Stark quenching for the $1s^22s^22p^3P_0$ level in beryllium-like ions
and parity violating effects

M. Maul, A. Schäfer
Naturwissenschaftliche Fakultät II
Physik —
der Universität Regensburg
93040 Regensburg

and

P. Indelicato
Laboratoire de Physique Atomique et Nucléaire, Boîte 93,
Université Pierre et Marie Curie, 4 place Jussieu,
F–75252 Paris CEDEX 05, France

ABSTRACT

In this paper we present some concepts in heavy ion atomic physics for
the extraction of parity violating effects. We investigate the effects of
the so-called Stark-quenching, i.e., the fast decay of a meta stable state
induced by a Stark field, and the superposition of one- and two-photon
transitions in beryllium-like heavy ions. It turns out that the discussed
theoretical phenomena for heavy ions with few electrons are beyond the
scope of present day experimental possibilities because one has to require
beam energies of up to 1 TeV/A, laser intensities of up to $10^{17}$ W/cm$^2$
and ion currents of up to $10^{11}$ ions per second in beryllium-like uranium.
However, especially the superposition of one- and two-photon transitions
is a very interesting phenomenon that could provide the germ of an idea
to be applied in a more favorable system.

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1 Introduction

The experiments done recently at CERN allow a very precise and excellent determination of the constants of the standard model of weak interactions \[1\]. However, it is important to test the theory also for small momentum transfers, where possibly the situation could be essentially different from LEP experiments. Such small momentum transfer experiments have been performed in several heavy atoms \[2\]. Recently the atomic parity violating experiment with cesium has been improved in precision for a factor of seven, so that one obtains a signal even for the anapole moment \[3\], which underscores the great potential which still lies in the atomic physics to compete with the high energy experiments for measurements of weak constants and phenomena.

In principle heavy ions offer an even better access to weak interaction processes than heavy atoms because of the large overlap between the nucleus and the electrons in inner shells. On the other hand this large overlap with the nucleus inserts the influence of nuclear effects. Recently, those effects have been studied intensively in hydrogen-like heavy ions. The nuclear polarization including vacuum polarization-nuclear polarization corrections results in an energy shift in hydrogen-like $^{208}$Pb for the ground state and the two first excited levels which is in the range of meV \[4\]. In the same range is the nuclear recoil effect in hydrogen-like uranium \[5\]. Another effect comes from the uncertainty of the nuclear radius which causes for the 1S energy of hydrogen-like uranium an uncertainty of 0.1 eV \[6\]. To give an idea as to the impact of those nuclear effects, we consider the level difference between the ground state and the first excited state in beryllium-like uranium which is approximately 260 eV (c.f. Tab. \[1\]). So the nuclear structure results in a per mille effect which has to be taken into account in all possible analyses of parity violating effects in heavy ions with few inner shell electrons. Detailed analyses for helium-like uranium \[7\] and uranium with up to five electrons \[8\] were undertaken to find a realistic experimental scheme to extract the pv signal. In this contribution we continue our search by analyzing a number of possible signals based on the inclusion of the Stark effect for analyzing parity violation effects in heavy ions.

The first excited state of beryllium-like uranium $1s^22s^2p^3P^0_0$, in the case of zero nuclear spin, is meta stable because it can decay only by a two-photon transition to the $1s^22s^21S^0_0$ ground state. In case of a non-vanishing nuclear spin the $1s^22s^2p^3P^0_0$ state gets an admixture from a $|3P_1\rangle$ state lying closely above due to hyperfine mixing which drastically reduces the lifetime of the meta stable $1s^22s^2p^3P^0_0$ state \[9\]. While this 'Hyperfine Quenching' is due to a magnetic field, in this contribution we want to investigate a similar effect due to an electric field, namely the 'Stark Quenching' in beryllium-like heavy ions. The principle to use the Stark effect for measuring atomic parity violation can be found already in \[10, 11\] and has been exploited extensively in earlier parity violating experiments in heavy atoms \[12, 13\]. The strength of the Stark effect which leads to a mixing of the levels $|1S_0\rangle$ and $|3P_1\rangle$ can be varied by experimental conditions. This is interesting for two reasons. On the one hand it provides an alternative means for measuring the the parity violating mixing of the two levels $1s^22s^2p^3P^0_0$ and $1s^22s^21S^0_0$ by adding another mixing between the $1s^22s^2p^3P_1$ and the $1s^22s^21S_0$ states. On the other hand it allows for a control of the lifetime of an atomic state by experimental conditions, which will certainly be useful for other atomic physics experiments.
2 Parity admixture between the $1s^22s2p^3P_0$ and $1s^22s^21S_0$ in beryllium-like heavy ions

