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Elementary particles in an introductory course on Quantum mechanics

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Motivation & challenge: why particles?

- atoms of today
- fascinating properties

- not an easy topic

Motivation & challenge: what is a particle?

If a student asks physicists, he/she might get very different answers, including

1. a point-like object with mass and various charges
2. particle is what we see in the detector
3. an irreducible representation of the Poincare group
4. a (collapsed) wave function
5. a minimum excitation of a quantum field

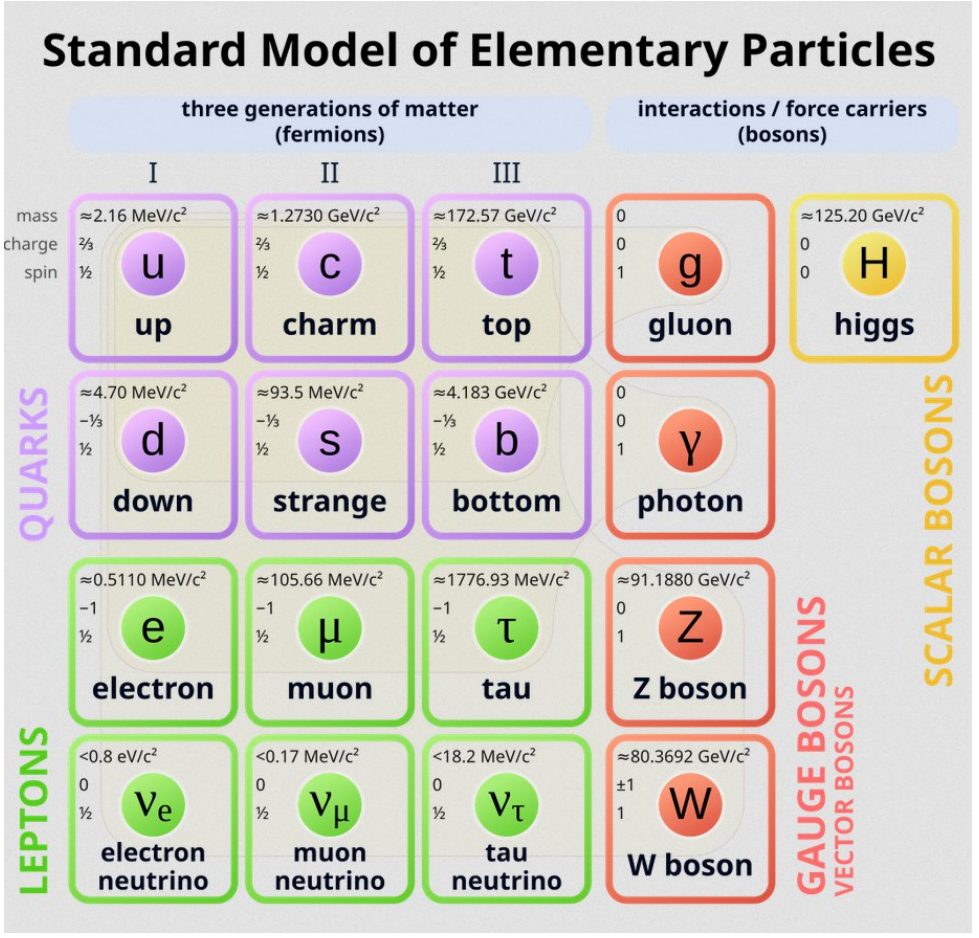
I discuss strong and weak points of these definitions

