ATOMIC PHYSICS:
QED, FUNDAMENTAL SYMMETRIES

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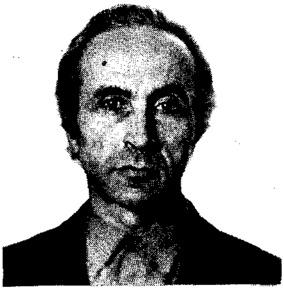

Abstract

This is a summary of the talks on the mentioned subjects presented at the Workshop.

The time allotted for the summary is short, and the number of the talks to be covered is large. I like all of them. I enjoyed those by my theoretical friends, *S. Barr* and *J. Sucher*. Could not but admire the experimental ingenuity with which modern traps for positrons and hydrogen are constructed (*K. Abdullah* and *T. Hijmans*). As to the spin-polarized hydrogen (*I. Silvera*), my fascination by those experiments lasts already for many years.

But I don't wish to make the summary talk a complete commonplace. So, with the hope to be able to say at least something of interest to the audience, I'll confine to comments on three subjects:

1. Precision measurements in hydrogen and positronium
2. Parity nonconservation in atoms
3. CP-violation

1. Precision measurements constitute for a long time the essential feature of atomic physics. Such measurements in hydrogen involving high levels and 1s - 2s transitions were described in the talks by *L. Julien* and *C. Zimmerman* respectively. Besides being a tool for metrology, those experiments are a source of valuable information on the electron-proton mass ratio and on the proton charge radius, they constitute a sensitive test of quantum electrodynamics. And who can predict at all what surprises await us at the next level of precision?

Such a surprise has been brought indeed by precise measurements of the orthopositronium decay rate (oPs$\dashrightarrow 3\gamma$), as discussed in the talk by *R. Conti*. The experimental value of this decay rate

$$\Gamma_{exp}^{oPs} = 7.0482(16)\mu s^{-1} \tag{1}$$

is by six standard deviations above the theoretical prediction

$$\Gamma_{th}^{oPs} = m\alpha^6 \frac{2(\pi^2-9)}{9\pi}\left[1 - 10.28\frac{\alpha}{\pi} - \frac{1}{3}\alpha^2 \log\frac{1}{\alpha}\right] = 7.03830\mu s^{-1}. \tag{2}$$

And positronium is presumably pure QED system!

To reconcile the theory with experiment staying within QED, one should assume that the correction $\sim (\alpha/\pi)^2$ should be

$$250(40)(\alpha/\pi)^2.$$

which may look unreasonably large. We believe nevertheless that the natural scale for the factor at $(\alpha/\pi)^2$ is about 100. The argument is as follows (I.B. Khriplovich, A.I. Milstein, A.S. Yelkhovsky, Phys.Scr. **46** (1993) 252). The large, -10.28, factor at the α/π correction to the decay rate (see (2)) means that the typical magnitude of the factor at the α/π correction to the decay amplitude is roughly 5. Correspondingly, this correction squared contributes about $25(\alpha/\pi)^2$ to the decay rate. Indeed, numerical calculations by Burichenko (Yad.Fiz. **56** (1993) 123 [Sov.J.Nucl.Phys. **56** (1993)]) have given factor 28.8(0.2) at $(\alpha/\pi)^2$ in this contribution.

Then, it is only natural to expect that the interference of the second-order radiative correction to the amplitude with the zeroth-order amplitude should contribute about twice as much to the decay rate as the square of the first-order correction. In other words, the natural scale for the total second-order radiative correction to the decay rate should be close to

$$100(\alpha/\pi)^2. \tag{3}$$

One more class of large corrections is of relativistic origin. As *Conti* claimed in his talk,

$$\alpha = \beta \ \ (\beta = v/c).$$

But of course it is other way around:

$$\beta = \alpha.$$

And even this is not always true. In particular, in the problem discussed

$$\beta = \alpha i \sqrt{3/4}.$$

Coming back to more serious tone, I wish to say that a preliminary result of calculating relativistic corrections to the orthopositronium decay rate gives for their contribution (I.B. Khriplovich, A.I. Milstein, A.S. Yelkhovsky)

$$\sim 5\alpha^2.$$

As distinct from usual radiative corrections, the relativistic ones do not contain π in denominator (π is almost a dimensional number!). In the common "radiative" form, with π in denominator, this correction constitutes

$$\sim 50(\alpha/\pi)^2. \tag{4}$$

Having in mind estimates (3) and (4), we believe that it is premature to talk about the contradiction between the QED and the experimental result (1) now, until the complete calculation of the second-order correction to the decay rate is done.