The first five atomic states of the beryllium-like heavy ions are

\[
\begin{align*}
|0\rangle &= |1S_0\rangle = |1s^22s^2 J = 0\rangle \\
|1\rangle &= |3P_0\rangle = |1s^22s2p_{1/2} J = 0\rangle \\
|2\rangle &= |3P_1\rangle = \alpha|1s^22s2p_{1/2} J = 1\rangle + \beta|1s^22s2p_{3/2} J = 1\rangle \\
|3\rangle &= |1P_1\rangle = \beta|1s^22s2p_{1/2} J = 1\rangle - \alpha|1s^22s2p_{3/2} J = 1\rangle \\
|4\rangle &= |3P_2\rangle = |1s^22s2p_{3/2} J = 2\rangle.
\end{align*}
\]

From the interaction due to the exchange of neutral $Z^0$ bosons between nucleus and electron shell one derives the Hamiltonian

\[
H_{pv} = \frac{G_F}{2\sqrt{2}}(1 - 4 \sin^2 \vartheta_W - \frac{N}{Z}) \rho \gamma_5.
\]

$G_F$ denotes Fermi’s constant, $\vartheta_W$ the Weinberg angle, $N$ the neutron number, $Z$ the proton number, and $\rho$ the nuclear density normalized to $Z$. This formula also demonstrates why highly charged heavy ions with few electrons are proper candidates for investigating parity non-conservation effects: The wave function admixture coefficient $\eta_{pv}$ which is given by

\[
\eta_{pv} = \frac{\langle i | \frac{G_F}{2\sqrt{2}}(1 - 4 \sin^2 \vartheta_W - \frac{N}{Z}) \rho \gamma_5 | f \rangle}{E_i - E_f} = \frac{\langle i | H_{pv} | f \rangle}{E_i - E_f},
\]

is very large (typically orders of magnitude larger than for the outer shell in neutral atoms) due to the big overlap between the nucleus and the electron states. The admixture is then described by the following matrix

\[
H_{\text{tot}} = \begin{bmatrix}
E_0 + \frac{1}{2} \Gamma_0 & W(0, 1) \\
W(1, 0) & E_1 + \frac{1}{2} \Gamma_1
\end{bmatrix},
\]

where $W(0, 1) = \langle 0 | H_{pv} | 1 \rangle$. The expression $\eta_{pv}$ is modified by radiative corrections \[14\], which together with other electroweak precision experiments give valuable constraints as to the mass of the Higgs boson and possible other particles connected to new physics \[4, 15, 16\].

Tab. \[1\] shows the various parity mixing coefficients $\eta_{pv}$ for some stable beryllium-like heavy ions from $Z = 26$ to $Z = 92$ with zero nuclear spin. In this table there is given also the energies of the two levels $1s^22s2p^3P_0$ and $1s^22s^21S_0$. The parity admixing effect is decreasing by four orders of magnitude from uranium to iron. How can one measure those admixture coefficients? There is in principle the possibility to use a laser to excite the $1s^22s2p^3P_0$ state starting from the ground state. One may use an ordinary optical laser and tune the energy with the help of the relativistic Doppler shift by choosing a particular angle towards the ion beam. As the laser light is coherent, in principle, it should only excite the parity violating 2E1 transition (and to a lower extent also 2M1). Therefore the transition amplitude will be proportional to $\eta_{pv}^2$ which is an extremely small number. For the energy gap of 260 eV to be covered for the beryllium-like uranium ion by an 1 eV laser by means of the Doppler shift, this would require ion energies of 260 GeV/u. This could be well covered by the planned LHC accelerator which is supposed to reach 2.76 TeV/u in Pb onto Pb collisions. For lighter ions this figure reduces accordingly. The experimental setup is sketched in Fig. \[1\].
In order to estimate the expected transition rates, we must determine at least approximately the two-photon transition amplitude. In principle one has to sum over all intermediate states. Here we only want to give a rough estimate taking into consideration only the states $|1S_0\rangle$, $|3P_0\rangle$, and $|3P_1\rangle$. Furthermore we use the one-photon transition matrix elements, to estimate the two-photon induced amplitude. To be more precise we use the following formulas for the spontaneous and induced transition rates (in atomic units). For the laser intensity distribution we take a simple box form with full width $\Gamma_{\text{laser}}$ and intensity $I_0$. In case of the two-photon transition the laser energy is chosen to be half of the transition energy: $\omega_{\text{laser}} = \omega_{i\rightarrow f}/2$. In atomic units we obtain:

$$W_{i\rightarrow f}(1\ \text{Photon spontaneous}) = \sum_{i,f,M,L} \frac{1}{2j_i + 1} \frac{\omega_{i\rightarrow f}}{2\pi c} |\langle f|a_{1,\lambda_{i}}^{(\lambda)}|i\rangle|^2$$

$$W_{i\rightarrow f}(1\ \text{Photon induced}) = \frac{(2\pi)^2 c I_0}{\omega_{i\rightarrow f}^2 \Gamma_{\text{laser}}} \sum_{i,f,M} \tilde{\epsilon} \cdot \tilde{Y}_{1M}^{(\lambda)}(\hat{k}) \langle f|a_{1,\lambda_{i}}^{(\lambda)}|i\rangle |^2$$

$$W_{i\rightarrow f}(2\ \text{Photon induced}) = \frac{(2\pi)^3 c^2 I_0^2}{\omega_{i\rightarrow f}^4 \Gamma_{\text{laser}}} \sum_{i,f,M,L} \tilde{\epsilon}_1 \cdot \tilde{Y}_{1M}^{(\lambda_{1})}(\hat{k}) \tilde{\epsilon}_2 \cdot \tilde{Y}_{1M}^{(\lambda_{2})}(\hat{k}) \left\{ \frac{\langle f|a_{1,\lambda_{i}}^{(\lambda_{1})}|n\rangle \langle n|a_{1,\lambda_{2}}^{(\lambda_{2})}|i\rangle}{E_i - E_n - \omega_{\text{laser}}} + (1 \leftrightarrow 2) \right\}^2$$

$\tilde{Y}_{1M}^{(\lambda)}(\hat{k})a_{1,\lambda_{i}}^{(\lambda)}$ are the usual terms of the multipole expansion into electric ($\lambda = 1$) and magnetic ($\lambda = 0$) $2L$-pole components. $\tilde{\epsilon}$ denotes the photon polarization vector. The sum $\sum_{i,f,...}$ is the sum over the $m$-quantum numbers of the initial state $i$, the final state $f$ etc. In case of the two-photon transition we must distinguish between the polarization of the first $\tilde{\epsilon}_1$ and the second $\tilde{\epsilon}_2$ photon. $\hat{k}$ is the unit vector of the photon momentum. This gives for the two spontaneous transitions between the $|1S_0\rangle$, $|3P_0\rangle$, and $|3P_1\rangle$ states: (Note that in case of the two-photon transition $\hat{k}$ is the same for both photons.)

$$W_{3P1\rightarrow 1S0}(E1) = \frac{1}{3} \frac{\omega_{3P1\rightarrow 1S0}^2}{2\pi c} |\langle 1S_0||E1||3P_1\rangle|^2$$

$$W_{3P1\rightarrow 3P0}(M1) = \frac{1}{3} \frac{\omega_{3P1\rightarrow 3P0}^2}{2\pi c} |\langle 3P_0||M1||3P_1\rangle|^2$$

(6)