→ **combine diverse definitions into a coherent whole**

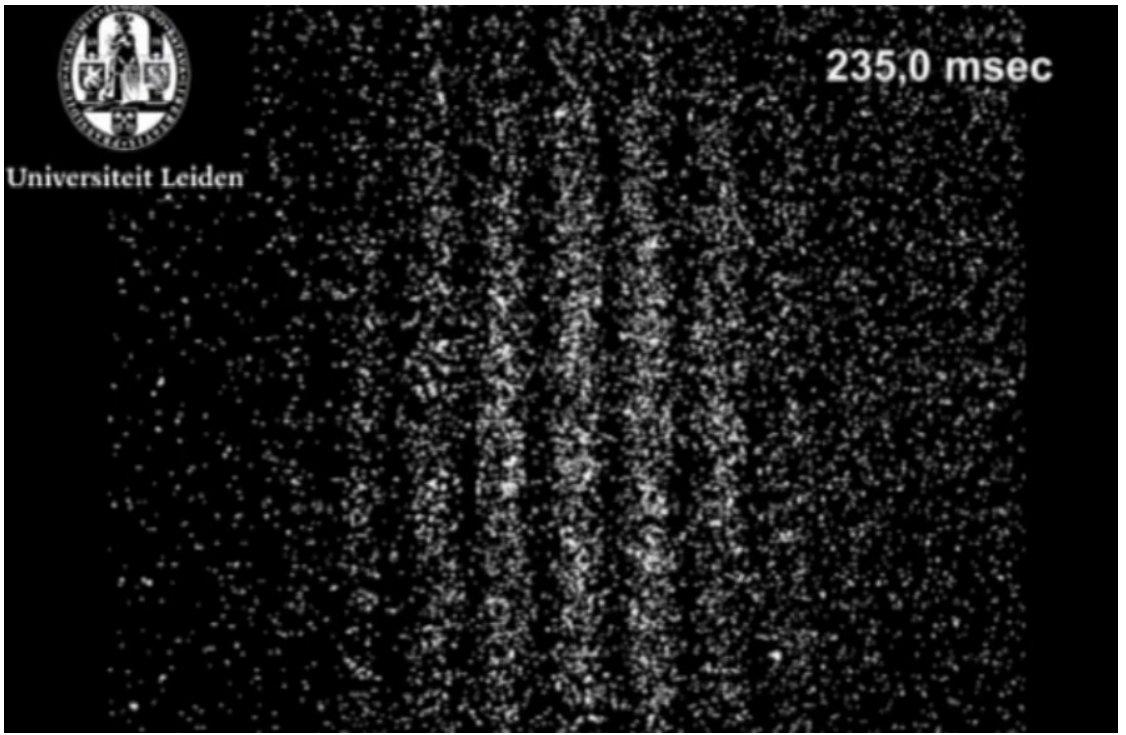
1. a pointlike object with mass and charges

- introduces players
- can compare with periodic table of elements
- mysteries of Standard model
- connection to energy content of the Universe

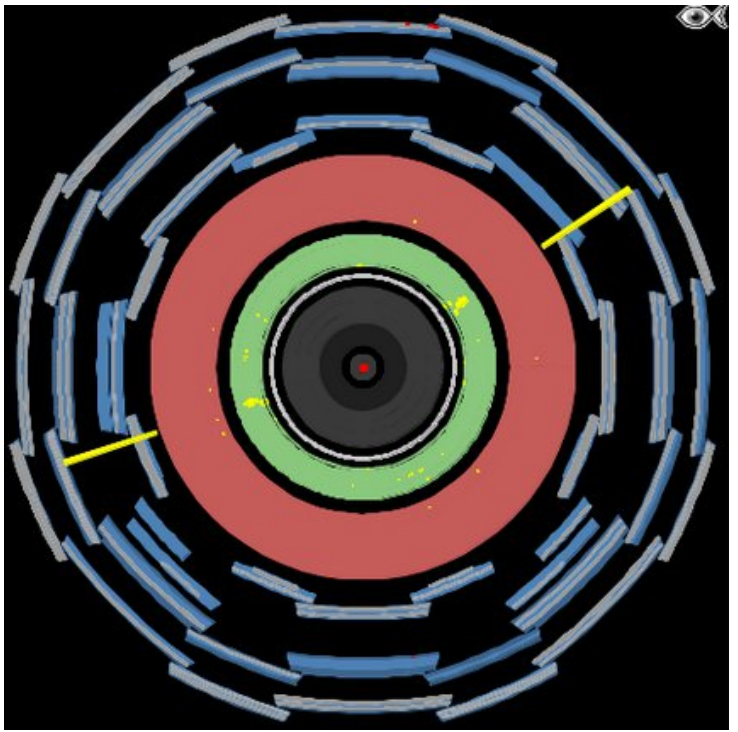
- remains at the surface
- difficulty with spin
- difficulty with many charges
- difficulty with gauge



2. … it is what we see in the detector



Individual photons recorded by an intensified CCD camera [1]



