Intense gamma radiation by accelerated quantum ions

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Laser Photon

ω

$4\gamma^2\omega$

Electron

γ

What are advantages?

Laser Photon

ω

$4\gamma^2\omega$

Partially-stripped Ion

γ

What is an advantage using ions?

- Bigger cross section.

$$\sigma_T = \frac{8\pi}{3} r_e^2 \quad \text{(Thomson cross section)}$$

$$\sigma_R = \frac{1}{2\pi} \lambda^2 \quad \text{(Resonance cross section)}$$

$$\left(\frac{\lambda}{r_e}\right)^2 \approx \left(\frac{0.1\ \text{nm}}{3\ \text{fm}}\right)^2 \approx 10^9 \quad (\lambda:\ 12\ \text{keV X-ray})$$

Can we exploit this advantage?

Contents

- Motivations for intense gamma rays
- Gamma generation using ions
  - Principle and practical limitations
- Examples
  - Si ions for 1 MeV
  - Ti ions for 2.5-7.5 MeV
- Summary and prospects

Previous/related studies

E. G. Bessonov and K.-J. Kim:
"Radiative Cooling of Ion Beams in Storage Rings by Broad-Band Lasers",
PRL76, 431 (1996)

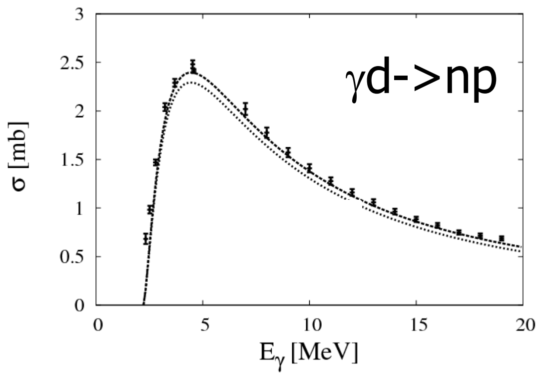
E. G. Bessonov:
"Light sources based on relativistic ion beams", NIM B309, 92 (2013)

M. W. Krasny:
"The Gamma Factory proposal for CERN", arXiv:1511.07794v1 [hep-ex] 24 Nov 2015

M. Yoshimura and N. S.:
"Neutrino pair and gamma beams from circulating excited ions",
Phys. Rev D 92, 073015 (2015)

Motivations

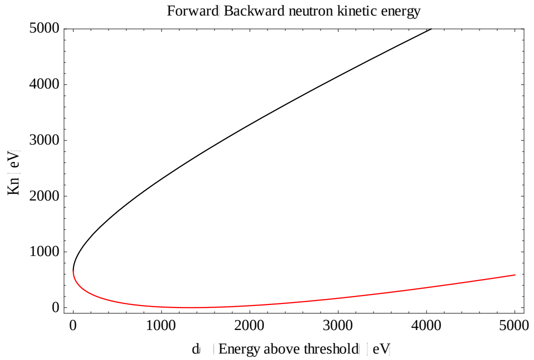
- Nuclear physics
  - Especially nuclear astronomy
- Cold neutron source
  - Fundamental physics, such as EDM measurement
  - Material science
- Others
  - Nuclear waste transmutation



Assume $\sigma_0 = 1$ [mb], $\Phi_\gamma = 10^{17}$ [sec^{-1}]

$N_{Target} = 3\times10^{23}$ [cm^{-2}] (60 cm Liq-D2)

Neutron yield=$\sigma_0\Phi_\gamma N_{Target} = 3\times10^{13}$ [sec^{-1}]



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Ion as an energy amplifier/converter

- Amplification (from laser photon to gamma)
  - Ion absorbs 2γ ω_L (laser energy) and emits 2γ times absorbed quanta in the forward direction $\boxed{\propto 4\gamma^2\omega_L}$

$$\hbar\omega_L = 5\ [\mathrm{eV}] \ \Rightarrow\ 5\ [\mathrm{keV}] \text{ for } \gamma\text{=500} \ \Rightarrow\ 5\ [\mathrm{MeV}]$$

