Prospects for an atomic parity-violation experiment in U^{90+}

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(Received 30 May 1989)

Parity mixing of electron states should be extremely strong for heliumlike uranium. We calculate its size and discuss whether it could be determined experimentally. We analyze one specific scheme for such an experiment. The required laser intensities for two-photon spectroscopy of the $2\,^3P_0$–$2\,^1S_0$ level splitting is of the order of 10^{17} W/cm^2. A determination of parity mixing would require at least 10^{21} W/cm^2.

One of the most important tests of the standard model of particle physics is the measurement of parity-violating effects in atoms. The highest experimental and theoretical precision has now been reached for cesium[1,2] and allows one to test radiative corrections to the Weinberg angle.[3] (Other systems under investigation are, e.g., thallium and bismuth.) Due to the parity-violating exchange of Z bosons, every electron state has a small admixture of a wave function with opposite parity, e.g., an $s_{1/2}$ state has a small $p_{1/2}$ component giving the $M1$ transition $7s_{1/2} \leftrightarrow 6s_{1/2}$ in cesium, an $E1$ admixture. Due to the extremely small size of this component the influence of the parity-violating transition amplitude can only be observed on a large collection of atoms, by studying the refractive properties of the vapor.

The size of parity mixing depends on two factors: (1) the overlap of the electron wave functions with the nuclear charge distribution and (2) the energy difference between adjacent states of opposite parity. Heliumlike uranium is a very interesting system because the nuclear overlap of the electron wave functions is large and two states of opposite parity but identical total spin happen to be almost degenerate, namely, $^3P_0(1s,2p)$ and $^1S_0(1s,2s)$, which are separated by about 1 eV out of a total binding energy of 165 keV.[4] An experiment using U^{90+} has, however, to differ in many respects from an experiment using cesium. Heliumlike uranium is only available in ion beams, and thus the experiment requires techniques of beam-foil spectroscopy. The $2\,^3P_0$ state is metastable, but still decays with a lifetime of about 10^{-10} s, which is just long enough to extract the beam. Figure 1 shows the level scheme of U^{90+}. With new accelerators presently under construction, a production of a beam of 10^7/s of monoenergetic U^{90+} ions in the $^3P_0$ state appears to be possible in the near future.

Precision experiments can be done best with optical photons. Thus a parity experiment in U^{90+} has to focus on the transition $2\,^3P_0 \rightarrow 2\,^1S_0$, which is an $E1$-$M1$ transition with a small, parity-violating $2E1$ component. Our idea is to try to induce this two-photon transition with an intense laser.[5] The different two-photon transitions require photons with different polarizations. For an $E1$-$M1$ transition the two photons are polarized orthogonally, while for $2E1$ and $2M1$ transitions both have the same polarization. Thus by using polarized light the rate of $2E1$ transitions could be extracted from the measurements. If both photons come from the same laser beam, the $E1$-$M1$ transition rate is actually zero for a $0^- \rightarrow 0^+$ transition because, first, within the coherence time all photons have the same polarization and, second, the relevant matrix element is proportional to $(\mathbf{k}_1 - \mathbf{k}_2)\cdot(\boldsymbol{\epsilon}_1 \times \boldsymbol{\epsilon}_2)$ where $\mathbf{k}_1, \mathbf{k}_2$ and $\boldsymbol{\epsilon}_1, \boldsymbol{\epsilon}_2$ are the momentum and polarization vectors of the two photons, such that it vanishes for $\mathbf{k}_1 = \mathbf{k}_2$.

If a transition occurs, the $^1S_0$ state decays nearly instantaneously to the ground state, emitting two high-

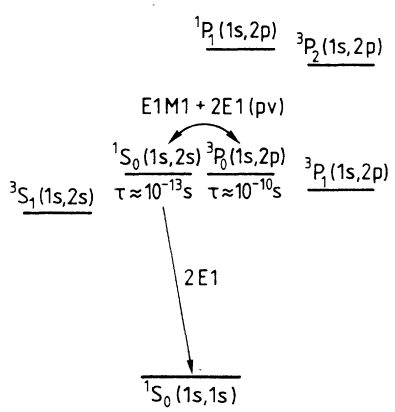

FIG. 1. Level structure of U^{90+} according to Ref. 4.