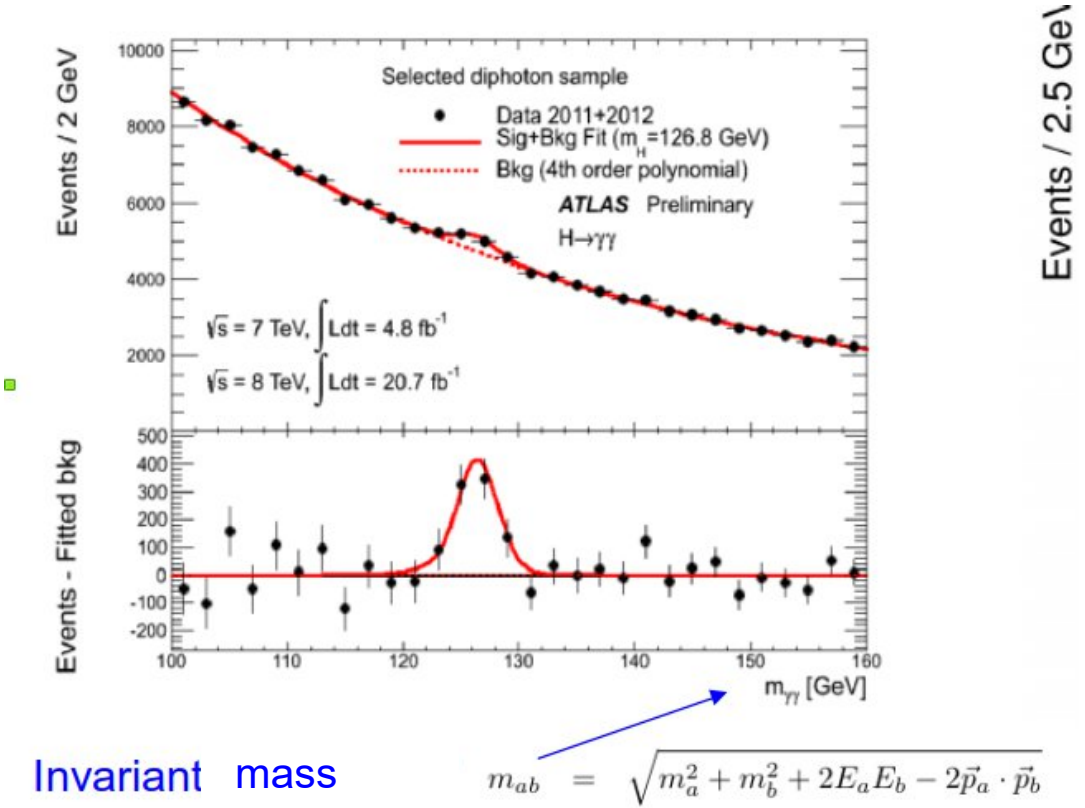
High energy photons in ATLAS detector [2]

[1] Leiden University video: https://www.youtube.com/watch?v=MbLzh1Y9POQ
[2] IPPOG ATLAS Masterclass, https://atlas.physicsmasterclasses.org/en/zpath_lhcphysics3.htm

2. ... it is what we see in the detector

- straightforward description of reality
- stimulates philosophy: can instruments alone reveal nature of reality?

- not the particle we see but the signal it generates
- does not explain things, need of theoretical picture



The way particle physicists see short-lived particles [3]

[3] ATLAS experiment preliminary analysis of H -> γ γ in 2012

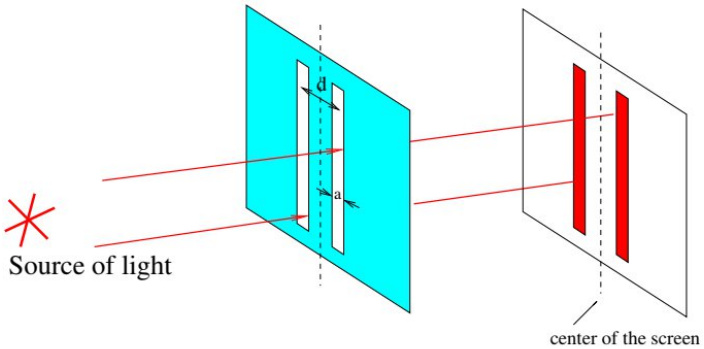
3. irreducible representation of Poincare group