  - Ion energy level $E[\text{H-like ion}] = Z^2 E[\text{H}]$
- Efficiency (number of gammas produced per ion)

$$\boxed{\#\text{ of gamma per ion} = A_{eg} \times \Delta T}\ (\Delta T : \text{Interaction time})$$

$$A_{eg} = 10^{13}\ [1/\mathrm{s}]\ \ \Delta\mathrm{T}= 1\ [\mathrm{ns}]\ \Rightarrow 10^4 \text{ gammas/ion}$$

  - Ion A coefficient $A_{eg}[\text{H-like ion}] = Z^4 A_{eg}[\text{H}]\quad$ (E1 transition)
- Angular divergence $\boxed{\propto 1/\gamma^2}$

Practical limitations/challenges

- Ion
  - Resonance energy/transition strength
  - Ionization loss
- Laser
  - Available power/color
  - Band width
- Accelerator
  - Beam energy (γ) & intensity
  - Beam size/energy spread
  - RF voltage
  - Vacuum (ion loss)

If laser power is too strong, multi-photon process leads to ionization loss.

Ion energy dispersion in accelerator is bigger than laser line width.

Laser

$$N_{rec} = \frac{I}{I+I_s} A_{eg} \Delta T \quad (I_s : \text{saturation intensity})$$

- Intensity
  - Number of recycling

$$\sigma_R(\omega) \frac{I_s}{\hbar\omega} = A_{eg} \quad \text{(absorption rate=decay rate)}$$

$$\sigma_R(E) = \frac{4\pi}{k^2}\left(\frac{\Gamma^2/4}{(E-E_R)^2+\Gamma^2/4}\right) \rightarrow \frac{4\pi}{k^2}\left(\frac{A_{eg}}{\hbar\Delta\omega}\right)$$

  - Example: $I_s = 6\ [\text{mW/cm}^2]\ \ (\lambda = 589\text{nm},\ 1/A_{eg} = 16\ \text{ns})$
  - As Z becomes large: $I_s[\text{H-like}] = Z^8 I_s[\text{H}]$
  - In Lab frame. $I_s[\text{Lab}] = \dfrac{I_s[\text{CM}]}{\gamma^2}$

Accelerator

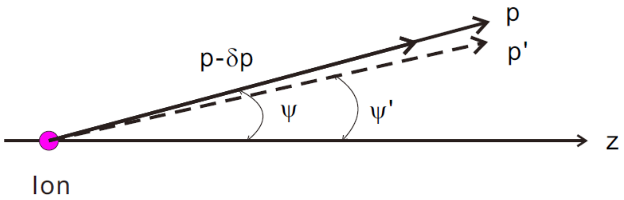
- Beam energy (γ)
  - γ=250
- Beam intensity
  - Number of ion/bunch=10^(9)
  - Bunch spacing=100 ns
- Beam size/energy spread
  - Transverse size: 0.3 mm
  - Energy spread: 5x10^(-3)
- RF voltage

We assume we use existing ring or accelerators, and number of ions in the ring.

Radiative cooling mechanism works. We use equilibrium value for energy spread.

