(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. Naturforsch. **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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Electromagnetic-Radiation Effect on alpha Decay

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General

In the previous Sem (Sem I) it was shown:

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

-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)

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

3) How low? strong?

Static Electric Fields

$\Delta t = a/(qE\Delta t/m)$, $\Delta t = \sqrt{ma/qE} \gg \hbar/\Delta\mathcal{E}$, $\Delta\mathcal{E}$-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 weakening of the condition! For deep states higher fields are “low”!

-Separation between ’high” and “deep” state: atoms $Z^{2/3}$, nuclei-closed shells

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

It was shown in the previous Sem (Sem II):

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

-Protons: $10^2 < E_0 < 10^{11} esu$ $(10^7 < I < 10^{23} w/cm^2)$

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

-Solution: time evolution of the wavefunction

-Fast ionization rate

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

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

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

Nucleus in electric field:

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

-Use fast ionization rate

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

-However: electronic shell appreciably screes off the field $E \rightarrow (\omega^2/\Omega^2)E$

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

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

Nucleus in low oscillating field

-Spontaneous proton (alpha) decay, $V(\mathbf{r})$ pot barrier (Coulomb), $\mathbf{E} = \mathbf{E}_0 \sin \omega t$

-Standard non-rel hamiltonian

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

-Henneberger (Pauli, Fierz, Kramers) can transf, $\psi = e^{iS}\varphi$,

$$\widetilde{H} = \frac{1}{2m}p^2 + \widetilde{V}(\mathbf{r}) \ , \ \widetilde{V}(\mathbf{r}) = V(\mathbf{r} - q\mathbf{E}/m\omega^2)$$

$$S = \frac{q}{\hbar m\omega^2}\mathbf{E}_0\mathbf{p}\sin\omega t - \frac{iqA_0^2}{8\hbar mc^2\omega}(2\omega t + \sin 2\omega t)$$

Technical 1

$V(r) \simeq Zq^2/r$; no field, tunneling from $r_1 = a$ to $r_2 = Zq^2/\mathcal{E}_r$, $\mathcal{E}_r$ radial energy of the charge; parameter $\xi = qE_0/m\omega^2 a \ll 1$, field present

$$\tilde{r}_1 = \left| \mathbf{a} - q\mathbf{E}/m\omega^2 \right|$$

and $\tilde{r}_2 = r_2$, where $\mathbf{a} = a\mathbf{r}/r$. Expand $\tilde{r}_1$ in powers of ξ

$$\tilde{r}_1 = a\left(1 - \xi \sin\omega t \cdot \cos\theta + \frac{1}{2}\xi^2 \sin^2\omega t \cdot \sin^2\theta\right) + \ldots \quad ,$$

θ the angle $\mathbf{r}$ with $\mathbf{E}_0$

Technical 2

Relevant factors in wavefunction

$$e^{\frac{iqE(t)}{\hbar m\omega^2}\cos\theta\cdot(p_2-p_1)+\frac{i}{\hbar}\int_{\widetilde{r}_1}^{\widetilde{r}_2} dr\cdot p_r(r)}$$

$p_r(r) = \sqrt{2m\left[\mathcal{E} - V(r)\right]}$, $p_{1,2} = p_r(\widetilde{r}_{1,2}) = \sqrt{2m\left[\mathcal{E} - V(\widetilde{r}_{1,2})\right]}$; $(p_2 = 0)$

tunneling probability (transmission coefficient) $w = e^{-\gamma}$,

$$\gamma = -A\xi \sin\omega t \cdot \cos\theta + B \ ,$$

$$A = \frac{2a|p_1|}{\hbar} \ , \ \xi = \frac{qE_0}{m\omega^2 a} \ , \ B = \frac{2}{\hbar}\int_{\widetilde{r}_1}^{\widetilde{r}_2} dr\, |p_r(r)|$$

$|p_1| = \sqrt{2m\left[V(\widetilde{r}_1) - \mathcal{E}\right]}$, $|p_r(r)| = \sqrt{2m\left[V(r) - \mathcal{E}\right]}$

Technical 3

Expand A in powers of ξ, take the time average

$$\gamma = -\frac{Zq^2}{2\hbar}\sqrt{\frac{2m}{Zq^2/a - \mathcal{E}}}\xi^2 \cos^2\theta + B...$$

$$B = \gamma_0 - \tfrac{a\xi^2}{2\hbar}\sqrt{2m(Zq^2/a - \mathcal{E})} + \tfrac{a\xi^2}{2\hbar}\sqrt{\tfrac{2m}{Zq^2/a-\mathcal{E}}}(3Zq^2/2a - \mathcal{E})\cos^2\theta$$

γ_0 no field; finally,

$$\gamma = \gamma_0 - \frac{a\xi^2}{2\hbar}\sqrt{2m(Zq^2/a - \mathcal{E})}\left[1 - \frac{Zq^2/2a - \mathcal{E}}{Zq^2/a - \mathcal{E}}\cos^2\theta\right]$$

Technical 4

Total disintegration probability

$$w_{tot} \simeq \left\{1 + \frac{a\xi^2}{2\hbar}\sqrt{2m(Zq^2/a - \mathcal{E})}\left[1 - \frac{Zq^2/2a - \mathcal{E}}{3(Zq^2/a - \mathcal{E})}\right]\right\} w_{tot}^0$$

(integrating over angle θ), $w_{tot}^0 = e^{-\gamma_0}$. Disintegration rate $(1/\tau)w_{tot}$, τ attempt time

Exponent γ_0,

$$\gamma_0 = \frac{Zq^2}{\hbar}\sqrt{2m/\mathcal{E}}\left(\arccos\sqrt{\mathcal{E}a/Zq^2} - \sqrt{\mathcal{E}a/Zq^2}\sqrt{1 - \mathcal{E}a/Zq^2}\right)$$

$(Zq^2/a \gg \mathcal{E})$

$$\gamma_0 \simeq \frac{\pi Zq^2}{2\hbar}\sqrt{2m/\mathcal{E}}\ , \ \ w_{tot} \simeq \left(1 + \frac{5a\xi^2}{12\hbar}\sqrt{2mZq^2/a}\right) w_{tot}^0\ .$$

Technical 5

Geiger-Nuttall $\ln(w^0_{tot}/\tau) = -a_0 Z/\sqrt{\mathcal{E}} + b_0$, a_0 and b_0 constants

The only effect of the radiation is to modify the constant b_0 to $b = b_0 + (5a\xi^2/12\hbar)\sqrt{2mZq^2/a}$

Conclusion

-Low field, charge accommodates in the field, adiabatically-introduced interaction;

-Besides oscillating and emitting higher harmonics, charge may tunnel out from the bound state

-Proton, alpha tunneling through the Coul barrier slightly enhanced by radiation,

-Second-order corrections, slight anisotropy

The Case of a Low Static Electric Field

- Low static field is taken up in the energy levels (by pert calcs);

-It is not available for the Henn tr anymore!

-We do tunneling through

$$V(\mathbf{r}) = \frac{Zq^2}{r} - q\mathbf{Er} = \frac{Zq^2}{r}\left(1 - \frac{Er^2}{Zq}\cos\theta\right)$$

-Small parameter $\alpha = Er_2^2/Zq = Eqr_2/\mathcal{E} \ll 1$ ($Z = 100$, $\mathcal{E} = 1MeV$, $\alpha = 10^{-4}E \ll 1$)

-Finally,

$$w_{tot} \simeq \left(1 + \frac{\alpha^2\gamma_0^2}{108}\right) w_{tot}^0$$