Precise definiton

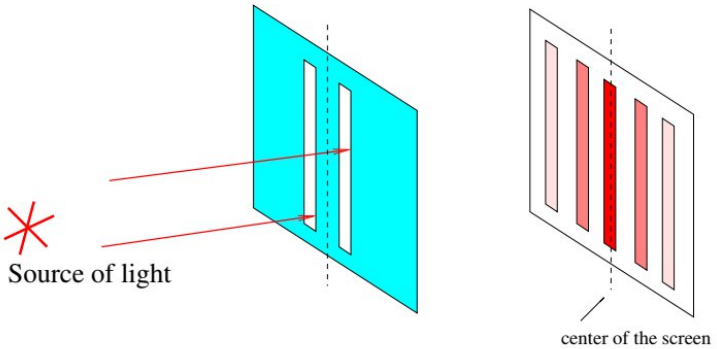
Seems too formal to explain

4. a (collapsed) wave (function)

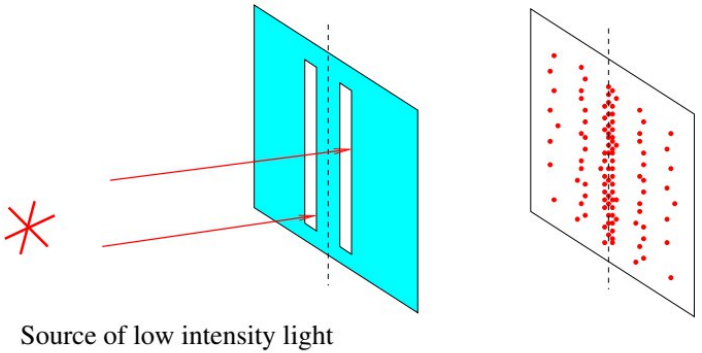
Double slit experiment



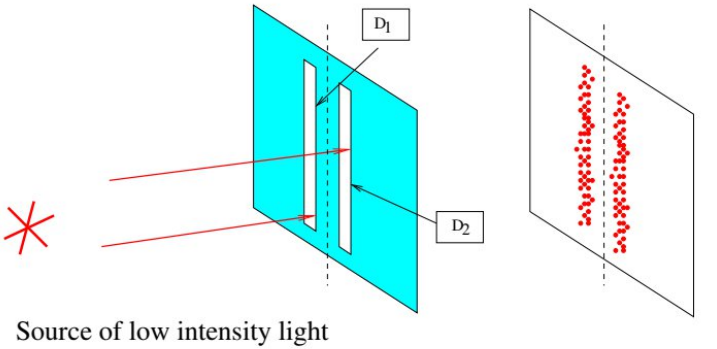
a) expectation for pointlike particles



b) Young‘s observation (wave behaviour)