$$\varepsilon_x \approx \frac{\hbar\omega^*}{\gamma^2 Mc^2} < \beta_x >$$

$$\sigma_\delta \approx \sqrt{\frac{\hbar\omega^*}{Mc^2}}$$



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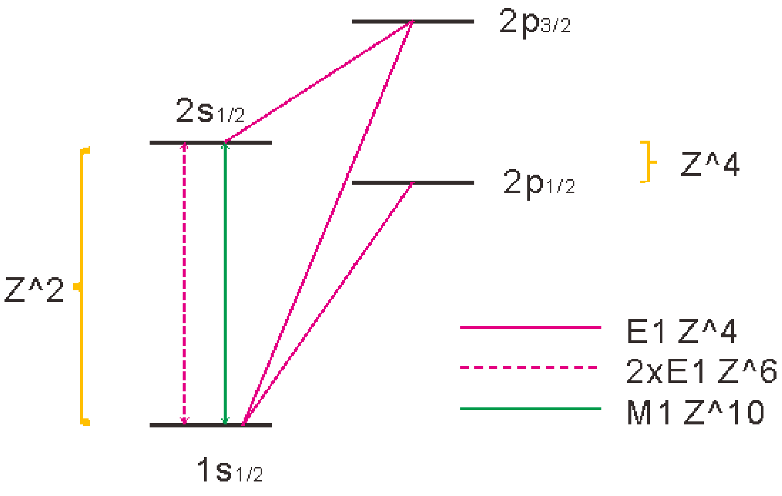
In the examples below, we assume to use

- Super-KEK-B ring
  - $\gamma=250$ (requires super-conducting magnets)
  - Ni=10^9 ions/bunch
  - t (bunch-to-bunch)=100 ns
  - C_0(Circumference)=3018 m

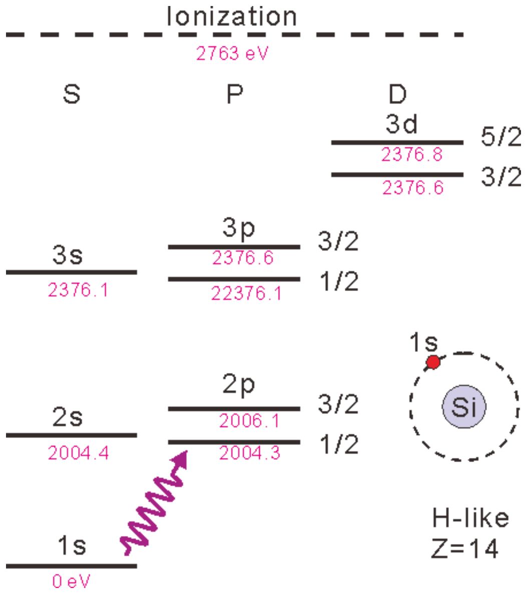
- Properties of H-like ion
  - Energy level
    - Z^2 dependence
  - Transition rates
    - E1 : Z^4 dependence
    - 2E1 : Z^6 dependence



H-like ions

(1) Example with Si H-like ions

- Ion
  - Z=14 Si H-like
  - Eeg=2 keV
- Laser (CW)
  - λ=314 nm
  - I/Is=3.3x10^(-4)
  - $<P_L>$=200 W
- Gamma rays
  - Eg= 1MeV
  - Flux 10^16 Hz



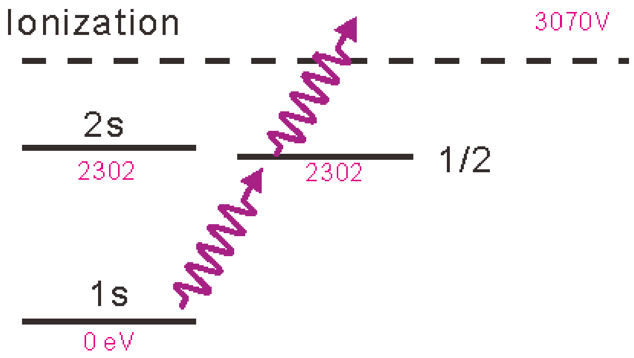
Assumed interaction time:
30 ns or 10m long