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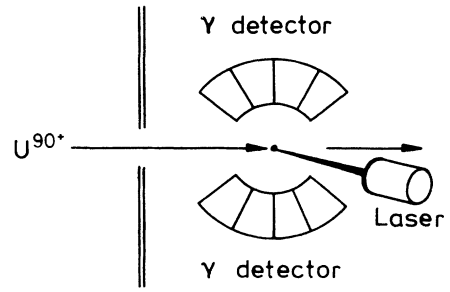

FIG. 2. Schematic view of the proposed experiment.

energy photons with a combined energy of about 96.3 keV, which can be used for detection. Figure 2 shows a schematic view of the proposed experiment. The crucial question is whether the stimulation of such a two-photon transition is at all feasible with presently available lasers. The calculation of the required laser intensity is the purpose of this work.

To analyze the prospects for the proposed experiment, the first number we need is the size of the parity admixture η, which should be given to very good approximation in first-order perturbation theory by

$$\eta=\frac{\langle 2\,^3P_0|(G_F/2\sqrt{2})(1-4\sin^2\theta_w-N/Z)\rho_{\rm el}\gamma_5|2\,^1S_0\rangle}{E(2\,^3P_0)-E(2\,^1S_0)} . \tag{1}$$

G_F is Fermi's constant, θ_w the Weinberg angle, N the neutron number, Z the proton number, and $\rho_{\rm el}$ the electric charge density (normalized to Z).

We have calculated η using a relativistic multiconfiguration Hartree-Fock (MCHF) computer program[6] developed by Desclaux following a method derived in Refs. 7 and 8. Table I shows the results we obtained for the binding energies. The results agree quite well with those obtained by Drake with a completely different technique.[9] The corresponding energies for thorium are also given. The uncertainties for the energy difference ΔE between the $^3P_0$ and $^1S_0$ states are comparable to its value. To illustrate this point let us note that already the uncertainty of the uranium nuclear radius leads to uncertainties of the order 0.5 eV for ΔE. We have used the extrapolated value given in Ref. 10. Using, e.g., the value recently derived by de Vries, de Jager, and de Vries[11] changes ΔE by $+0.37$ eV.

The value of ΔE is crucial for our scheme. If it would turn out to be, e.g., 2 eV, an optical laser could be used. (The photon energy ω has to be $\Delta E/2$. Note that the Doppler effect can be used to adjust the laser frequency to the resonance frequency.) If the required photon energy would be substantially smaller, no suitable laser is available. If it would be much smaller, a maser would have to take the place of the laser. We shall see, however, that enormous intensities are required, which can only be achieved by strongly focusing a powerful laser. Either uranium or thorium will have a ΔE in the eV range so that is not likely to be a problem.

In principle, the energy difference could also be adjusted by choosing an appropriate isotope. It has recently been shown that isotope-dependent nuclear polarization effects induce shifts of the order of 1 eV in inner-shell s states in uranium.[12] It should, therefore, be possible to find a uranium (or thorium) isotope where the $^3P_0$–$^1S_0$ energy difference is about 1 eV. It is, however, very ques-

TABLE I. Contributions to the binding energies (in eV) of the $^3P_0$ and $^1S_0$ states. Also cited are the results from Ref. 9.

	U^{90+}		Th^{88+}	
Level	$^1S_0(1s,2s)$	$^3P_0(1s,2p)$	$^1S_0(1s,2s)$	$^3P_0(1s,2p)$
Coulomb energy	−165 494.025	−165 524.083	−157 170.891	−157 195.784
Magnetic energy	66.551	152.318	61.381	140.227
Retardation	4.945	−10.043	4.524	−9.492
Mass polarization	0.000	−0.041	0.000	−0.040
Electric correlation	−0.528	−0.332	−0.432	−0.319
Magnetic correlation	−0.615	−0.517	−0.590	−0.480
Self-energy	418.380	362.660	382.406	331.435
Self-energy screening correction	−4.280	−1.018	−3.903	−0.921
Vacuum polarization first order	−109.299	−96.465	−96.539	−85.224
Vacuum polarization correction, higher order	4.466	4.021	3.823	3.440
Total	−165 114.406	−165 113.500	−156 820.220	−156 817.158
ΔE	−0.906		−3.062	
Drake[a]	−165 106.008	−165 107.824	−156 812.877	−156 812.159
ΔE[a]	1.816		−0.718	

[a]Reference 9.

tionable whether sufficiently strong beams of such isotopes can be produced.

Using the MCHF wave functions η turns out to be

$$|\eta| = \frac{4.62\times10^{-6}\ \text{eV}}{|\Delta E|} \ . \tag{2}$$

For $\Delta E = 1$ eV this number is about six orders of magnitude larger than for cesium.

