Laser Irradiated Enhancement of Atomic Electron Capture Rate For New Physics Search

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1. Introduction

Electron capture processes have a potential Power to Search New Physics !

1. Majorana nature of neutrinos

$$(Z, A) + e^- \rightarrow (Z-2, A) + e^+$$

2. Lepton Flavor Violations

$$\mu + e \rightarrow 2\gamma$$

M. Yoshimura, hep-ph/0611362 , hep-ph/0507248

Ikeda, Nakano, Sakuda, Tanaka and Yoshimura, hep-ph/0506062

3. Mono energetic neutrino beam

M. Rolinec and J. Sato, hep-ph/0612148

J. Sato, Phys.Rev.Lett.95:131804,2005.

$$(Z, A) + e^- \rightarrow (Z-1, A) + \nu_e$$

Electron capture processes are important !

But

- ✓ The capture rate is generally low …
- ✓ LFV and LNV are rare events…

To obtain a high statistics

↓

Enhance the capture processes !

How to enhance the capture processes?

An interesting way is

LASER irradiation to an atom

M. Yoshimura, hep-ph/0507248

- ✓ Laser Power is $\sim \mathcal{O}(\mathrm{W/mm^2})$
- ✓ Laser Energy ~ several eV
- ✓ Mixture of Electron States

We found

another Enhance mechanism by a LASER

Key point of our work

Electron Capture Rate

$$\Gamma \sim \underline{|\Psi(0)|^2} \times \underline{|\mathcal{M}|^2}$$

Wave function of the electron

Amplitude of capture process with a free electron

$$|\Psi(0)|^2 \propto m_e^3$$

Make the electron effectively heavier !

Naïve explanation of our mechanism

Wave picture

Under the laser irradiation

→ Change of the de Broglie wave length

↕

Change of the momentum → **Change of the mass**

$$\mathbf{p} \to \mathbf{p} + e\mathbf{A}$$

$$m_e \to \sqrt{m_e^2 + (e\mathbf{A})^2}$$

↕ ↕

Change of the energy

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2. Non-Relativistic Equation with LASER filed

Dirac equation

$$i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{x},t) = \left[c\alpha\cdot(\hat{\mathbf{p}} + e\mathbf{A}(\mathbf{x},t)) + \beta m_e c^2 - e\phi(\mathbf{x})\right]\Psi(\mathbf{x},t)$$

Vector potential Coulomb potential

The two identical laser is irradiated from the both sides

$$\mathbf{A}(\mathbf{x},t) = 2\sqrt{\frac{2\hbar N}{\epsilon_0\omega}}\cos(\mathbf{k}\cdot\mathbf{x})\cos(\omega t + \phi_\alpha)\mathbf{a}_\mathbf{k}$$

$N\cdots$ Average photon number density

Effective mass

$$c\alpha \cdot \mathbf{A} + \beta m_e c^2 \longrightarrow \beta m_{eff} c^2$$

Diagonalized by U

$$m_{eff}(\mathbf{x},t)c^2 = \sqrt{m_e^2 c^4 + \left(ec^2 \mathbf{A}(\mathbf{x},t)\right)^2},$$

$$U(\mathbf{x},t) = \begin{pmatrix} 1 \cos\Theta(\mathbf{x},t) & -\sigma\cdot\mathbf{a}(\mathbf{x},t)\sin\Theta(\mathbf{x},t) \\ \sigma\cdot\mathbf{a}(\mathbf{x},t)\sin\Theta(\mathbf{x},t) & 1\cos\Theta(\mathbf{x},t) \end{pmatrix},$$

$$\mathbf{a}(\mathbf{x},t) \equiv \frac{\mathbf{A}(\mathbf{x},t)}{|\mathbf{A}(\mathbf{x},t)|},$$

$$\sin\Theta(\mathbf{x},t) = \frac{(m_{eff}(\mathbf{x},t) - m_e)c^2}{\sqrt{\left(ce\mathbf{A}(\mathbf{x},t)\right)^2 + (m_{eff}(\mathbf{x},t) - m_e)^2 c^4}},$$

$$\cos\Theta(\mathbf{x},t) = \frac{|ce\mathbf{A}(\mathbf{x},t)|}{\sqrt{\left(ce\mathbf{A}(\mathbf{x},t)\right)^2 + (m_{eff}(\mathbf{x},t) - m_e)^2 c^4}}.$$

$$i\hbar\frac{\partial}{\partial t}\Phi = \left[cU^{\dagger}\alpha U\cdot\hat{\mathbf{p}} + \beta m_{eff}c^{2} - e\phi\right]\Phi$$

$$- U^{\dagger}\left\{i\hbar\frac{\partial}{\partial t}U - c\alpha\cdot(\hat{\mathbf{p}}U)\right\}\Phi$$

$$\Phi \equiv U^{\dagger}\Psi$$

Neglect

assumptions

1. The wave length of the laser is much larger than the size of the atom.

   → Ignore the position dependence of U, m_{eff}

2. the oscillation period of the laser is longer than the time interval which we consider.