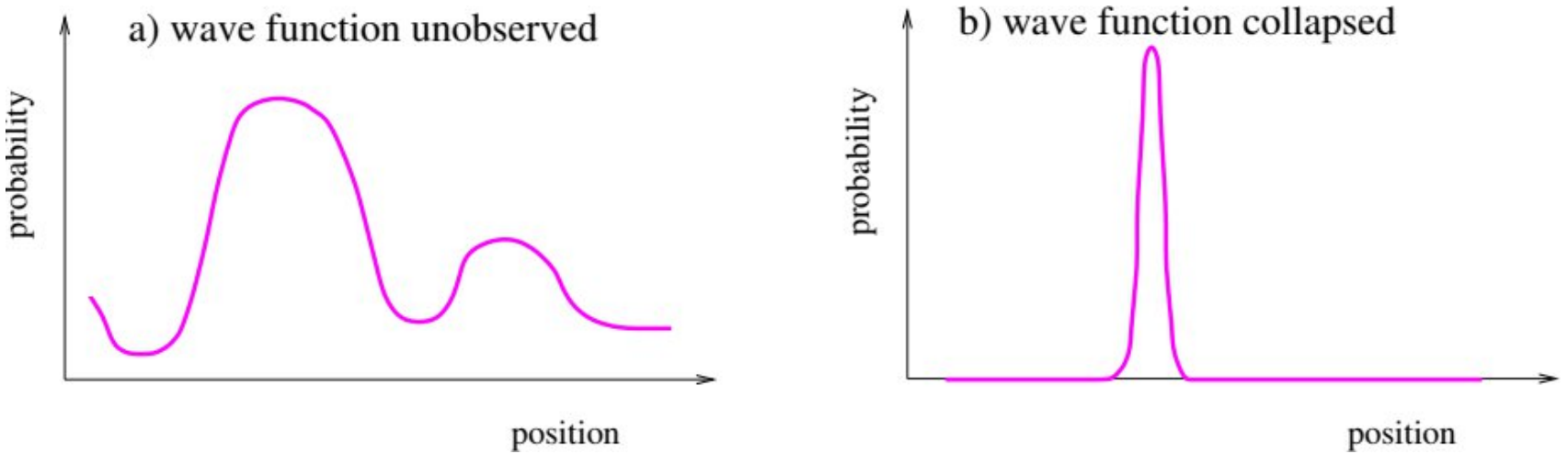
c) wave-particle duality



d) detectors to find out the path of a single photon

4. a (collapsed) wave (function)

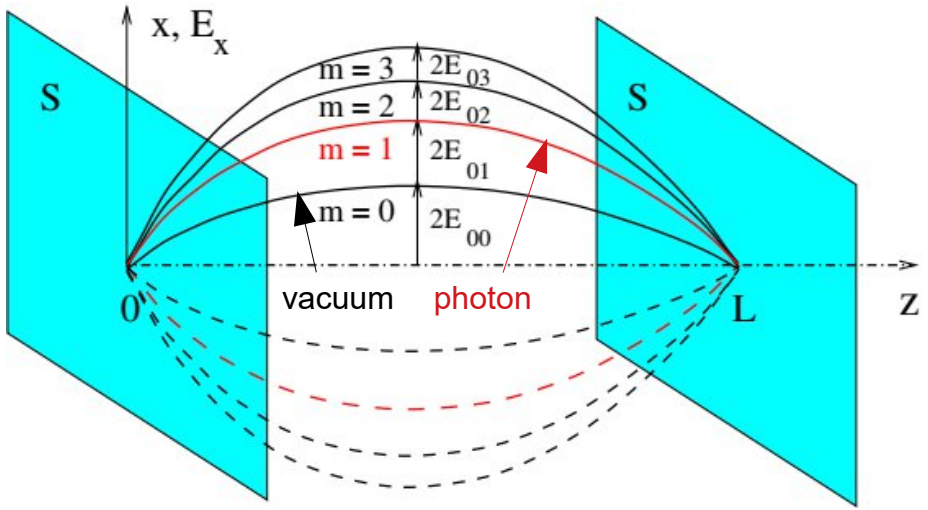
Collapse of the wavefunction



- double slit experiment goes to the heart of QM mysteries
- connects to „what we see in the detector“
- goes to the probabilistic nature of QM

?

5. a minimum excitation of quantum field (example: photon in a box)

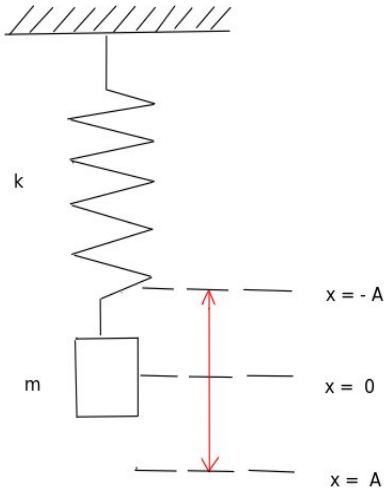


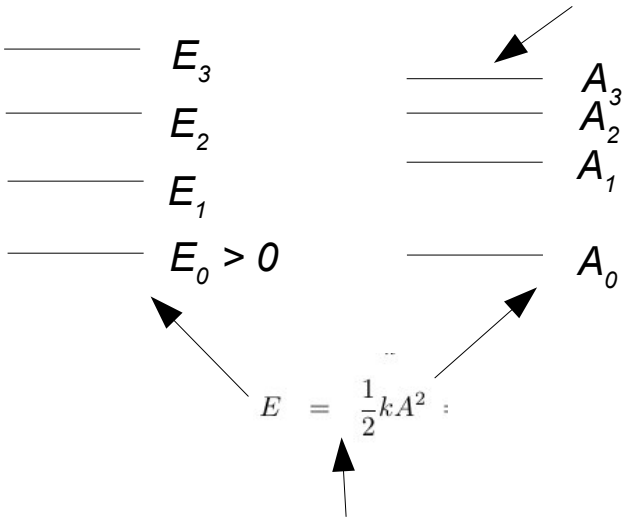
- based on relatively familiar classical oscillator and classical standing wave
- quantization the same as for HO