Let us next calculate the laser intensity needed to stimulate the $2E1$ transition. Using the lowest MCHF wave functions, comprising the configurations $(1s,2s)$, $(1s,2p)$, $(1s,3s)$, $(1s,3p)$, and $(1s,3d)$, we calculated the $2E1$ matrix element approximately. Using the notation of Ref. 13, the transition rate for two-photon absorption at resonance, assuming that the width of the levels is much larger than the energy spread of the photons, is

$$W = 8\pi^2 \frac{n_\omega^2 \omega^2}{\Gamma} \left| \sum_s \frac{2\langle f|Q(E1)|s\rangle\langle s|Q(E1)|i\rangle}{E_i - E_s - \omega} \right|^2 , \tag{3}$$

where

$$n_\omega = \frac{I}{\omega(\text{eV})} 1.6\times10^{-6}\ \text{eV}^3 \tag{4}$$

is the photon density and I is the laser intensity in W/cm^2. Γ is the total width of the initial and final state including the laser width. It is dominated by the $^1S_0$ decay width. Inserting the decay width from Ref. 4 and our MCHF wave functions we get for the transition rate for the parity-violating $2E1$ transition

$$W_{(E1)^2} = (I\times10^{-21})^2 \text{ns}^{-1} \ . \tag{5}$$

Since the two-photon decay to the ground state from the $^3P_0$ and $^1S_0$ states cannot be distinguished experimentally, the rate (5) must at least be comparable to the spontaneous decay rate $W^{sp}_{^3P_0} \approx 10/\text{ns}$ of the $^3P_0$ state, requiring a laser intensity I of order 10^{21} W/cm^2. The strongest tabletop lasers available today reach 10^{16}–10^{17} W/cm^2. In view of the rapid development of laser technology, however, the required intensity—optimally combined with picosecond pulsing—does not appear to be entirely utopian.

To induce the normal $E1$-$M1$ transition one has to use two lasers or one has to split the laser beam and arrange for a path difference of the two beams larger than the coherence length. The probability is substantially larger than for the $2E1$ transition

$$W_{\text{E1M1}} = (I\times2\times10^{-17})^2 \text{ns}^{-1} \ , \tag{6}$$

where we have assumed that both laser beams have the intensity I and come from nearly opposite directions. Therefore, using a strongly focused high-intensity laser, the $E1$-$M1$ transition could be used to measure the energy difference between the $2\,^3P_0$ and $2\,^1S_0$ level. This is a very interesting quantity in itself because it furnishes a stringent test of relativistic few-body theory. Precise knowledge of this splitting is also essential for the calculation of all parity violating effects in U^{90+}.

However, we are forced to conclude that the proposed experiment to measure parity violation in heliumlike uranium is not feasible with present technology, even if no technical difficulties other than the principal ones discussed here arise.

Even so, it may be worthwhile to emphasize some interesting details.

(i) While the usual atomic P violation experiments have enormous difficulties in avoiding fake effects due to stray electric fields, this would pose no problem for our scheme. The parity mixing induced by a background $\mathbf{E}\cdot\mathbf{B}$ field is of the order

$$\eta' = \frac{E_i B_j}{\Delta E} \frac{\langle {}^3P_0|\mu_j|{}^3P_1\rangle\langle {}^3P_1|d_i|{}^1S_0\rangle}{110\ \text{eV}} \ . \tag{7}$$

With $E \ll 10^3$ V/m and $B \ll 10^{-2}$ T, we find $\eta' \approx 10^{-12}/\Delta E(\text{eV}) \ll \eta$. Thus background fields are not a source of problems for this experiment.

(ii) The ions have to be fast to allow their extraction within the lifetime of the $^3P_0$ state. Furthermore, they have to be focused strongly as the large laser intensities are only obtained in a very small region of space, and one would like to bunch the ions in coincidence with the laser pulses. All of these measures lead to uncertainties in the Doppler effect. The counting rates decrease if the uncertainty $\Delta\gamma\cdot\omega$ becomes larger than the transition width $\Gamma \approx 5\times10^{-3}$ eV. For $\omega = 0.5$ eV, this is the case for $\Delta\gamma > 0.01$.

We conclude that the measurement of parity violation in the L shell of the U^{90+} ion by means of two-photon spectroscopy is not feasible with presently available technology. On the other hand, this technique may offer a practical way to determine the energy difference between the $2\,^3P_0$ and $2\,^1S_0$ states in heliumlike uranium with very high precision.

We thank W. R. Johnson, J. P. Desclaux, and J. R. Reinhardt for helpful discussions. Laboratoire de Physique Atomique et Nucléaire is unité associée au Centre National de la Recherche Scientifique No. 771.

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