   → Ignore the time dependence of U, m_{eff}

Non-Relativistic Limit

$$i\hbar\frac{\partial}{\partial t}\Phi(\mathbf{x},t) = \left[c\alpha\cdot\hat{\mathbf{p}} + \beta m_{eff}c^2 - e\phi(\mathbf{x})\right]\Phi$$
$$+ c\{-(\alpha\cdot\mathbf{a}) + \beta\sin 2\Theta + (\alpha\cdot\mathbf{a})\cos 2\Theta\}(\mathbf{a}\cdot\hat{\mathbf{p}})\Phi$$

1. Take the direction of $\mathbf{A}$ to z
2. Separate the time dependence

$$E\varphi(\mathbf{x},t) = \left[\frac{\hat{\mathbf{p}}^2}{2m_{eff}} - e\phi(x) - \frac{\tilde{s}^2}{2m_{eff}}\hat{p}_z^2\right]\varphi(\mathbf{x},t)$$

$$\tilde{s} \equiv \sin 2\Theta$$

Virial theorem

$$\frac{\langle H_{int}\rangle}{\langle H_0\rangle} = \frac{1}{3}\tilde{s}^2 < \frac{1}{3}$$

We can solve the equation by using the solution of Hydrogen-like atom

3. Wave Functions

Solve the non-relativistic equation perturbatively

$$E\varphi(\mathbf{x},t) = \left[\frac{\hat{\mathbf{p}}^2}{2m_{eff}} - e\phi(x) - \frac{\tilde{s}^2}{2m_{eff}}\hat{p}_z^2\right]\varphi(\mathbf{x},t)$$

In the following, we consider 1s state.

0th order

$$\varphi_{nlm}^{(0)}(\mathbf{x}) = R_{nl}(r)Y_{lm}(\theta,\phi)$$

$$R_{nl} \propto m_{eff}^{3/2}$$

$$E_n^{(0)} = -\frac{m_{eff}c^2}{2\alpha^2}\frac{1}{n^2}$$

Only l=even and m=0 states appear

1st order

$$\varphi_{100}^{(1)}(\mathbf{x}) = \tilde{s}^2 \sum_{n=2} f_{n00}^{(1)} \varphi_{n00}^{(0)} + \tilde{s}^2 \sum_{n=3} f_{n20}^{(1)} \varphi_{n20}^{(0)}$$

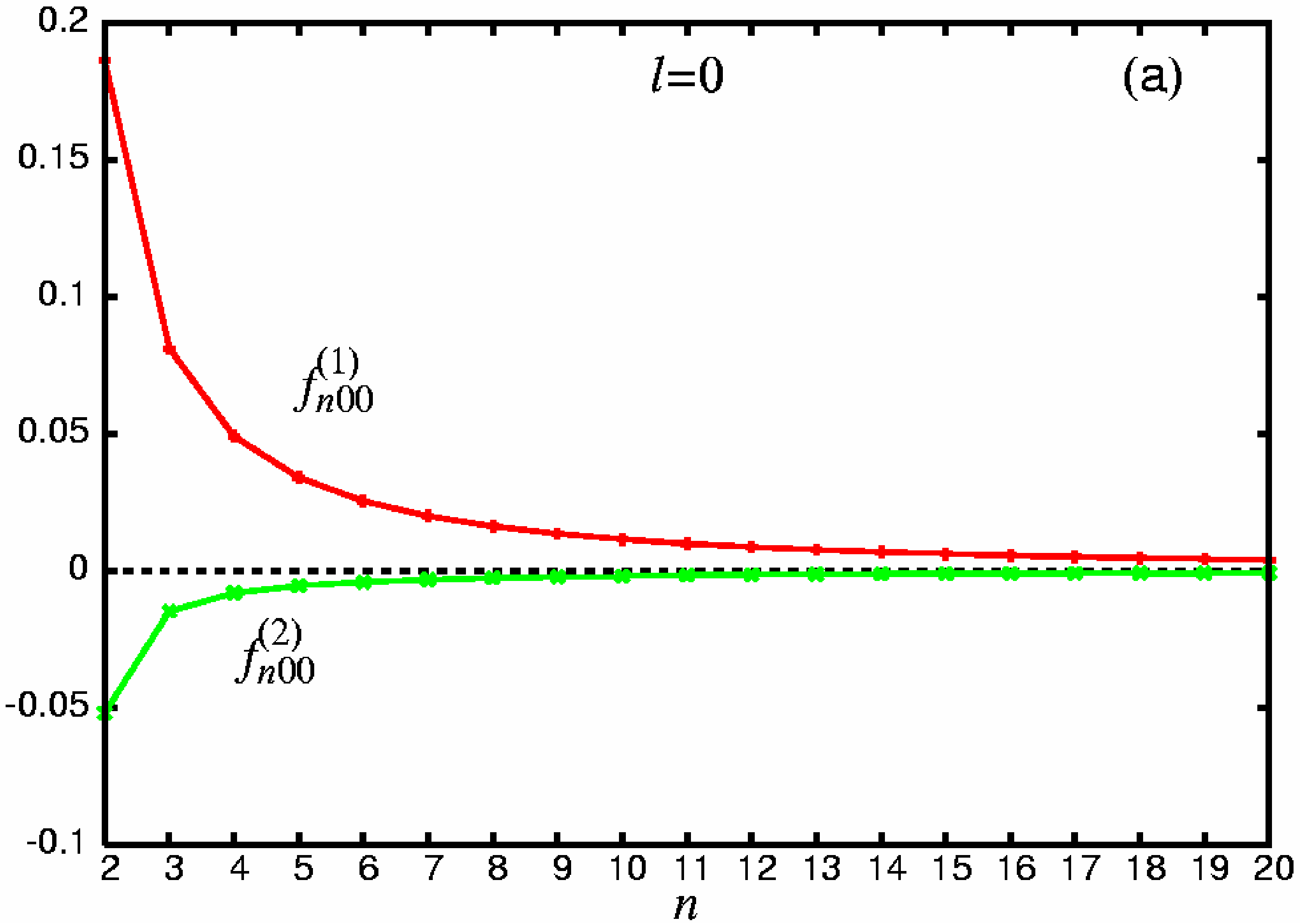
$$E_1^{(1)} = \frac{\tilde{s}^2}{3} E_1^{(0)}$$

