New opportunities in nuclear physics with high-power lasers and multi-photon absorption

ECT* workshop:

New opportunities and challenges in nuclear physics with high power lasers

Chieh-Jen (Jerry) Yang

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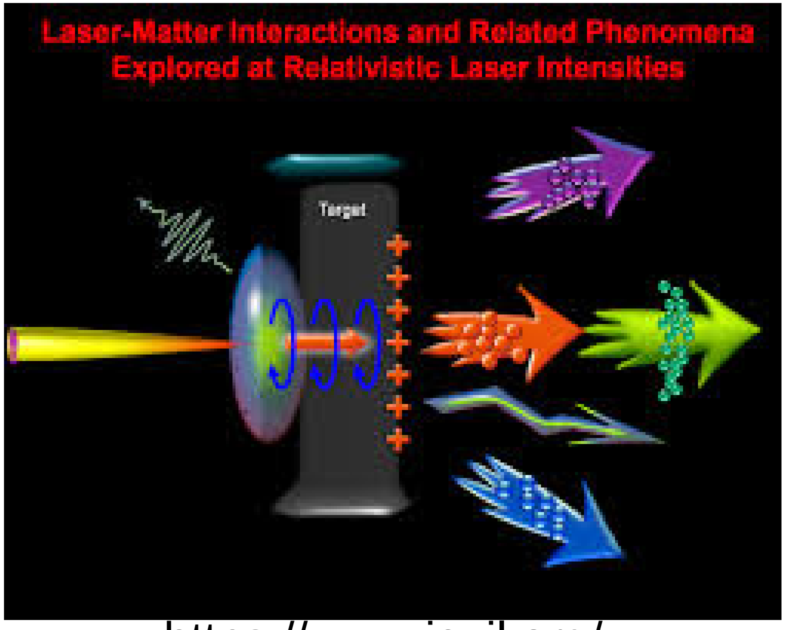
Collaborators: Klaus Spohr, Paolo Tomassini, Vojtech Horny, Domenico Doria

HPLS + NP: where are we? What are we looking for?

- HPLS could provide very intense beams: neutrons, ions, e-, low- and high-energy photons.
- In principle, those beams are energetic enough (MeV-GeV) to be used in nuclear or particle physics research.

A very simple explanation for beams from laser-plasma interaction
(for NP people)



https://www.icuil.org/

- Key: total # maybe not great, but the intensity is, ∵ compress in time + space.

10~50 fs 3~100 μm

More is different P.W. Anderson

- In our case, it's the intensity that makes the difference.

$I_{viaHPLS} >> I_{traditional}$ (up to 10^{10} due to compression in t)

This is unique for us only (not for traditional accelerators).

Use for probe short-lived, rare events—link to fundamental research
Medical treatment (gamma-flash, BNCT, ion therapy)--link to practical application
Isomer manipulation or efficient nuclear transition in general

