(ELI-NP at Magurele - “Pulse and Impulse of ELI”)

Extensive Light Investigations-ELI-apoma Laboratory

1) "**Polaritonic pulse** and coherent X- and gamma rays from Compton (Thomson) backscattering" (MA&MGan), J. Appl. Phys. **109** 013307 (2011) (1-6)

2)”Dynamics of **electron–positron pairs** in a vacuum polarized by an external radiation field” (MA), Journal of Modern Optics, **58** 611 (2011)

3)”**Classical interaction** of the electromagnetic radiation with two-level polarizable matter” (MA), Optik **123** 193 (2012)

4)”**Coherent polarization** driven by external electromagnetic fields” (MA&MGan), Physics Letters **A374** 4848 (2010)

5)''Coupling of **(ultra-) relativistic atomic nuclei** with photons'' (MA&MGan), AIP Advances **3** 112133 (2013)

6)''Propagation of **electromagnetic pulses** through the surface of dispersive bodies'' (MA), Roum J. Phys. **58** 1298 (2013)

7)''**Giant dipole oscillations** and ionization of heavy atoms by intense electromagnetic pulses'' (MA), Roum. Reps. Phys. **67** 837 (2015)

8)''**Parametric resonance**'' in molecular rotation spectra'' (MA&LC), Chem. Phys. **472** 262 (2016)

9)''**Motion of an electric charge in laser fields**'' (CM&MA), Roum. J. Phys. **62** 117 (2017)

10)''**Scattering** of non-relativistic charges by electromagnetic radiation'' (MA) Z. Naturforschung **A72** 1173 (2017)

11)''**Fast atom ionization** in strong electromagnetic radiation'' (MA) - 2017

12)''Electromagnetic-radiation effect on **alpha decay**'' (MA) - 2017

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Fast Charge Ejection in Strong Electric Fields

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2018

General

-Bound charges in electric field (els in atoms, ions, molecules, at clstrs; ions in mols, at clstrs; protons, alpha particle in at nuclei); mean-field bound states, one-particle states

-Fire upon them an el field (static or oscill):

-$\tau = a/c$, a-dim bnd state; els: $\tau = 10^{-19}s$, prtns: $\tau = 10^{-24}s$

-Very short times, $\Delta\mathcal{E} = \hbar/\tau$, els: $1keV$, prts: $100MeV$

-Very high energy, no en levels! - indep of field strength!

Subsequently, Two courses:

1) If the field is low, it is accommodated, en levels, perturbation theory, **adiabatic interaction**, ionization by tunneling (low rate); or it may affect the tunneling

2) If the field is strong, different, **fast ejection (**ionization, decay)

Low Static Electric Fields

How low? $\Delta t = a/(qE\Delta t/m)$, $\Delta t = \sqrt{ma/qE} \gg \hbar/\Delta\mathcal{E}$, $\Delta\mathcal{E}$-level separation

$$qEa \ll \frac{(\Delta\mathcal{E})^2}{(\hbar^2/ma^2)}$$

(cond for adiabatic interaction)

For electrons: $E \ll 10^4 esu$ ($\simeq 10^6 V/cm$) ($\Delta t \gg 10^{-15} s$, $qEa \ll 0.1 eV$)-very high

For protons: extremely high

For any static el field it is safe (and necessary) to work with pert theory, st states

Low Static Electric Fields

-Class subject: Oppenheimer, Lanczos (1929), hydrogen atom

-Polarization, Stark effect, Epstein, Schwarzschilld (1930)

-El field brings a pot barrier, tunneling

$$w/t_a \simeq \frac{1}{t_a} e^{-\frac{\mathcal{E}^{3/2}}{qEa(\hbar^2/ma^2)^{1/2}}}$$

$\mathcal{E}$-binding energy (t_a-attempt time); note that exp is very small, due to the cond of low field above

-Result valid for any charge in neutral bound-state

Important obs

-Single-particle states in a mean field

-Above considerations for high-energy charges

-For deep-lying charges $\Delta\mathcal{E} \simeq (\hbar^2/ma^2)n, \; a \to a/n, \; qEa \ll \hbar^2/ma^2$!

-Appreciable relaxation of the condition! For deep states higher fields are “low”!

-Separation between ’high” and “deep” state below

Low Oscillating Electric Fields

-Laser radiation $\mathbf{A} = \mathbf{A}_0 \cos(\omega t - \mathbf{kr}) \simeq \mathbf{A} = \mathbf{A}_0 \cos \omega t$ (finite motion, non-rel) ($E = -(1/c)\partial A/\partial t$)

-$qE_0/m\omega^2 \ll a$

$$\xi = \frac{qE_0}{m\omega^2 a} \ll 1$$

-note: $qE_0 a \ll (\hbar\omega)^2/(\hbar^2/ma^2)$!

-For els: $E_0 \ll 10^4 esu$ (laser int $I \ll 10^{11} w/cm^2$), for protons: $E_0 \ll 10^2 esu$ ($I \ll 10^7 w/cm^2$) (opt laser $\omega = 10^{15} s^{-1}$); rather restrictive, compare with high-power lasers

-At the same time $\xi \ll 1$ implies non-rel motion: $qA_0 \ll mc^2$ (even lower, fine str)

Low Oscillating Electric Fields

-Class problem: Keldysh, Perelomov, Krainov (1960-1980)

-Ionization rate (imaginary-time tunneling)

$$w/t_a \simeq \frac{1}{t_a} e^{-\frac{\mathcal{E}_b}{\hbar\omega} \ln \frac{2\omega\sqrt{2m\mathcal{E}_b}}{|q|E_0}}$$

-Note that $\xi \ll 1$ (low field cond) ensures $w \ll 1$ (as required) (improper ext $\sim e^{-const/E_0}$)

High Oscillating Electric Fields

-Els: $10^4 < E_0 < 10^8 esu$ $(10^{11} < I < 10^{18} w/cm^2)$

-Protons: $10^2 < E_0 < 10^{11} esu$ $(10^7 < I < 10^{24} w/cm^2)$

-No stationary states, no en levels, no perturbation,...