2nd order

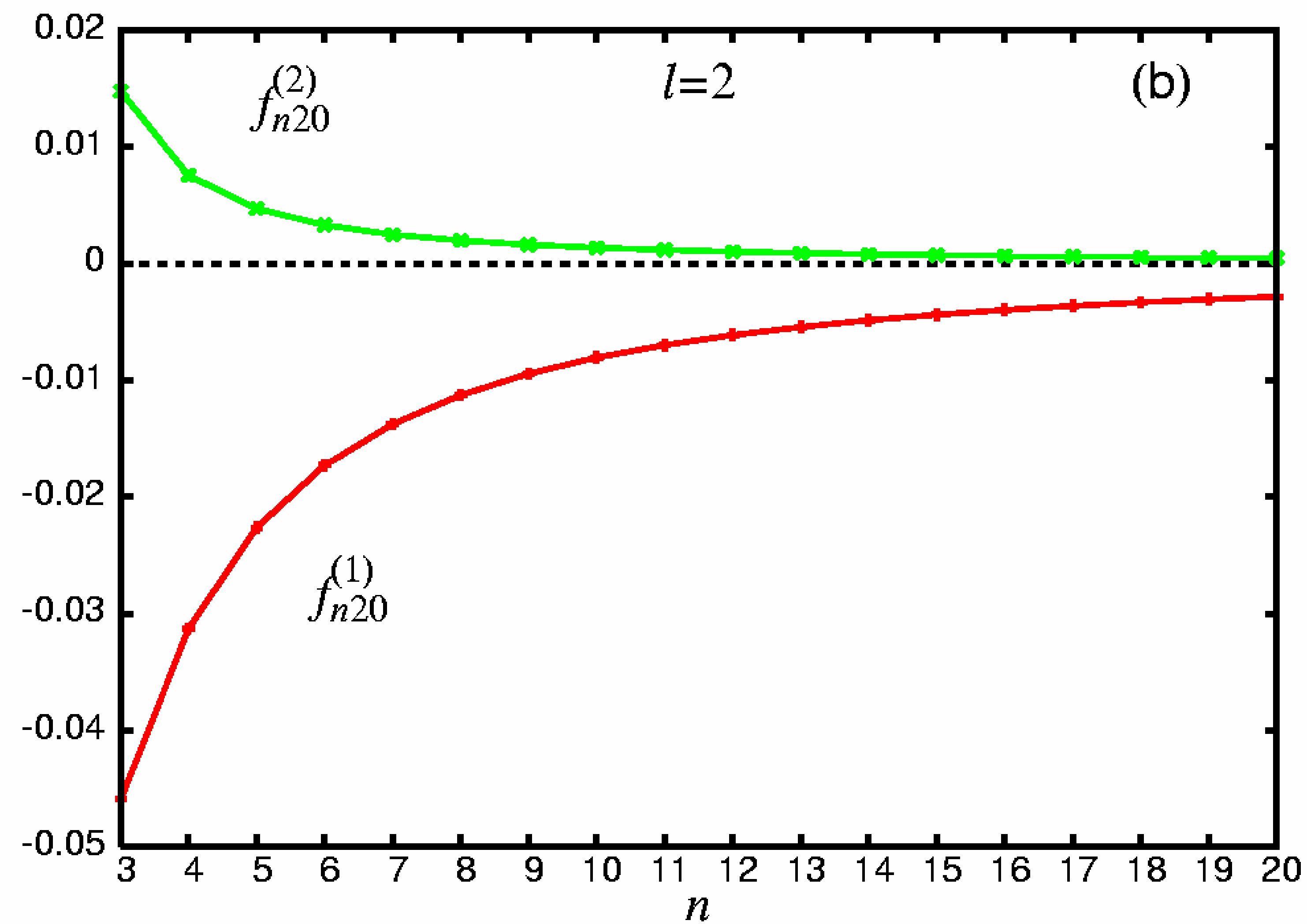
$$\varphi_{100}^{(2)}(\mathbf{x}) = \tilde{s}^4 \sum_{\substack{n \neq 1 \\ l=0,2,4}} f_{nl0}^{(2)} \varphi_{nl0}^{(0)} + \tilde{s}^4 C^{(2)} \varphi_{100}^{(0)}$$

$$E_1^{(2)} = \tilde{s}^4 E_1^{(0)} \left[\frac{3}{4} {f_{200}^{(1)}}^2 + \sum_{n=3} \frac{n^2 - 1}{n^2} \left({f_{n00}^{(1)}}^2 + {f_{n20}^{(1)}}^2 \right) \right]$$