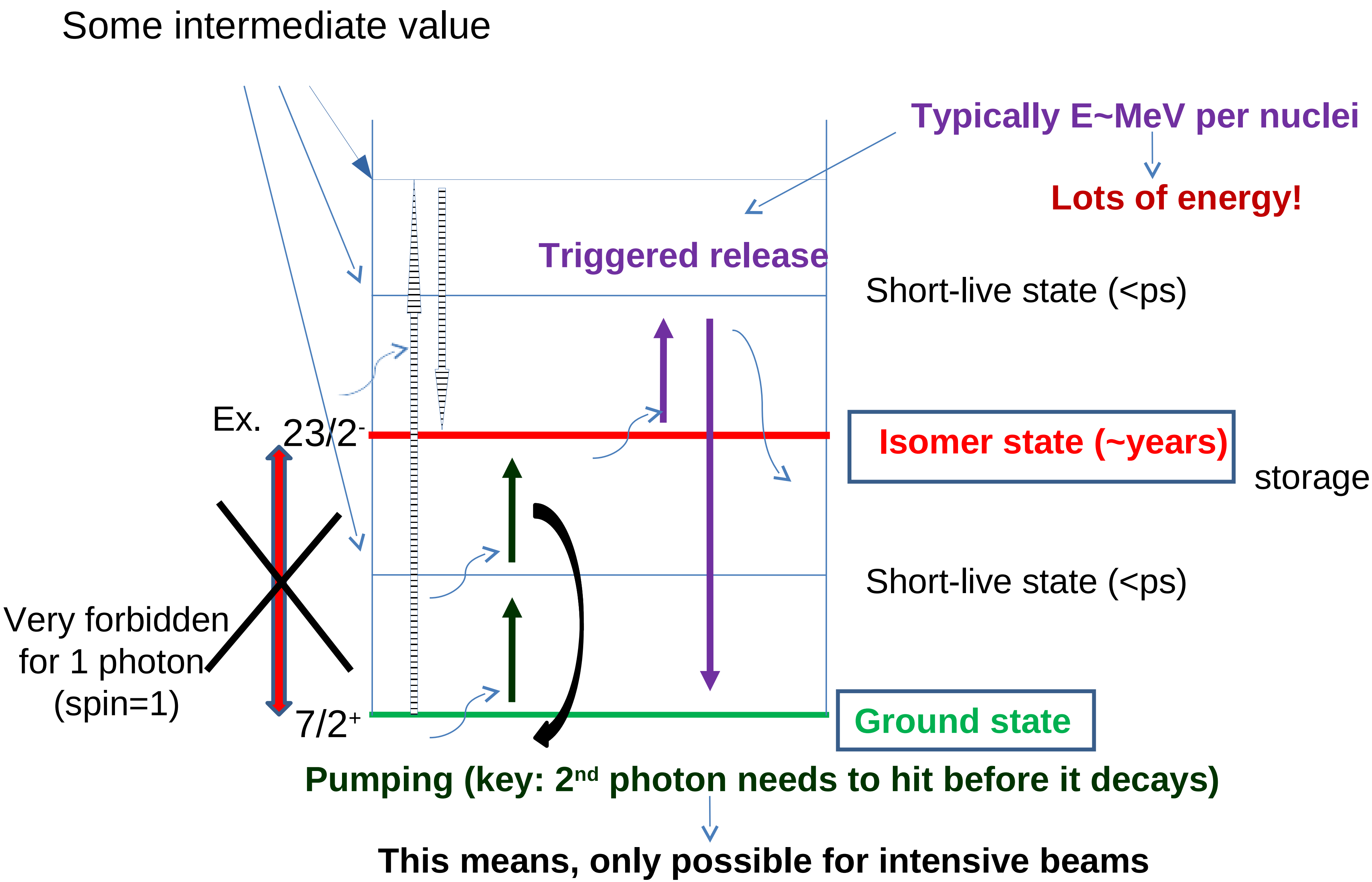
↓

I'll discuss this later

Isomer pumping/depletion (or in general, manipulation of nuclear transitions)

Applications:

Nuclear battery ($t_{1/2}$ > 10 years, e.g., ^{93m}Nb, ^{113m}Cd, ^{178m}Hf, etc.), medical purpose (^{131}I, ^{177}Lu, ^{186}Rh, etc), and more.



Some intermediate value
Typically E~MeV per nuclei
Lots of energy!
Triggered release
Short-live state (<ps)
Ex.
23/2-
Isomer state (~years)
storage
Very forbidden
for 1 photon
(spin=1)
Short-live state (<ps)
7/2+
Ground state
Pumping (key: 2nd photon needs to hit before it decays)
This means, only possible for intensive beams

Practical requirements (sequential, 2 steps pumping)

- To have ~1000 events of 1+1 steps pumping, need **10^{16}** photons (with E≈1 MeV) per 100 μm^2. Only photons deposited within ~ps counts. => not a problem for PW HPLS.

