FROM THE CURRENT LITERATURE

Nonconservation of parity in atoms

I. B. Khriplovich

Institute of Nuclear Physics, Siberian Division of the Academy of Sciences of the USSR, Novosibirsk

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This note may be regarded as an addendum to the paper by M. A. Bouchiat and L. Pottier[1] (a translation of which is published in the Russian-language edition of this issue).

I note at the outset that it is clear, in particular from Ref. 1, that it is now generally acknowledged that parity nonconservation (PNC) in atoms is a fact, and that it is correctly described by the standard model of the electroweak interaction. I recall that it is only a few years ago that a heated discussion was taking place on this topic, and was indeed reflected, for example, on the pages of this Journal (see the previous review of the subject in Ref. 2).

There is a further point that is worth emphasizing (and was emphasized by the authors of Ref. 1): to this day, and even after the discovery of the W amd Z bosons (the conveyors of the weak interaction) in proton-antiproton colliding beams in 1983, optical experiments continue to be an excellent source of information on the structure of these interactions.

What new has happened in this area in the recent past? The Oxford group have published two experimental results on bismuth. The new data on the infrared line[3] give the following value for the PNC parameter:

$$R = -(10.0 \pm 1.0)\cdot 10^{-8}$$

which is in excellent agreement with the result of the Seattle group for the same line (see the table in Ref. 1). The 6s–7s transition in cesium is thus no longer the only example of undisputed quantitative agreement between the results of independent groups.

The Oxford group has also published data on the red line[4]:

$$R = -(9.3 \pm 1.4)\cdot 10^{-8}.$$

This number is quoted in Ref. 1 with a somewhat lower uncertainty ($\pm 1.15\times 10^{-8}$) with a reference to a thesis and a private communication. The remaining quantitative discrepancy between the Novosibirsk results, on the one hand, and those reported by the Physics Institute of the Academy of Sciences of the USSR and the Oxford group (see the table in Ref. 1) is the last echo of the discussion mentioned above that raged a few years ago.

What should be expected of further experiments in this field? Their immediate aim (apart, that is, from removing the above discrepancy) is to provide precision measurements of the standard-model parameter $\sin^2\theta$ and the weak nuclear charge Q_W, which in turn should enable us to determine the effect of radiative corrections in terms of the electroweak interaction (see Ref. 1). Of course, such precision measurements will have to be accompanied by precise calculations. In this respect, the situation with cesium is particularly promising. The precision of the cesium experiments is fully comparable with the precision attained for other atoms. However, the uncertainty in the atomic calculations of PNC effects in cesium was[5] 2% and can hardly be improved upon. The same uncertainty is estimated in Ref. 1 as being 5% which seems very conservative. The point is that, in their previous paper, cited in Ref. 1, the Novosibirsk Group had already estimated their uncertainty as 3%, and it was precisely this calculation[6] that was described in Ref. 1 as the most complete of those available at the time. In this situation, it is therefore somewhat unreasonable of the authors of Ref. 1 to estimate the uncertainty in the theoretical calculations as being equal to the spread of the results reported by different groups.

There is, however, another way of estimating $\sin^2\theta$ in atomic physics, which is practically free of theoretical uncertainties.[7] We are referring to experiments with samarium, which has stable isotopes in the range $A = 144$–154, so that the difference between the number of neutrons is $\Delta N = 10$. The value of $\sin^2\theta$ can be found from the ratio $\Delta Q_W/Q_W$.

Moreover, this approach has a further advantage in so far as PNC experiments are concerned. Samarium is similar to other rare earths in that it has a dense spectrum and, correspondingly, small energy differences between levels of opposite parity. In general, this tends to enhance the PNC effects. The main configuration of samarium consists of the seven levels $4f^6 6s^2\ {}^7F_J$. The magnetic dipole transitions between them lie in the far infrared, and are available for PNC experiments. However, M1 transitions to levels of the next configuration with the same parity, i.e., $4f^6 6s^2\ {}^5D_J$, $0 < J < 4$, lie in the optical range, and are suitable candidates for these experiments. Moreover, the ${}^5D_J$ levels lie in a dense part of the spectrum, so that an enhancement of the PNC effects may be expected. Unfortunately, because of the complicated structure of the atomic states of the rare earths, this enhancement is not as large as could be naively expected. Nevertheless an enhancement factor of about 10 can be counted upon.

However, until quite recently, the precise position of the ${}^5D_J$ levels was not known. Three of them, namely, ${}^5D_1$ ($E = 15914.55$ (3) cm^{-1}), ${}^5D_2$ ($E = 17864.29$ (3) cm^{-1}), and ${}^5D_3$ ($E = 20195.76$ (3) cm^{-1}) were discovered experimentally[8] very recently. Further advances may be expected in this area.