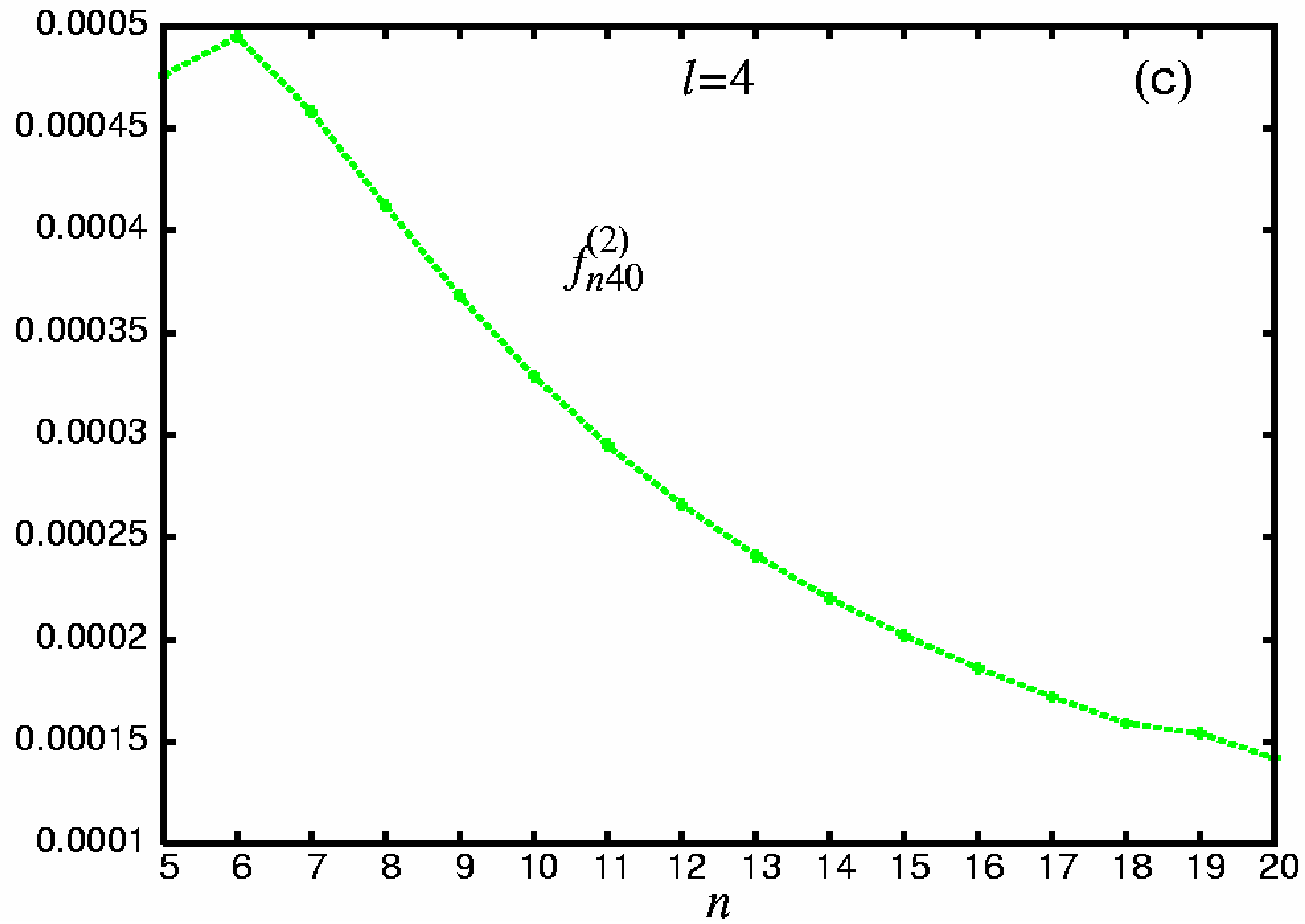
$f^{(1)}_{n00}$ and $f^{(2)}_{n00}$



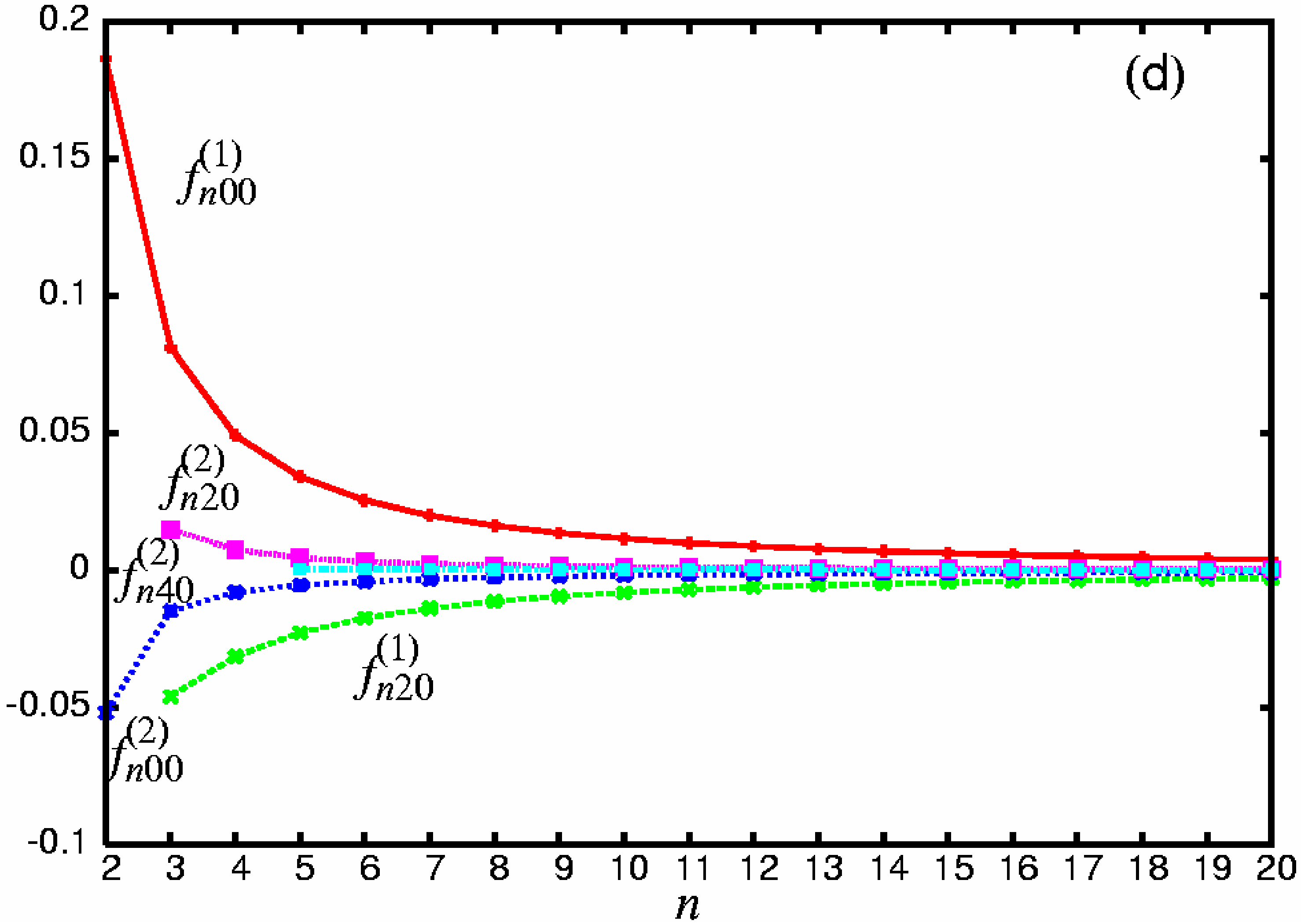
$f^{(1)}_{n20}$ and $f^{(2)}_{n20}$



$f^{(2)}_{n40}$



0.0005
0.00045
0.0004
0.00035
0.0003
0.00025
0.0002
0.00015
0.0001
5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
n
l=4
(c)
$f^{(2)}_{n40}$