With the transition probabilities we get also the reduced matrix elements which we can in turn use to calculate the transition rates for induced absorption which is the same for induced emission (without the contribution from spontaneous emission). The $\hat{k}$ vector of the laser light points into the x-direction with polarization vector $\tilde{\epsilon} = (0, \epsilon_y, \epsilon_x)$: $\epsilon_x^2 + \epsilon_y^2 = 1$. The laser intensity is given by $I_0$ and the width of the laser is $\Gamma_{\text{laser}}$ assuming a box like frequency distribution. We obtain for the one-photon and two-photon induced absorption/emission rates:

$$W_{\text{laser; pv}}(2E1) = \frac{1}{2} \frac{\pi c^2 I_0^2}{\Gamma_{\text{laser}} \omega_{\text{laser}}^4} |\langle 1S_0||E1||3P_1\rangle|^4$$

$$\times |\epsilon_1 \epsilon_2 + \epsilon_1 \epsilon_2|^2$$

4
\[ W_{\text{laser; nat}}(E1M1) = \frac{1}{2} \frac{\pi c^2 I_0^2}{\Gamma_{\text{laser}}^2} \frac{|\langle 1S_0| E1 |3P_1 \rangle|^2 |\langle 3P_1 | M1 | 3P_0 \rangle|^2}{(E_{1S0} - E_{3P1} - \omega_{\text{laser}})^2} \]
\[ \times |\epsilon_{1z} \epsilon_{2z} + \epsilon_{1y} \epsilon_{2y}|^2 . \]

In case of the 2E1 transition coherence of the two photons results in \(|\epsilon_{1z} \epsilon_{2z} + \epsilon_{1y} \epsilon_{2y}|^2 = 1\). For the E1M1 transition we average over all polarizations of the two photons which gives an additional factor 1/2. The energy width of the laser has been assumed to be \(\Gamma_{\text{laser}} = 1\) eV in the moving frame. We have chosen this value because high laser intensities are incompatible with small line widths. From Tab. 3 it can be read off that in the case of uranium for a counting rate of 1000 photons per second, an apparatus of three meters length along the beam, and a luminosity of \(10^{11}\) ions per second for inducing the parity conserving amplitude by induced emission a laser intensity of at least \(10^{14}\) W/(cm)^2 is necessary, which may be practically attainable. For the parity violating amplitude \(10^{20}\) W/(cm)^2 is required, which exceeds present technical possibilities. Moreover, for a separation of the parity non-conserving E1E1 transition from the unwanted E1M1 transition the latter one has to be suppressed by means of the laser polarization for at least 12 orders of magnitude in uranium which does not seem to be a practical scheme either. The E1M1 amplitude is slightly increasing for lighter ions, but because of the smaller admixture coefficients \(\eta_{\text{pv}}\) the interesting 2E1 transition rate decreases about five orders of magnitude from uranium to iron.

### 3 Stark-quenched amplitude

It may very well be that the transition amplitudes are too small to be measured. Therefore it is interesting to search for possible amplification factors. The idea is analogous to the hyperfine quenching technique, but this time it would be done with a Stark field. To observe such a quenching effect would be of great interest in its own. We calculate the Stark-quenched amplitude simply by diagonalizing the matrix

\[ H_{\text{tot}} = \begin{bmatrix} E_0 + \frac{i}{2} \Gamma_0 & W_{\text{Stark}}(0, 2) \\ W_{\text{Stark}}(2, 0) & E_2 + \frac{i}{2} \Gamma_2 \end{bmatrix} , \]

with

\[ W_{\text{Stark}}(i, j) = \langle i|\vec{E}\cdot\vec{e}_z|j \rangle \]

Here \(\vec{E} = (0, 0, E_z)\) is the electric Stark field. The real part of the 2x2 matrix in Eq. (8) of each eigenvalue is the energy of the corresponding level and the imaginary part is its lifetime. In Tab. 3 we give the resulting lifetime \(\tau_{\text{Stark}}\) together with the values of the energy separation \(\Delta E_0\) of the unperturbed states and the additional energy shift due to the influence of the Stark field \(\Delta E_{\text{Stark}}\). The crucial parameter is obviously the electric field strength which can be applied to induce the Stark mixing. Present technique allows up to \(E = 3 \times 10^8\) V/m. This would correspond for uranium to a lifetime of \(1.104 \times 10^9\) seconds which is still by far too large. Through Lorentz contraction the applied electric field for an 1 TeV/A - accelerator is increased by a factor 1000. This is partly off set by the time dilation of the decay. Thus the net gain is \(\gamma\) instead of \(\gamma^2\). As a result the lifetime would be reduced to \(110.4\) s.
4 Separating parity violating and parity conserving transitions by Stark effect