In the conclusion of this section it is worth mentioning that terms of relativistic origin absolutely dominate the corrections of the relative order α^4 to the positronium nP levels (I.B. Khriplovich, A.I. Milstein, A.S. Yelkhovsky, Phys.Rev.Lett. **71** (1993) 4323). By the way, in this problem

$$\beta = \alpha/2n.$$

2. Parity nonconservation in atoms has gone already a long way,
from

the pioneering works by Bouchiat and Bouchiat (1974)
which transformed the subject from science fiction into science attracting attention to heavy atoms,
pointing out the P-odd correlations of experimental interest in strongly forbidden M1 transitions;

from

the first experimental observation of electron-nucleon weak interaction due to neutral currents,
by measuring optical activity of bismuth vapour near normal M1 transitions (Novosibirsk, 1978)

to

present precision tests of the electroweak theory:
the experimental accuracy in cesium has reached now 2% (Boulder, 1988),
the theoretical one is about 1% (Novosibirsk, 1989; Notre Dame, 1990).

Recent precision measurements of the optical activity of lead and thallium vapours with the accuracy 1% in Pb and about 0.5% in Tl were described by *S. Lamoreaux.*

It is certainly a challenge for atomic theory to reach the corresponding accuracy. That would mean not only new independent tests of the standard model, but a new level of precision for those tests. And at present the accuracy of atomic calculations of parity-nonconserving effects is no better than 8% in lead and 3% in thallium.

However, from the talk by *A.-M. Pendrill* we have learned about the impressive progress achieved in the theoretical description of the thallium hyperfine structure constants and E2 amplitude for $6p_{1/2} - 6p_{3/2}$ transition in Tl. This progress makes the accuracy about 1% in calculating parity-nonconserving effects in thallium sufficiently realistic. But to guarantee such a precision the theoretical calculations should be accompanied by as precise measurements of E1 amplitudes in thallium.

New generation of the experiments with cesium, in preparation now, are discussed in the talks by *M.-A. Bouchiat* and *D. Cho.*

Quite curious situation takes place in dysprosium where there are opposite parity levels separated by tiny energy interval. Ingenuous spectroscopic investigations described by *D. DeMill* have shown that the interval between hyperfine components belonging to those levels is in some cases as small as 3 MHz (compare with 10^3 MHz in the hydrogen Lamb shift!). The experiment is being prepared now to investigate parity-nonconserving effects in this system. Theoretical uncertainties do not allow to predict reliably the expected magnitude of those effects. So, the success of such an experiment here is to a large degree a matter of good luck. But at least it is a first-rate atomic spectroscopy.

One more aim of the experiments discussed is the search for nuclear anapole moments. Anapole is a new electromagnetic moment arising if parity is not conserved. Nuclear anapole moment is induced by P-odd nuclear forces. Atomic P-odd effects dependent on nuclear spin are dominated by contact electromagnetic interaction of electrons with nuclear anapole moment.

The problem of experimental observation of a new physical phenomenon, nuclear anapole moment, is by itself a fascinating one. Moreover, if the theoretical results of one-particle approximation, which are remarkably stable by nuclear standards, will be supplemented by a serious treatment of many-body effects, those experimental investigations will give reliable quantitative information on P-odd nuclear forces.

3. Up to now CP-violation has been observed in K-meson decays only. That is why the discussion in the talks by *D. Garreta* and *R. Legac* of CP-odd effects in kaon decays, as studied at LEAR, is so interesting.