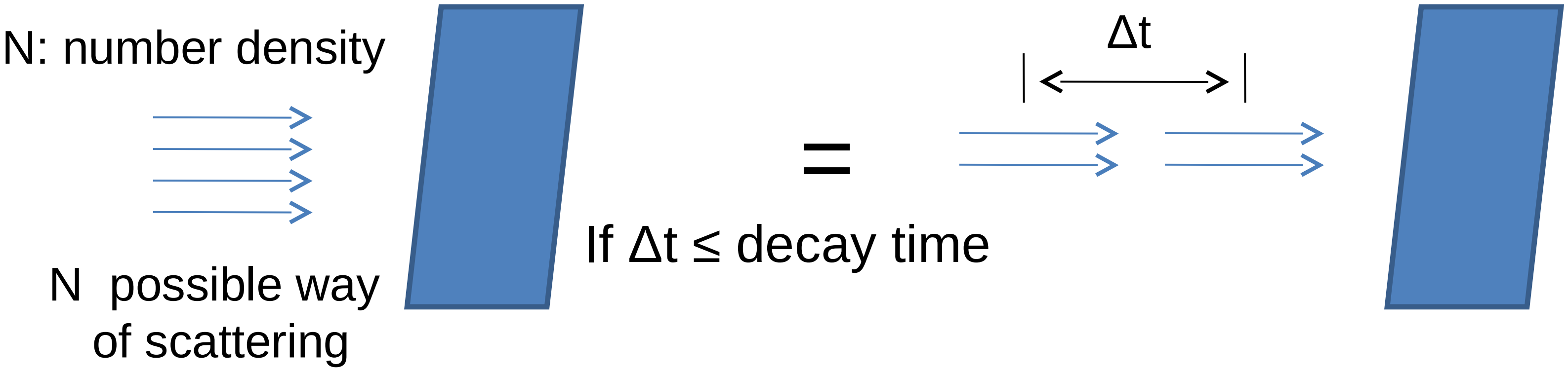
This is the problem! PIC simulations give at most **10^9 photons** at such energy.

* The number can varying ×/÷100 times dep. on the nuclei selected and detailed nuclear model used.

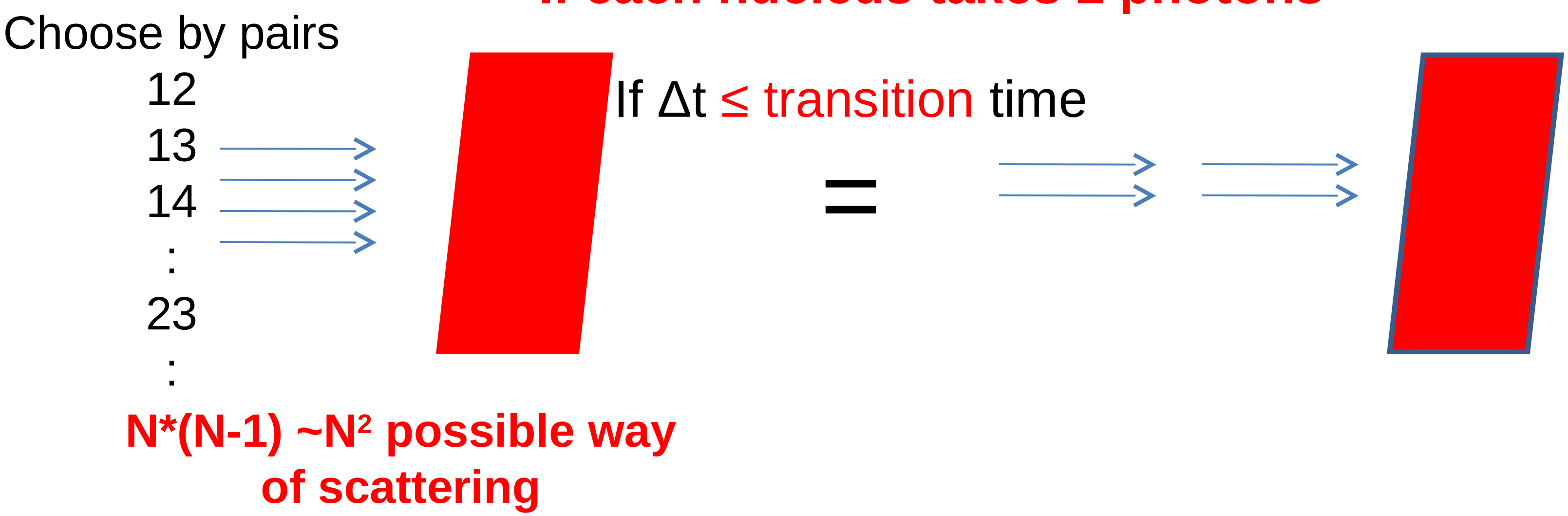
Yields (per step per area)=(# of γ/per area)*σ*(# density of nuclei)*(target length)

Is there other chances?

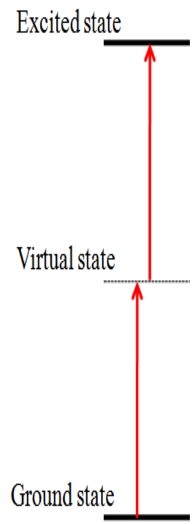
If each nucleus only takes 1 photon



If each nucleus takes 2 photons



2 Photon absorption (2PA)



First predicted by M. Goeppert-Mayer at 1931, not observed until laser used.