In the last section we have seen that, by means of the Stark effect, we can induce a small parity conserving $\text{M}_1$-transition between the admixed $|{^3P_1}\rangle$ component of the ground state, and the $|{^3P_0}\rangle$ state. In addition there is, though it is much weaker, also a second transition which can be used, namely the pv admixed $|{^1S_0}\rangle$ component of the $|{^3P_0}\rangle$ state to the Stark admixed $|{^3P_1}\rangle$ state within the ground state, see Fig. 2. Suppose now that we place our heavy ion in a Stark field $\vec{E}$ pointing into the z-direction, and orient the laser beam along the x-direction with polarization vector $\vec{\epsilon} = (0, \epsilon_y, \epsilon_z)$ (see Fig. 3), where $\epsilon_y^2 + \epsilon_z^2 = 1$, then the transition rate from the 0+ ground state to the 0- first excited state is given by

$$W_{0^+ \to 0^-} = W_{\text{laser; Stark}} (\text{M}_1) \epsilon_y^2 + W_{\text{laser; Stark+pv}} (E1) \epsilon_z^2$$

(10)

with

$$W_{\text{laser; Stark}} (\text{M}_1) = \frac{1}{2} \eta_{\text{Stark}}^2 \pi c I_0 \Gamma_{\text{Stark}} |\langle{^3P_0}|\text{M}_1|{^3P_1}\rangle|^2$$

$$W_{\text{laser; Stark+pv}} (E1) = \frac{1}{2} \eta_{\text{Stark}}^2 \eta_{\text{pv}}^2 \pi c I_0 \Gamma_{\text{Stark}} \Gamma_{\text{pv}} |\langle{^1S_0}|E1|{^3P_1}\rangle|^2.$$ 

(11)

The remarkable point here is that the sort of transition being excited depends fully on the polarization of the laser. If the laser light is polarized along the z-direction ($\epsilon_y = 0$) only the parity violating transition occurs. However, the two amplitudes differ by a factor $\eta_{\text{pv}}^2$ which is of order $10^{-16}$, so the unwanted $\text{M}_1$ transition has to be suppressed by more than 16 orders of magnitude by controlling the linear polarization of the laser, which is of course beyond the scope of present day technology. Furthermore, as both are Stark induced, this is anyway an extremely weak transition. In Tab. 4 we refer again to $E_{\text{eff}} = 10^{10}$ V/m and calculate the two induced transition rates. For uranium an intensity of at least $I = 10^{26}$ W/cm$^2$ would be needed for a counting rate of 1000 photons per second and a detector of three meters along the beam and a luminosity of $10^{11}$ ions per second of the parity violating transition, which is of course completely impossible. We do think however, that the basic mechanism is quite remarkable and we will search for cases for which the Stark and parity violating admixture are larger. For the lighter ions the situation is deteriorating for the Stark induced E1 transition while it becomes slightly better in case of the M1 transition.

5 Isolating parity violating effects via Stark induced excitations

In this chapter we combine parity violating effects with Stark quenching. The idea is the following: We consider a beryllium-like heavy ion with zero nuclear spin and a special laser which emits two sorts of photons, one with full energy and one with half that energy. Such lasers are already in use. The frequency splitting is due to special nonlinear crystals and the phase coherence is preserved during the process. The laser light is emitted in a certain angle to the direction of the ion beam in order to use the Doppler effect in such a way that the full energy is equal to the $1s^22s^22p^3{^3P_0}$ and the $1s^22s^21s^2{^1S_0}$ transition energy. In order to keep a fixed phase between the Stark amplitude and the parity violating amplitude, it is necessary to have a standing wave of both sorts of photons with full and with half energy. The difficult point is however that one needs a certain phase shift between the two waves
which comes from the fact that the interference part is proportional to \( \cos \phi \) with \( \phi \) being the phase difference of the two amplitudes. The phase shift needed can only be estimated when the full two-photon transition is calculated. As we use only a rough approximation we must leave this phase shift as a free parameter.

