, what is an AM and why is it interesting?

Forty years ago it was pointed out [2] that a system which does not transform into itself under space inversion (or in other words, has no definite parity) generates a special distribution of magnetic fields which looks like the magnetic field created by a current in toroidal winding, and differs from the fields due to common electromagnetic multipoles, such as dipole or quadrupole moments. The term 'anapole' for this special source of electromagnetic fields was suggested by A S Kompaneets.

For many years the anapole remained a theoretical curiosity only. The situation has changed due to the investigation of parity nonconservation in atoms. Since these small effects increase with the nuclear charge Z, all the experiments are carried out with heavy atoms. The main contribution to the effect is independent of nuclear spin and caused by the parity-violating weak interaction of electron and nucleon neutral currents. This interaction is proportional to the so-called 'weak' nuclear charge Q, which is numerically close (up to the sign) to the neutron number N. Thus in heavy atoms the nuclear-spin-independent weak interaction is additionally enhanced by about two orders of magnitude. Meanwhile the nuclear-spin-dependent effects due to neutral currents not only lack the mentioned coherent enhancement, but are also strongly suppressed numerically in the electroweak theory. Therefore, the observation of parity-violating nuclear-spin-dependent effects in atoms looked absolutely unrealistic.

However, in 1980 it was demonstrated [3] that these effects in atoms are mainly caused not by the weak interaction of neutral currents, but by the electromagnetic interaction of atomic electrons with the nuclear AM. It should be mentioned first of all that the magnetic field of an anapole is contained within it, in the same way as the magnetic field of a toroidal winding is completely confined inside the winding. It means that the electromagnetic interaction of an electron with the nuclear AM occurs only as long as the electron wave function penetrates the nucleus. In other words, this electromagnetic interaction is as local as the weak interaction, and they cannot be distinguished by their manifestations. The nuclear AM arises due to parity nonconservation in nuclear forces and is therefore proportional to the same Fermi constant G, which determines the magnitude of the weak interactions in general and that of neutral currents in particular. The electron interaction with the AM, due to its electromagnetic nature, introduces an additional small factor into the effect discussed, the fine-structure constant $\alpha = 1/137$. How, then, does this effect become dominant? The answer follows from the same analogy with a toroidal winding. It is only natural that the interaction discussed is proportional to the magnetic flux through such a winding, and hence in our case to the cross-section of the nucleus, i.e. to $A^{2/3}$ where A is the atomic number. In heavy nuclei this enhancement factor is close to 30 and essentially compensates for the smallness of the fine-structure constant α. As a result, the dimensionless effective constant $\varkappa$ which characterizes the anapole interaction in units of G is not so small in heavy atoms, but is numerically close to 0.3 (we use in this note the same definition of the effective constant as in Refs [3, 4]).

Nevertheless, the interaction discussed constitutes only about one percent of the main atomic parity-nonconserving effect independent of the nuclear spin, which is caused by the 'weak' charge Q and is enhanced therefore as N. To single out the anapole interaction one should compare the parity-nonconserving effects for different hyperfine components of an optical transition. The main effect, independent of the nuclear spin, will obviously be the same for all components. But the anapole interaction depends on the mutual orientation of the nuclear spin and the electron total angular momentum, and changes therefore from one hyperfine component to another. The observation of this tiny effect is an extremely difficult problem and it is no accident that the discovery of the nuclear AM took place after many years of hard work by several groups [5 – 9].

The result obtained in Ref. [1] for the total effective constant of the parity-violating nuclear-spin-dependent interaction is $\varkappa_{\text{tot}} = 0.44 \pm 6$ (to derive this number from the experimental data we use here the results of atomic calculations [10, 11]; these calculations performed using different approaches are in excellent agreement). If one excludes the neutral current nuclear-spin-dependent contribution from the above number, as well as the result of the combined action of the 'weak' charge Q and the usual hyperfine interaction, the answer for the anapole constant will be $\varkappa = 0.37 \pm 6$. Thus, the existence of an AM of the ^{133}Cs nucleus is reliably established. A beautiful new physical phenomenon, an peculiar electromagnetic multipole has been discovered.

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But does the discussed result reduce to only this? Let us note that all the detailed nuclear calculations for the AM of the ^{133}Cs nucleus [4, 12 – 16] are in agreement. At the so-called 'best values' [17] of the constants for parity-nonconserving nuclear forces, theoretical predictions for $\varkappa$ are restricted to the interval 0.22 – 0.28. Such a stability of theoretical results is unique for nuclear physics. The agreement among various atomic calculations for the anapole effect in cesium is even better. Therefore, the reliability of the theoretical predictions (at given values of the parity-violating nuclear constants) is sufficiently high here, so that the discussed experiment is a serious confirmation for the mentioned 'best values'. In no way is this confirmation trivial. The point is that the magnitude of parity-nonconserving effects found in some nuclear experiments is much smaller than that following from the 'best values' (see review [18]). In all these experiments, however, either the experimental accuracy is not high enough, or the theoretical interpretation is not sufficiently convincing. Experiment [1] looks much more reliable in both respects. Therefore, in line with its general physics interest the investigation of nuclear AM in atomic experiments is first-rate, almost table-top nuclear physics.

Seventy years ago studies of atomic hyperfine structure gave the first clue to the existence of nuclear magnetic moments. Since then atomic and molecular spectroscopy have served as a source of valuable information on nuclear properties, such as multipole moments and the radii of nuclei. Now a new chapter in this story has opened: optical spectroscopy brings data on parity-nonconserving nuclear forces.

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† The paper contains also a mention of the analogous result obtained by V G Vaks.