The searches for electric dipole moments of neutron, atoms and molecules constitute another source of information on CP-violation. In the talk by *S. Lamoreaux* a record-breaking upper limit on electric dipole moment (EDM) of anything was reported. The measurements of atomic EDM of a mercury isotope result in

$$d(^{199}Hg)/e < 1.3 \cdot 10^{-27} cm. \tag{5}$$

The measurements in atomic thallium, as reported by *S. Ross*, brought the following upper limit on electron EDM:

$$d(e)/e < 10^{-26} cm. \tag{6}$$

New experiment with xenon is being prepared by *T. Chupp.* I learned also, but in private discussions only, from *E. Hinds* and *A. Weiss* about their new projects. Let us hope that at the next Moriond Workshop we will hear exciting news from these experiments.

But what is the real significance of the limits obtained? How do they relate to, say, the results of studying the neutron EDM? The answer to this question is given in Table where the limits on the constants of an effective Hamiltonian

$$H = \frac{G}{\sqrt{2}} \sum_i k_i O_i$$

($G = 10^{-5}/m_p^2$ is the Fermi constant, m_p is the proton mass) for the CP-odd interaction of u-, d-quarks and gluons are presented (V.M. Khatsymovsky, I.B. Khriplovich, Phys.Lett. **B296** (1992) 219).

Clearly, the atomic experiments are as informative as the neutron ones. In fact, they are complementary to each other. But still, what is the real value of both?

$k_i O_i$	$d(n)/e < 10^{-25}cm$	$d(^{199}Hg)/e < 1.3 \cdot 10^{-27}cm$
$k_s(\bar{q}_1 i\gamma_5 q_1)(\bar{q}_2 q_2)$	$\|k_s\| < 3 \cdot 10^{-5}$	$\|k_s\| < 3 \cdot 10^{-6}$
$k_s^c(\bar{q}_1 i\gamma_5 t^a q_1)(\bar{q}_2 t^a q_2)$		
$q_1 = q_2$	$\|k_s^c\| < 10^{-4}$	$\|k_s^c\| < 10^{-5}$
$q_1 \neq q_2$	$\|k_s^c\| < 10^{-4}$	$\|k_s^c\| < 2 \cdot 10^{-3}$
$k_t(1/2)\epsilon_{\mu\nu\alpha\beta}(\bar{u}\sigma_{\mu\nu}u)(\bar{d}\sigma_{\alpha\beta}d)$	$\|k_t\| < 10^{-5}$	$\|k_t\| < 2 \cdot 10^{-4}$
$k_t^c(1/2)\epsilon_{\mu\nu\alpha\beta}(\bar{u}\sigma_{\mu\nu}t^a u)(\bar{d}\sigma_{\alpha\beta}t^a d)$	$\|k_t^c\| < 10^{-5}$	$\|k_t^c\| < 2 \cdot 10^{-4}$
$k_q^g\, m_p\, \bar{q}\gamma_5\sigma_{\mu\nu} g G^a_{\mu\nu} t^a q$	$\|k_q^g\| < 2 \cdot 10^{-7}$	$\|k_q^g\| < 5 \cdot 10^{-8}$
$k^g(1/6)\epsilon_{\mu\nu\alpha\beta} f^{abc} G^a_{\mu\nu} G^b_{\alpha\rho} G^c_{\beta\rho}$	$\|k^g\| < 5 \cdot 10^{-5}$	$\|k^g\| < 3 \cdot 10^{-2}$
$\theta(\alpha_s/8\pi)(1/2)\epsilon_{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta}$	$\|\theta\| < 3 \cdot 10^{-10}$	$\|\theta\| < 10^{-9}$

Table

Although dipole moments have not been discovered up to now, the limits obtained in those experiments have played an extremely important role, allowing one to exclude a number of the models of CP-violation.

In particular, to explain CP-violation in kaon decays by the so-called θ-term (see the last line of Table) one should assume $\theta \sim 10^{-3}$ which is definitely excluded.

The model where spontaneous breaking of CP-violation in the Higgs sector is the only, or main, source of CP-odd effects in kaon decays (Weinberg model of CP-violation) is also excluded. Moreover, present upper limits on $d(n)$ and $d(e)$ are close to the predictions of the model of spontaneous breaking of CP-violation in the Higgs sector at the "natural" choice of its parameters.

The conclusion is clear. Atomic experiments give valuable information on elementary particle physics NOW, and will give even more valuable one in future.