Furthermore the laser light must be linearly polarized. And the spin of the two photons with half energy and the one with full energy must be the same. The linear polarization has the big advantage that it has components with negative as well as with positive circular polarization and in this way there exist always two photons which couple to spin zero for the 2E1 transition.

Now the ion is placed in a Stark field to induce the admixture of the \( 1s^2 2s^2 2p^3 P_1 \) state to the \( 1s^2 2s^2 1S_0 \) state. The laser will coherently induce two transition amplitudes. One is the M1 amplitude of the photons with full energy which is Stark induced and the other is the parity violating amplitude which is the 2E1 amplitude, from the two photons of half energy

\[
W = |\sqrt{W_{\text{laser}; \text{Stark}}(M1)\epsilon_y} + \sqrt{W_{\text{laser}; \text{pv}(2E1)e^{i\phi}}|^2 = W_{\text{laser}; \text{Stark}}(M1)\epsilon_y^2 \\
+ 2\epsilon_y \sqrt{W_{\text{laser}; \text{Stark}}(M1)} \sqrt{W_{\text{laser}; \text{pv}(2E1)} \cos(\phi)} .
\] (12)

The coordinate system is shown in Fig. 3. The direction of the \( \hat{k} \) vector of the photon is given by the x axis. The Stark field points along the z-axis. The polarization vector \( \epsilon \) is then lying in the \( z - y \) plane. The situation is most favorable if it points in the y-direction. We then may take simply the values from Tab. 2. We now use the maximum laser intensity available, i.e., \( I = 10^{17} \text{W/cm}^2 \) with phase difference properly adjusted so that we can set \( \phi = 0 \). Furthermore we use a realistic Stark field of \( E = 10^9 \text{V/m} \) with a Doppler amplification of \( 10^3 \) taken already into consideration. The width of the laser is taken to be \( \Gamma_{\text{laser}} = 1 \text{ eV} \) in the moving frame of the ion. We then get a counting rate of 8000 photons per second. For a detector of three meters along the beam and a luminosity of \( 10^{11} \) ions per second the parity violating contribution could be isolated by reversing the sign of the linear dependent E1-2E1 interference amplitude

\[
W = (8.25703 \times 10^{-0} \pm 5.02553 \times 10^{-02}) \text{s}^{-1} .
\] (13)

This is an asymmetry of \( 6.1 \times 10^{-3} \). For a counting rate of 8000 photons per second and a detector of three meters along the beam and a luminosity of \( 10^{11} \) ions per second, one would need a run of \( 2 \times 3.5 \) hours for a signal with a relative error of 1 \% and subsequently about 29 days for an error of 0.1 \%. On the other hand, lets say it would be possible to construct a laser with a line width of \( \Gamma = 0.01 \text{eV} \) in the moving frame the counting rate would be hundred times higher, thus reducing the time for the 0.1% - experiment to 7 hours. This shows how crucial all numbers given here depend on the experimental conditions and on the atomic structure. In both cases we can only present some plausible estimates here. On the other hand, it is our aim to present a few concepts which give some ideas how, with technical progress, such an experiment might be feasible probably in another atomic system or in a heavy ion system with more than four or five electrons.

Note that the asymmetry will increase with every gain in laser power, because the interference term increases as \( I_0^{2.5} \), while the E1 amplitude increases only linearly with \( I_0 \). Furthermore reducing the Stark field by one order of magnitude will amplify the asymmetry also by an order of magnitude, but at the same time
the transition amplitude is reduced by two orders of magnitude too, so one has to carefully optimize the parameter choice. The asymmetry values for other ions under the same conditions are displayed in Tab. 3. The asymmetry is decreasing for the lighter ions down to iron and this means that these ions offer no favorable alternative to uranium.

In summary we have examined a few theoretical concepts for parity violating experiments. We applied these concepts on beryllium-like uranium which unfortunately leads to presently unrealistic requirements on experimental device. Lighter ions than uranium are no alternative because the weak effects decrease without being compensated by an amplification by the Stark quenching effect. But we stress again, that the discussed effect of the superposition of one- and two-photon transition should be experimentally accessible in other more favorable conditions where not necessarily heavy ions need to be involved, and this will allow to study interesting phenomena.