We now turn to the next important task, namely, the search in atoms for spin-dependent PNC effects. It has been recognized[9,10] for some years now that parity nonconserving nuclear forces and not neutral currents are the main source of these effects (see the discussion in the last section of Ref. 1). The point in question is the electromagnetic interaction of the electron with the so-called *anapole moment* of the nucleus. The anapole moment is a special electromagnetic property of a system in which spatial parity is not conserved. A system of this kind exhibits a helical spin structure and a special magnetic-field distribution that corresponds to the field produced by a toroidal coil.[11] The anapole moment is the source of this kind of field.

Naturally, the magnitude of the anapole moment is pro-

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portional to the magnetic induction in the system, i.e., the square of its linear size. For a heavy nucleus, this gives rise to a large enhancement factor, $\sim A^{2/3}$ (Ref. 10). This factor largely compensates the natural small quantity $e^2 = \alpha = 1/137$ in the electromagnetic interaction between the electron and the anapole moment of the nucleus. Calculations[10] show that the anapole moment of heavy nuclei is such that the interaction produced by it exceeds by a substantial factor the effects induced by the constants $C^2_{p,n}$ (see Ref. 1), at least for odd-Z nuclei. The discovery of the anapole moment moment—a new electromagnetic property of the nucleus—would be of enormous interest. Moreover, in contrast to other nuclear PNC effects, the nuclear anapole moment can be calculated with adequate precision. Measurement of this quantity would therefore provide us with valuable information about parity violating nuclear forces.

How could we measure the nuclear anapole moment? The first method relies on a precise comparison of atomic PNC effects in different hyperfine structure components of an optical transition.[12] This method is discussed in Ref. 1.

There is, however, a less obvious approach to this problem. Once again, we turn to the rare earth experiments.[7] With a bit of luck, it might be possible to find convenient levels of opposite parity that are anomalously closely spaced, but have total electron angular momenta differing by unity, i.e., $\Delta J = \pm 1$. Such levels can only be mixed by nuclear-spin-dependent PNC interaction that is a vector in the electron variables. The weak interaction background, which depends on Q_W and is usually the dominant one, is thus sharply reduced.

Here experiments of both types are possible. We can investigate optical activity or perform experiments similar to those carried out on cesium and thallium. It is important to remember, however, that effects that depend on the nuclear spin will vanish as we average over the hyperfine structure. This means that, in such experiments, the hyperfine structure should be resolved; however, in the rare earths, it is sometimes very small.

We must now consider yet another range of problems that was not touched upon in Ref. 1, but undoubtedly constitutes a particularly ineresting and important area in research into the weak interaction by optical methods. We are referring to searches for T-invariance violation in atoms and molecules. So far, such effects have been observed only in the decay of neutral kaons. Although it is now almost a quarter of a century since the discovery of these effects, the nature of the phenomenon is still essentially a puzzle.

Searches for T-invariance violations have been continuing with neutrons for many years. The aim has been to detect the electic dipole moment (EDM) of the neutron. We recall that T-invariance demands that the EDM of a nondegenerate quantum mechanical system must be zero. The most accurate result obtained[13] for the neutron ADM, d_n, is interpreted in Ref. 13 as providing the following upper limit at the 95% confidence level:

$$\left|\frac{d_n}{e}\right| < 2.6\cdot 10^{-25}\,\text{cm}. \tag{1}$$

Although the dipole moment of the neutron has not been detected, these experiments have been exceedingly important in radically reducing the number of possible models of T-invariance violation.

Searches for the dipole moment in atoms and molecules have also been continuing for many years. The situation in this area (and also studies of spatial parity violations in atoms and molecules) are reviewed in a recent book.[14] Here, we confine our attention to recent results of searches for T-invariance violations in atomic phenomena. Recent reports have given upper limits for the EDM of the ^{129}Xe atom (Ref. 15), the TlF molecule (Ref. 16), and the ^{199}Hg atom (Ref. 17). Xenon (in its ground state) and mercury were investigated from this point of view apparently for the first time.

TABLE I. Limits on the constants k_i and the T-odd interaction between light quarks.