-Solution: time evolution of the wavefunction

-$E = 0$, $t < 0$; $E = E_0 \sin(\omega t + \alpha)$, $t > 0$; what is α?; statistical

-Single-particle states, mean field (dont forget!)

-Dipole hamiltonian (high-energy states)

$$H_d = H_0 - q\mathbf{r}\mathbf{E}\ ,\ \ H_0 = \frac{1}{2m}p^2 + V(\mathbf{r})$$

-Standard non-rel hamiltonian

$$H_s = \frac{1}{2m}\left(\mathbf{p} - \frac{q}{c}\mathbf{A}\right)^2 + V(\mathbf{r})$$

-Goeppert-Mayer, Henneberger (Pauli, Fierz, Kramers) can transf, e^{iS}

$$\widetilde{H} = \frac{1}{2m}p^2 + \tilde{V}(\mathbf{r})$$

-Displaced potential (rad "dressed")

$$\tilde{V}(\mathbf{r}) = V\left(x, y, z + \zeta(t)\right)$$

$$\zeta(t) = \frac{qE_0}{m\omega^2}\left[\omega t \cos\alpha - \sin(\omega t + \alpha) + \sin\alpha\right]$$

$-\xi = qE_0/m\omega^2 a \gg 1$,

$$\left|\zeta(\tau)\right|/a \simeq \frac{1}{2}\xi(\omega\tau)^2\left|\sin\alpha\right| = 1$$

-Ejection (ionization, decay) rate

$$\frac{1}{\tau} \simeq \sqrt{\xi/\pi}\omega = \sqrt{\left|q\right| E_0/\pi m a} \gg \omega$$

$(N = N_0 e^{-t/\tau})$

-High-energy states ($p^2/2m+V$, p more definite)

-Successive (multiple) ionization acts; Core shake-up, excitation

-at most $\simeq Z^{2/3}$ electrons; for protons (alpha) down to closed shells

-What happens with the deep states? (not $p^2/2m+V$!)

-Deep states long relaxation, high fields are low for them

-Valid criterion $qE_0a \gg \Delta\mathcal{E} \cdot \hbar\omega/(\hbar^2/ma^2)$, much more relaxed (since $\hbar\omega \ll \Delta\mathcal{E}$)!

-for deeper charges, low-rate tunneling

-intermediate regime $\xi \simeq 1$

-Angular distribution: added momentum

$$\mathbf{p}_e = m\bar{\dot{\zeta}}\mathbf{e}_z = -\frac{1}{2}\sqrt{\pi m \left|q\right| E_0 a}\,\sin\alpha \cdot \mathbf{e}_z$$

Initially, uniform distr $\mathbf{p}(\beta)$ angle β: $\mathbf{P}(\theta) = \mathbf{p} + \mathbf{p}_e$,

$$\cos\theta = \cos\beta\left[1 + (4\cos^2\beta - 1)\frac{\pi\left|q\right| E_0 a}{8\mathcal{E}}\right]$$

High Static Electric Field

$\mathbf{A} = -c\mathbf{E}t$

$$\frac{1}{\tau} = (|q|\, E/2ma)^{1/2}$$

Pulse Time Profile

$$\zeta(t) = \frac{q}{m}\int_0^t dt_1 \int_0^{t_1} dt_2 \mathbf{E}(t_2)$$

Example: $\mathbf{E} = T\mathbf{E}_0\delta(t - t_0)$, $1/\tau = \simeq qTE_0/ma$ (diff $\sim \sqrt{E_0}$)

Conclusion

If the electric field is sufficiently high the “structure” pot is vanishing and the charge is set free, with a high rate (matter is “destroyed”)

Applications:

-electrons from atoms, molecules, at clstrs ($10^{11} < I < 10^{18} w/cm^2$)

-electrons from ions, mol ions,... (Coulomb pot barrier vanishing)

-ions from mols (fragmentation) ($10^{17} < I/A^2 < 10^{23} w/cm^2$) (slower)

-proton emission ($10^7 < I < 10^{23} w/cm^2$)?

-Spontaneous alpha decay appreciably enhanced by strong el fields?

Be aware 1): strong fields by short laser pulses! - longer than ionization rate! (recombination)

Proton and alpha emission

-Nuclei in heavy atoms

-Electronic shell: appreciable screening $E \rightarrow (\omega^2/\Omega^2)E$

-$\Omega \simeq 10^{16} Z(s^{-1})$ ($30Z(eV)$); reduction factor in E, $10^{-3}/Z^2$

-ex: $10^{11} esu$ ($I = 10^{24} w/cm^2$)$\rightarrow 10^4 esu$ ($I = 10^{10} w/cm^2$)

Last obs

-Right side ineq, non-relativ motion

-What happens for higher fields?

- em mom p in $(\mathbf{p} - q\mathbf{A}/c)^2/2m$ increases as to compensate $\mathbf{A}$, as long as the bs subsists

-charge immediately ejected, and

-injected in the high field, which

-accelerates it rapidly to rel velocities