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Figure 1: Experiment for a direct excitation of the parity violating 2-photon transition.

| Z  | Name | A  | $\eta_{pv}$          | $E_0$ [eV] | $E_1$ [eV] |
|----|------|----|----------------------|------------|------------|
| 26 | Fe   | 56 | $-9.92977 \times 10^{-12}$ | -22101.06  | -22057.63  |
| 36 | Kr   | 84 | $-5.38643 \times 10^{-11}$ | -43312.20  | -43249.34  |
| 46 | Pd   | 106| $-1.82287 \times 10^{-10}$ | -72101.15  | -72016.56  |
| 56 | Ba   | 138| $-6.02963 \times 10^{-10}$ | -109047.58 | -108937.27 |
| 66 | Dy   | 164| $-1.62324 \times 10^{-09}$ | -154980.78 | -154839.01 |
| 76 | Os   | 192| $-4.24362 \times 10^{-09}$ | -211088.34 | -210907.49 |
| 82 | Pb   | 208| $-7.41341 \times 10^{-09}$ | -250322.86 | -250114.37 |
| 92 | U    | 238| $-1.91644 \times 10^{-08}$ | -326604.06 | -326345.37 |

Table 1: Parity mixing coefficients $\eta_{pv}$ and energies for the states $E_0 = 1s^2 2s^2 \cdot S_0$ and $E_1 = 1s^2 2s^2 2p^3 P_0$ in stable beryllium-like heavy ions from Z=26 - Z=92 with zero nuclear spin.
$^3P_1 + \eta_{\text{Stark}}^{} 1S^0$

$^3P_0 + \eta_{\text{PV}}^{} 1S^0$

Figure 2: Stark- and parity violating admixtures to the first energy levels of beryllium-like uranium.

$\text{M1} \quad \text{E1}$

$^1S^0 + \eta_{\text{Stark}}^{} 3P^1 + \eta_{\text{PV}}^{} 3P^0$

Table 2: Approximated two-photon transition rates for the unpolarized transition into the $1s^22s2p^3P^0$ state from the ground state via the E1M1 mode and the laser induced parity violating excitation via the 2E1 mode. All rates in the table are given in $(\text{cm})^4/(\text{W}^2\text{s})$. 

| Z | Name | A  | $\frac{W_{\text{in}}\text{nat}(E1M1)}{I_0^2}$ | $\frac{W_{\text{in}}\text{pv}(2E1)}{I_0^2}$ |
|---|-----|----|----------------------------------|----------------------------------|
| 26 | Fe  | 56 | $6.10280\times10^{-26}$          | $8.80191\times10^{-44}$          |
| 36 | Kr  | 84 | $2.25969\times10^{-25}$          | $7.71405\times10^{-42}$          |
| 46 | Pd  | 106| $2.07329\times10^{-25}$          | $6.92070\times10^{-41}$          |
| 56 | Ba  | 138| $1.07531\times10^{-25}$          | $3.35726\times10^{-40}$          |
| 66 | Dy  | 164| $4.48448\times10^{-26}$          | $8.90796\times10^{-40}$          |
| 76 | Os  | 192| $1.68055\times10^{-26}$          | $2.08910\times10^{-39}$          |
| 82 | Pb  | 208| $9.03356\times10^{-27}$          | $3.31807\times10^{-39}$          |
| 92 | U   | 238| $3.24557\times10^{-27}$          | $7.64682\times10^{-39}$          |
Figure 3: Geometry of the laser-induced experiments.