	d_n	$d\,(^{199}\text{Hg})$
1. $\frac{G}{\sqrt{2}} k_u i\,(\bar{u}\gamma_5 u)(\bar{u}u)$	$2\cdot 10^{-4}$	$1\cdot 10^{-4}$
2. $\frac{G}{\sqrt{2}} k^c_u\, i\,(\bar{u}\gamma_5 t^a u)(\bar{u}t^a u)$	$1.5\cdot 10^{-4}$	$5\cdot 10^{-4}$
3. $\frac{G}{\sqrt{2}} k_d i\,(\bar{d}\gamma_5 d)(\bar{d}d)$	$2.5\cdot 10^{-4}$	$1,5\cdot 10^{-4}$
4. $\frac{G}{\sqrt{2}} k^c_d i\,(\bar{d}\gamma_5 t^a d)(\bar{d}t^a d)$	$4\cdot 10^{-4}$	$6\cdot 10^{-4}$
5. $\frac{G}{\sqrt{2}} k_{du} i\,(\bar{d}\gamma_5 d)(\bar{u}u)$	$2\cdot 10^{-4}$	$1\cdot 10^{-4}$
6. $\frac{G}{\sqrt{2}} k^c_{du} i\,(\bar{d}\gamma_5 t^a d)(\bar{u}t^a u)$	$1\cdot 10^{-3}$	$4\cdot 10^{-2}$
7. $\frac{G}{\sqrt{2}} k_t \frac{1}{2} \varepsilon_{\mu\nu\varkappa\lambda}\,(\bar{u}\sigma_{\mu\nu}u)(\bar{d}\sigma_{\varkappa\lambda}d)$	$3\cdot 10^{-5}$	$5\cdot 10^{-3}$
8. $\frac{G}{\sqrt{2}} k^c_t \frac{1}{2} \varepsilon_{\mu\nu\varkappa\lambda}\,(\bar{u}\sigma_{\mu\nu}t^a u)(\bar{d}\sigma_{\varkappa\lambda}t^a d)$	$2.5\cdot 10^{-4}$	$5\cdot 10^{-3}$
9. $\frac{G}{\sqrt{2}} k^g_u m_p \bar{u}\sigma_{\mu\nu}\gamma_5 g G^a_{\mu\nu} t^a u$	$2\cdot 10^{-5}$	$1,5\cdot 10^{-6}$
10. $\frac{G}{\sqrt{2}} k^g_d m_p \bar{d}\sigma_{\mu\nu}\gamma_5 g G^a_{\mu\nu} t^a d$	$1\cdot 10^{-5}$	$1,5\cdot 10^{-6}$

The result obtained for TlF is a serious step forward as compared with previous investigations of this molecule.

The result of the mercury experiment[17] is

$$\frac{d\,(^{199}\mathrm{Hg})}{e} = (0.7 \pm 1.5)\cdot 10^{-26}\ \mathrm{cm}, \qquad (2)$$

and is apparently physically the most significant. This restriction on the EDM of mercury is more stringent than the neutron result given by (1). It is, however, necessary to note the following point. An atom in an external electric field is in a steady state, so that the average force acting on the nucleus and on each electron is zero. For a system of nonrelativistic point particles interacting in accordance with Coulomb's law this means that the mean electric field acting on each particle is completely screened off. The EDM of each individual particle cannot then manifest itself in any way. In a system with closed electron shells (such as Xe, TlF, and Hg in the ground state), the screening of the nuclear EDM is not complete taking its finite dimensions into account. The fact that these dimensions are small in comparison with the size of the atom (even in the case of the K shell), gives rise to a sharp reduction in the factor used to convert the EDM of the atom to the dipole moment of the nucleus. While the latter can be quite naturally interpreted as being the manifestation of the EDM of a valence nucleon, the upper limit on the nucleon dipole moment that follows from (2) turns out to be very insignificant in comparison with (1), i.e., it is weaker by roughly three orders of magnitude. A distinct impression is thus gained that searches for T-odd effects in atoms and molecules can generally be of no interest to elementary particle physics.

In actual fact, this is not the case at all. The EDM of the nucleus is induced not only by the dipole moment of the outer nucleon, but also by the T-odd nucleon-nucleon interaction. As was demonstrated in Ref. 18, it is this second mechanism for the nuclear EDM that may turn out to be the more effective. Moreover, the T-odd interaction between quarks and gluons may be more effectively transferred to T-odd nuclear forces than to the EDM of the nucleon. This problem was examined in Ref. 19 where an effective Hamiltonian was constructed for the T-odd interaction in a system of light u and d quarks, and upper limits were found for the constants in this interaction that follow from the experimental results (1) and (2). The results for xenon, but not those for mercury, were used directly in Ref. 19 because the latter were published after Ref. 19 was written. However, no difficulties arise when the results are recalculated from xenon to mercury. Table I lists the results given in Ref. 19. The first column shows several variants of the T-odd interaction (u and d label the quark fields, t^a are the generators of the SU(3) color group, $G^a_{\mu\nu}$ are the gluon field strengths, and g is the coupling constant between the gluon field and the quarks). The second and third columns show the limits on the corresponding dimensionless constants k_i that follow from the experimental results on the EDM of the neutron and the ^{199}Hg atoms. Inspection of the table clearly shows that searches for the atomic EDM are now physically just as significant as those for the neutron EDM.

The conclusion is that these experiments are not simply exercises in atomic spectroscopy, but are yet another source of first-rate information on the nature of T-invariance violation.

I hope that I have succeeded in providing a further confirmation of the importance and fascination of optical studies of the weak interactions between elementary particles.

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