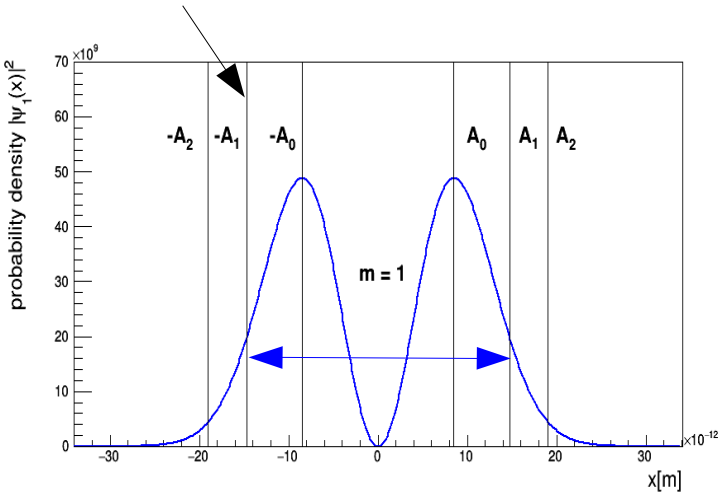
- quantization of HO challenging
- only noninteracting photon

photon is quantized electromagnetic wave with minimum amplitude (m = 1 state)

5. a minimum excitation of quantum field (example: photon in a box)







$$E = \frac{1}{2}m\omega^2 x(t)^2 + \frac{1}{2}m\dot{x}(t)^2 = \frac{1}{2}kA^2$$

$$E = E_n = \hbar\omega(m + \frac{1}{2}), \quad m = 0, 1, 2, 3, \ ...$$

classical oscillator (HO)

quantum oscillator

5. a minimum excitation of quantum field (example: photon in a box)

electric field (standing wave)

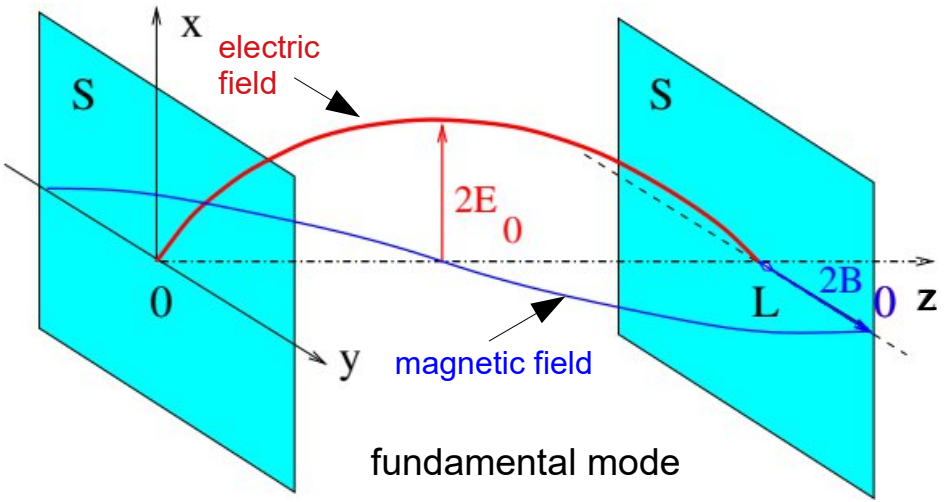
$$\vec{E} = 2E_0 \cos\omega t \, \sin kz \, \vec{i} = 2E_0 \, q(t) \, \sin kz \, \vec{i}.$$

energy

$$E = \frac{1}{2}M\omega^2 q^2(t) + \frac{1}{2}M\dot{q}^2(t) \qquad M = 2\frac{\epsilon_0 LSE_0^2}{\omega^2}$$

equivalent to classical HO if q(t) ↔ x(t)

$$E = \frac{1}{2}m\omega^2 x(t)^2 + \frac{1}{2}m\dot{x}(t)^2$$



fundamental mode

standing elmag. wave is formally equivalent to classical HO

Conclusions

Inclusion of particles in an introductory QM course after hydrogen atom

1. a point-like object with mass and various charges
2. particle is what we see in the detector
4. a (collapsed) wave function

Solid ground

5. a minimum excitation of a quantum field (work in progress)