| Z  | Name | A  | $\Delta E_0$ [eV] | $\Delta E_{\text{Stark}}$ [eV m$^2$/V$^2$] | $\tau_{\text{Stark}}$ [s V$^2$/m$^2$] |
|----|------|----|------------------|---------------------------------|---------------------------------|
| 26 | Fe   | 56 | 43.43           | 2.49577 \times 10^{-26}        | 1.06087 \times 10^{+23}         |
| 36 | Kr   | 84 | 62.86           | 3.66802 \times 10^{-26}        | 1.13326 \times 10^{+22}         |
| 46 | Pd   | 106| 84.59           | 2.98420 \times 10^{-26}        | 5.57576 \times 10^{+21}         |
| 56 | Ba   | 138| 110.31          | 1.94884 \times 10^{-26}        | 4.95469 \times 10^{+21}         |
| 66 | Dy   | 164| 141.77          | 1.19901 \times 10^{-26}        | 5.49249 \times 10^{+21}         |
| 76 | Os   | 192| 180.85          | 7.28323 \times 10^{-27}        | 6.77734 \times 10^{+21}         |
| 82 | Pb   | 208| 208.49          | 5.39661 \times 10^{-27}        | 7.98197 \times 10^{+21}         |
| 92 | U    | 238| 258.69          | 3.31798 \times 10^{-27}        | 1.10446 \times 10^{+22}         |

Table 3: Lifetime $\tau_{\text{Stark}}$ together with the values of the energy separation $\Delta E_0$ of the unperturbed state and the Stark-perturbed state $\Delta E_{\text{Stark}}$. 
Table 4: Transition coefficients for the Stark induced E1-transition $W(E1)$ and the Stark induced M1-transition $W(M1)$.

| Z | Name | A | $W(M1)/I_0$ [(cm)$^2$/s] | $W(E1)/I_0$ [(cm)$^2$/s] |
|---|------|---|--------------------------|--------------------------|
| 26 | Fe   | 56 | $1.81692 \times 10^{-13}$ | $1.31025 \times 10^{-31}$ |
| 36 | Kr   | 84 | $5.60774 \times 10^{-13}$ | $9.57175 \times 10^{-30}$ |
| 46 | Pd   | 106| $4.67842 \times 10^{-13}$ | $7.80833 \times 10^{-29}$ |
| 56 | Ba   | 138| $2.37390 \times 10^{-13}$ | $3.70583 \times 10^{-28}$ |
| 66 | Dy   | 164| $1.00881 \times 10^{-13}$ | $1.00195 \times 10^{-27}$ |
| 76 | Os   | 192| $3.93855 \times 10^{-14}$ | $2.44801 \times 10^{-27}$ |
| 82 | Pb   | 208| $2.18246 \times 10^{-14}$ | $4.00671 \times 10^{-27}$ |
| 92 | U    | 238| $8.25703 \times 10^{-15}$ | $9.72709 \times 10^{-27}$ |

Table 5: Magnitude of the asymmetry which can be obtained in two Stark induced experiments where the sign of the Stark field is reversed in the second experiment. The technical parameters are given in the text.

| Z | Name | A | $W$ [1/s] | Asymmetry = $\sqrt{\frac{W(E1)}{W(M1)}}$ |
|---|------|---|-----------|---------------------------------|
| 26 | Fe   | 56 | $1.81692 \times 10^{+02} \pm 7.99809 \times 10^{-04}$ | $4.40201 \times 10^{-06}$ |
| 36 | Kr   | 84 | $5.60774 \times 10^{+02} \pm 1.31542 \times 10^{-03}$ | $2.34572 \times 10^{-05}$ |
| 46 | Pd   | 106| $4.67842 \times 10^{+02} \pm 3.59877 \times 10^{-02}$ | $7.69229 \times 10^{-05}$ |
| 56 | Ba   | 138| $2.37390 \times 10^{+02} \pm 5.64617 \times 10^{-02}$ | $2.37843 \times 10^{-04}$ |
| 66 | Dy   | 164| $1.00881 \times 10^{+02} \pm 5.99549 \times 10^{-02}$ | $5.94311 \times 10^{-04}$ |
| 76 | Os   | 192| $3.93855 \times 10^{+01} \pm 5.73690 \times 10^{-02}$ | $1.45660 \times 10^{-03}$ |
| 82 | Pb   | 208| $2.18246 \times 10^{+01} \pm 5.38106 \times 10^{-02}$ | $2.46559 \times 10^{-03}$ |
| 92 | Ur   | 238| $8.25703 \times 10^{+00} \pm 5.02553 \times 10^{-02}$ | $6.08637 \times 10^{-03}$ |