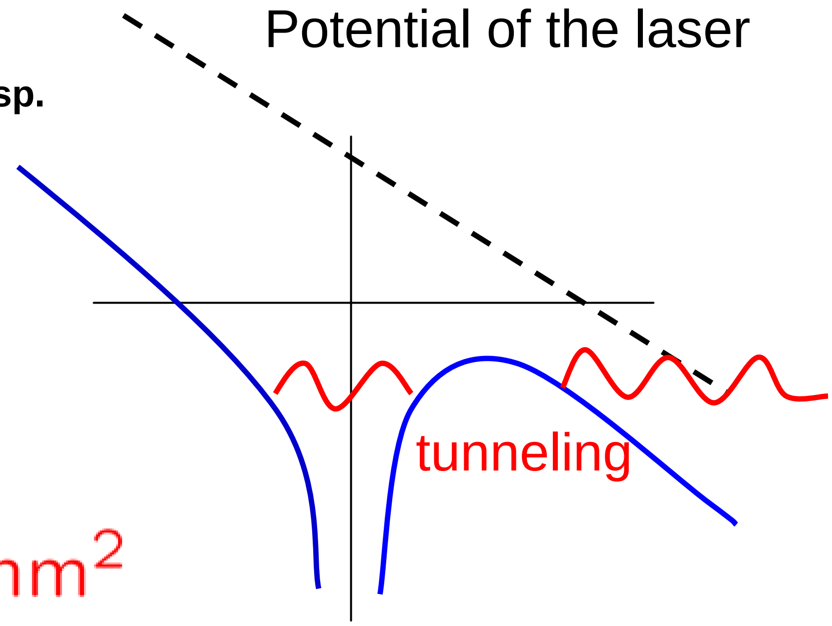


Probability density is determined by the 0th order

4. Competitive Ionizations

Tunnel Ionization

Ammosov, et al. Zh. Eksp. Teor. Fiz, 1986



probability $\propto \exp(-\mathcal{E}_C/\mathcal{E}_L)$

$\mathcal{E}_C \cdots$ Coulomb electric field
$\mathcal{E}_L \cdots$ Laser electric field