Two-photon ionization loss

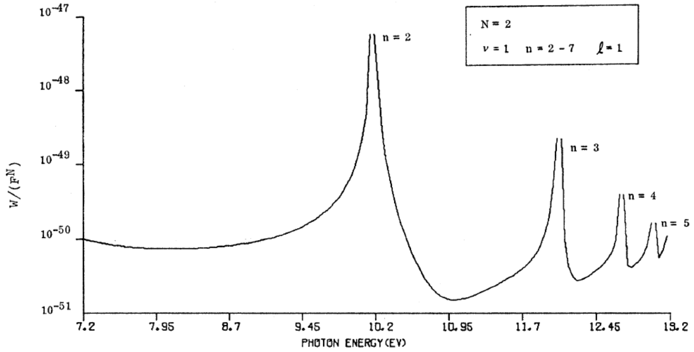
- Restrict I/Is

$$\sigma(E_p,Z)=Z^{-8}\sigma(E_p/Z^2,1)$$

Zernik: Two-Photon Ionization of Atomic Hydrogen", PRA 135 A51 (1964)



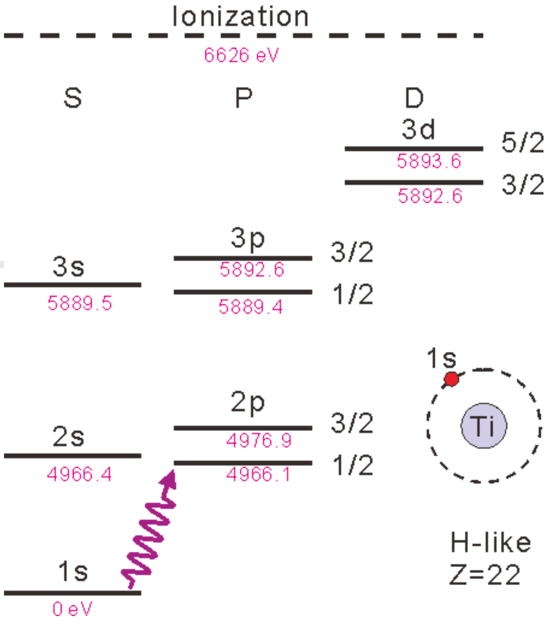
- Need to estimate effect of width of lasers



Bebb and Gold: "Multiphoton Ionization of Hydrogen and Rare-Gas Atoms" PR143, 1 (1966)

(2) Example with Ti ion

- Ion
  - Z=22 Ti H-like
  - Eeg=5 keV
- Light source (Undulator/FEL)
  - E=10 eV
  - I/Is=4x 10^(-6) or 5x10^(-4)
  - $<P_L>$=100 W or 12kW
- Gamma rays
  - Eg= 2.5 MeV
  - Flux 8.2x10^14 Hz or 10^17 Hz



10 eV light source options

- Undulator option

$$E_e = 400\ [\mathrm{MeV}],\quad I_e = 100\ \mathrm{mA}$$

$$\lambda_u = 5\ [\mathrm{cm}],\quad N_u = 1000,\quad K = 2$$

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

$$P = \left(\frac{N_u}{6}\right) Z_{vac} I_e \left(\frac{2\pi c}{\lambda_u}\right) \gamma^2 K^2 \approx 100\ \ [\mathrm{W}]$$

- SASE-FEL option

The band width is given by1/Nu, which matches with the requirement.

$$\rho_{FEL} = \left(\frac{K^2 \lambda_u^2}{32\pi\gamma^3} \frac{I_p}{I_A}\right)^{1/3}, \qquad I_A = 17000\ \ [\mathrm{A}]$$

$$I_p = \frac{Q}{(\pi\sigma_x^2)(2.35\sigma_t)} \approx 3.6 \times 10^9\ \ [\mathrm{A}]$$

$$P = \rho_{FEL} P_{beam} \approx 13\ [\mathrm{KW}]$$

Summary and prospects

- Intense MeV gamma rays using ions
  - Open up new/interesting fields of science.
- Examples of specific design are given
  - To produce 1-10 MeV with intensity of 10^15-10^17 Hz
  - Using the KEK ring (γ=250).
  - Admittedly these are all preliminary
- Detailed design studies are needed, and underway.
  - Better ions and/or transitions
  - Stronger light source with wideband
  - Cooling method, especially energy

THANK YOU FOR YOUR ATTENTION.

Collaboration:

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