⇨ Intensity $\leq 10^{13}$W/mm^2

Multi-photon Absorption Ionization

L'Huillier, et al. Phys.Rev.A, 1989

Cross section $\propto (I\alpha/E_\gamma)^{E_{bin}/E_\gamma}$ $\xrightarrow[E_\gamma \to 0]{}$ 0

⇨ Energy $<< E_{bin}$

Vector potential $\mathbf{A}^2 \propto I/E_\gamma^2$ ⟶ Large!

High intensity but very low energy laser

In the following

Intensity, $I \simeq 10^{10}$ W/mm^2

Energy, $E_\gamma \simeq 10^{-3}$ eV

Static assumption is valid

$$\lambda = 1.3 \times 10^{-3} \text{ m} >> 1 \text{ Å}$$

$$T_L = 4.1 \times 10^{-12} \text{ sec} >> 1.5 \times 10^{-16} \text{ sec} = T_e$$

Time average

$$\mathbf{A}^2(\mathbf{x}, t) = \frac{4\hbar^2 I}{\epsilon_0 \; E_\gamma^2 c}$$

5. Enhancement of Atomic Electron Capture Rate

Capture Rate

$$\Gamma = |\Psi(0)|^2 \int d\mathrm{LIPS}|\mathcal{M}|^2$$

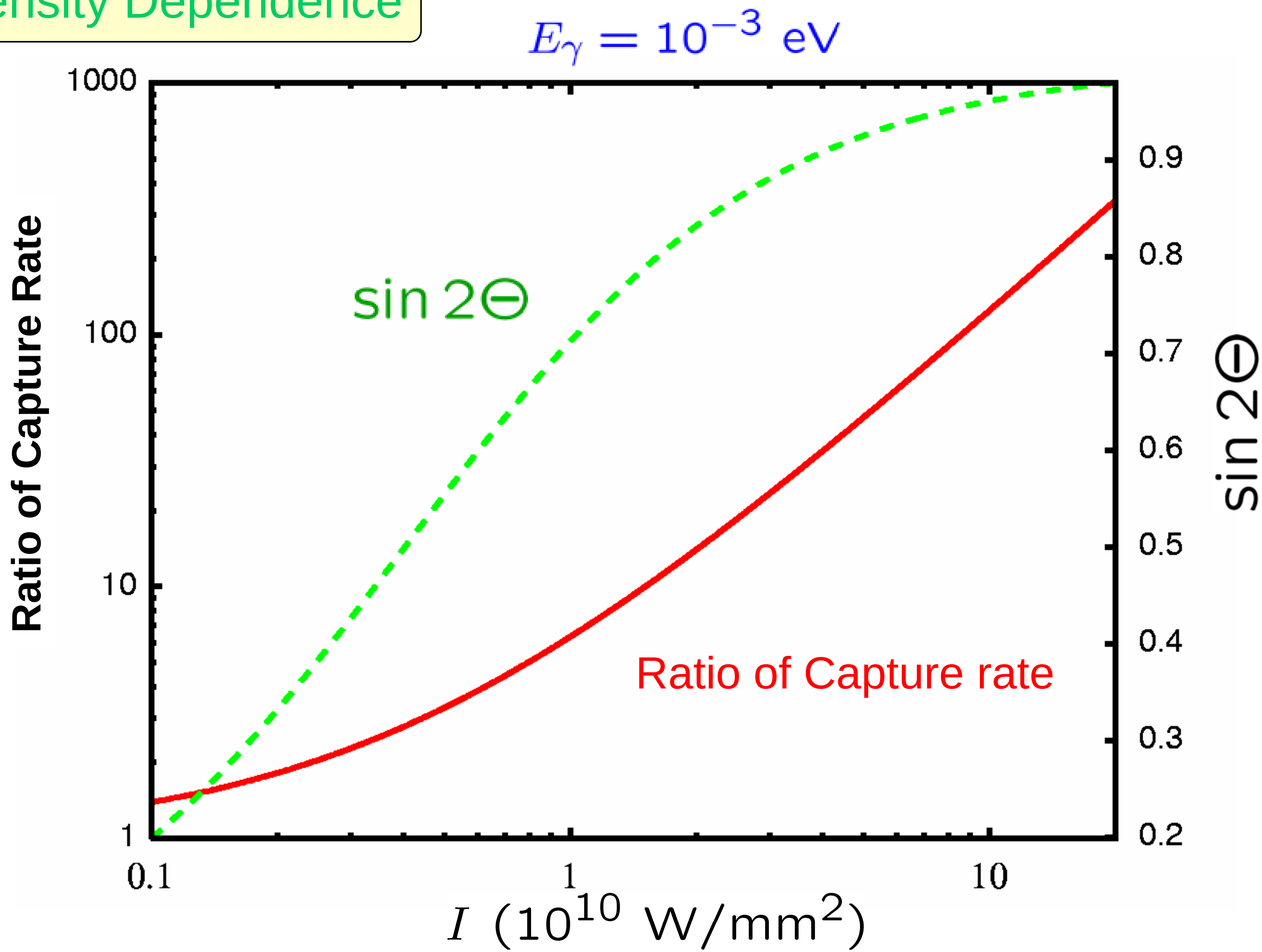
Enhancement rate

$$\frac{\Gamma_{laser}}{\Gamma} = \frac{|\varphi^{(0)}_{laser}|^2}{|\varphi^{(0)}|^2} \simeq \left(\frac{m_{eff}}{m_e}\right)^3$$

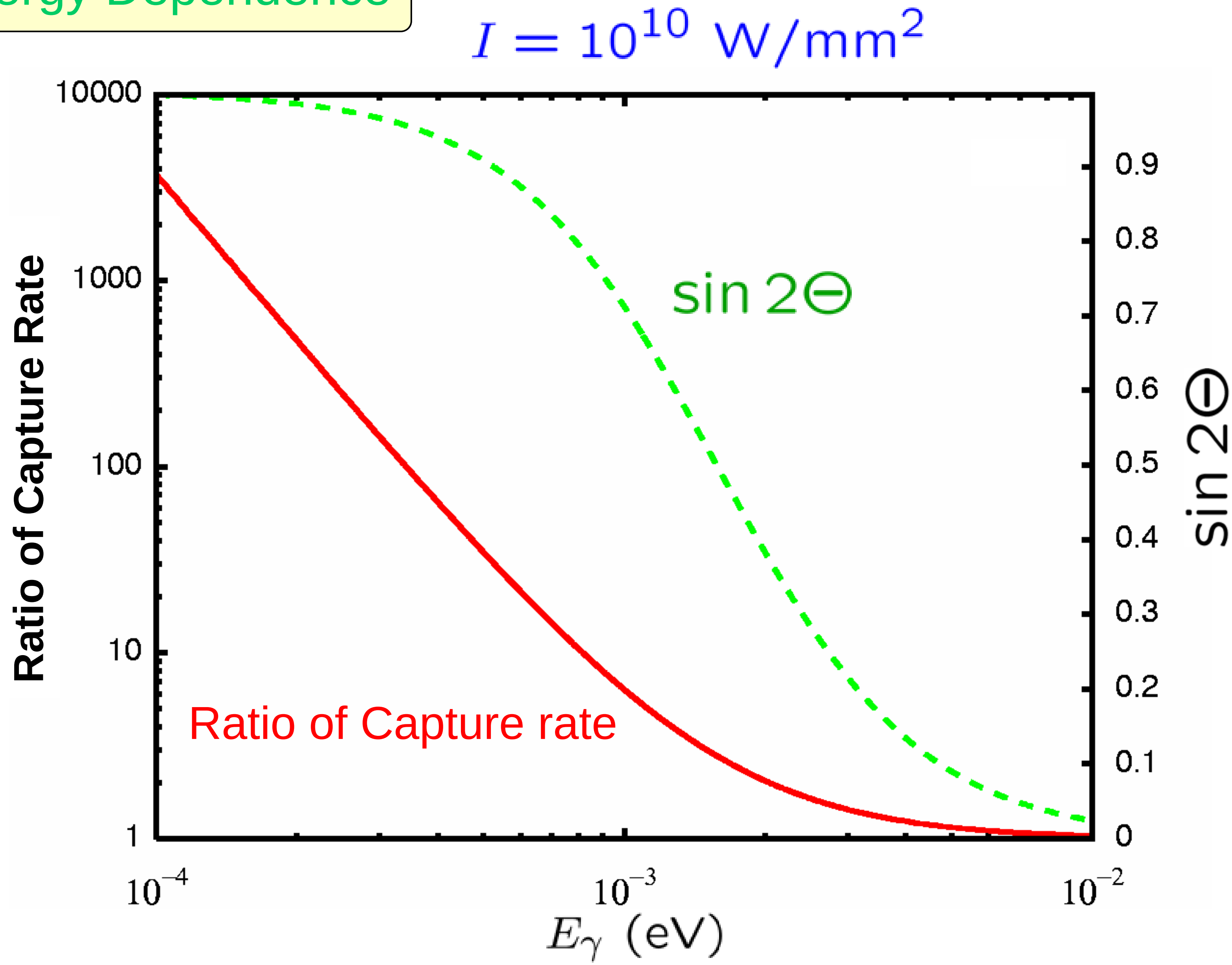
$$m_{eff} = \sqrt{m_e^2 + 32\pi\hbar^3 c^2 \alpha \frac{I}{E_\gamma^2}}$$

→ Increase function of I/E_γ^2

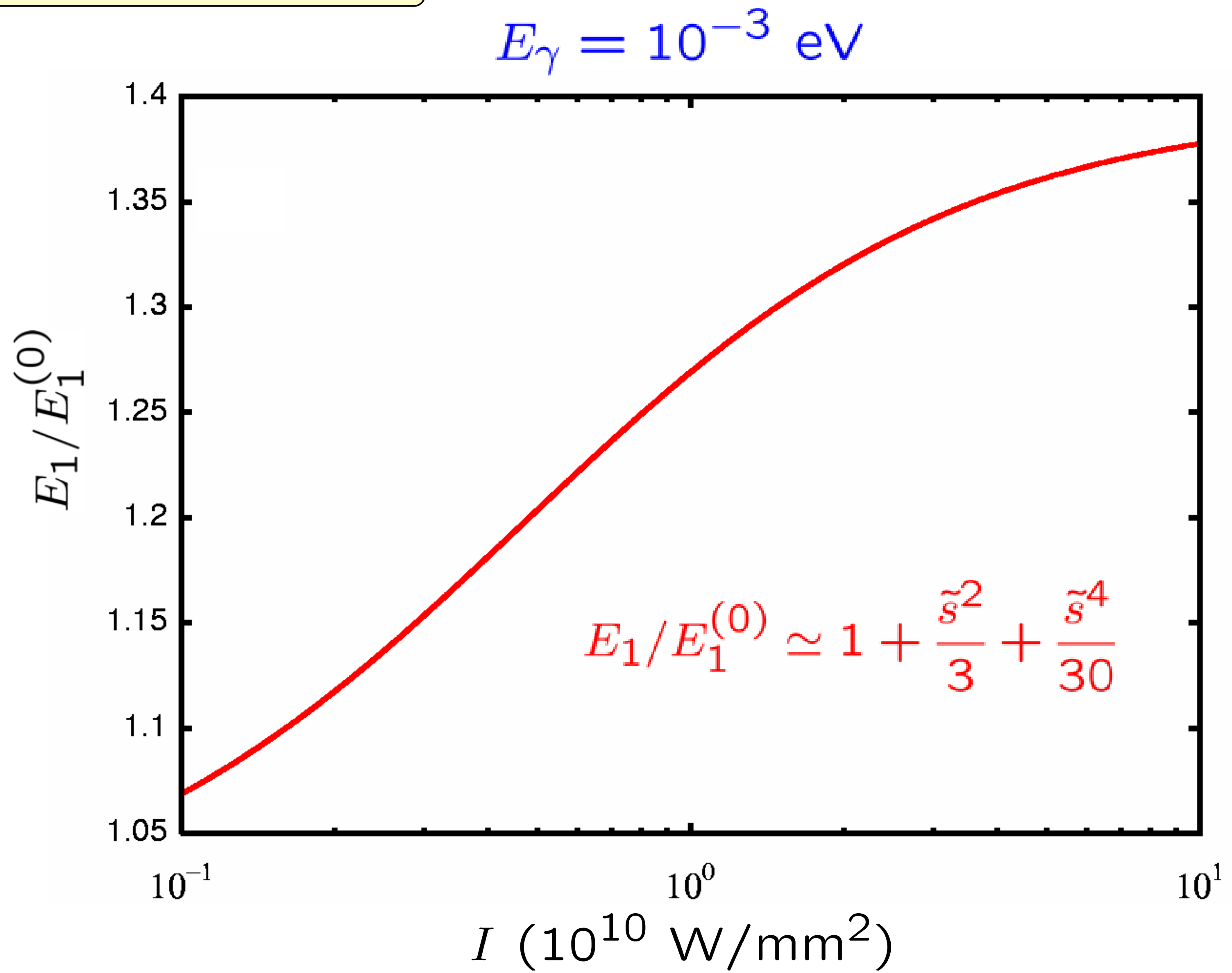
Intensity Dependence



Energy Dependence



Intensity Dependence



6. Summary and Future Work

We have investigated a mechanism to enhance atomic electron capture decay by a laser irradiation

1. The mass of electron becomes effectively heavier under the laser irradiation.
2. The non-relativistic equation with effective mass was derived.
3. Tunnel ionizations and MPI are suppressed when $I \leq 10^{13}$ W/mm^2 and E_γ is low.
4. The lower energy beam is better when the intensity is the same.
5. The order of magnitude enhancement can be theoretically achieved.

1. We considered the short time interval

→ We have to consider the time dependence of the laser for more realistic situations.

2. We replaced the vector potential by its time average

→ We have to calculate the time average of m_{eff}^3 for longer time period.

Electron Capture Rate

$$\Gamma = \underline{|\Psi(0)|^2} \underline{\int d\text{LIPS}|\mathcal{M}|^2}$$

can enhance ?

determined by the fundamental physics

$\Psi(0)$ $\cdots$ a wave function of a bound electron at the center

$\mathcal{M}$ $\cdots$ amplitude of the capture process with the free electron

$d\text{LIPS}$ $\cdots$ the Lorentz invariant phase space