2PA first observed in atomic/molecule cases 1961.

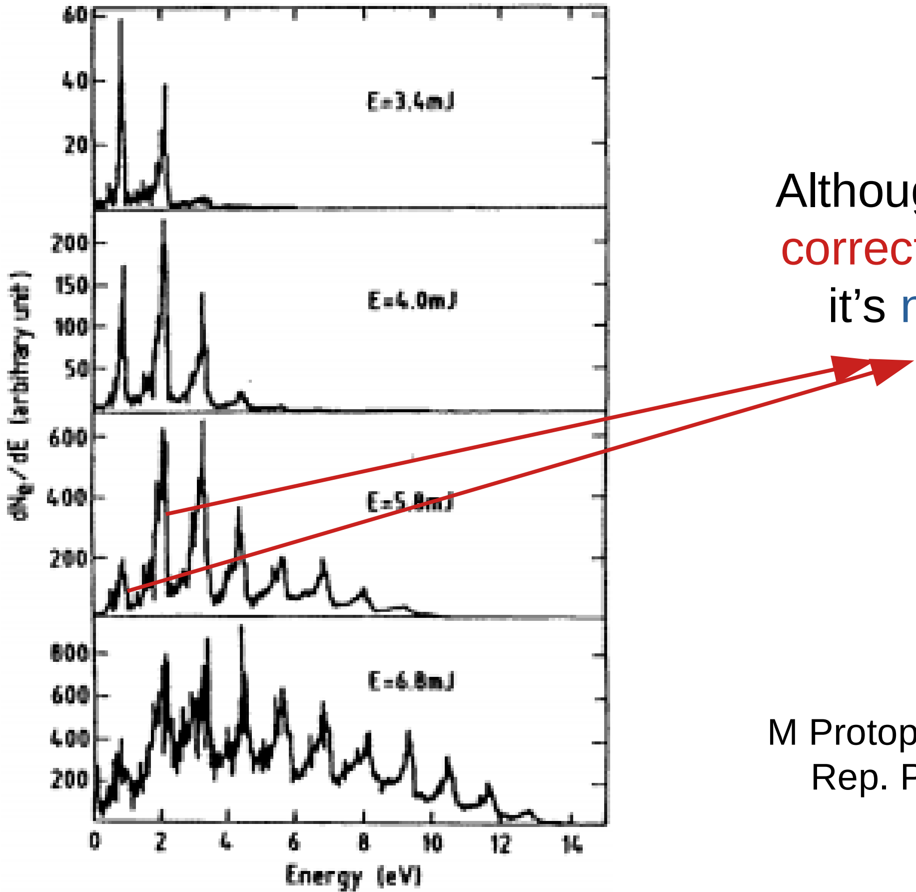
Yields per unit time~ $I^2 * \sigma_{GM}$, instead of $I * \sigma$.

($1\ \sigma_{GM} = 10^{-50}\ cm^4\ s$)

2nd order effect, with a smaller cross section, but the yield can exceed 1PA for higher Intensity. Experimentally, yields from (n+1)PA >nPA has been observed for n>10 in atomic photoionization.

2PA or nPA in atomic case

- Yield from nPA comparable or larger than (n-1)PA has been observed for n>10.



Although nPA belongs to high-order correction on the interaction kernel, it's not perturbative on the final amplitude.

M Protopapas, C H Keitel and P L Knight, Rep. Prog. Phys. 60 (1997) 389-486.

This is a combinatorial-based quantum effect

$$Y_{2PA} \propto I_1 * I_2 * \sigma_{2pa}$$

$$unit:[cm^4][s]$$

$$Y_{nPA} \propto I_1 * I_2 * \ldots * I_n * \sigma_{nPA}$$

$$unit:[cm^{2n}][s^{n-1}]$$

This is a combinatorial-based quantum effect

Very small

Grow with I_2

$$Y_{2PA} \propto I_1 * (I_2 * \sigma_{2pa}) = I_1 * \sigma_{eff}^{2PA}(I_2)$$

$$unit:[cm^4][s]$$

$$unit:[cm^2]$$

Extremely small

$$Y_{nPA} \propto I_1 * (I_2 * \ldots * I_n * \sigma_{nPA}) = I_1 * \sigma_{eff}^{nPA}(I_2, \ldots, I_n)$$

$$unit:[cm^{2n}][s^{n-1}]$$

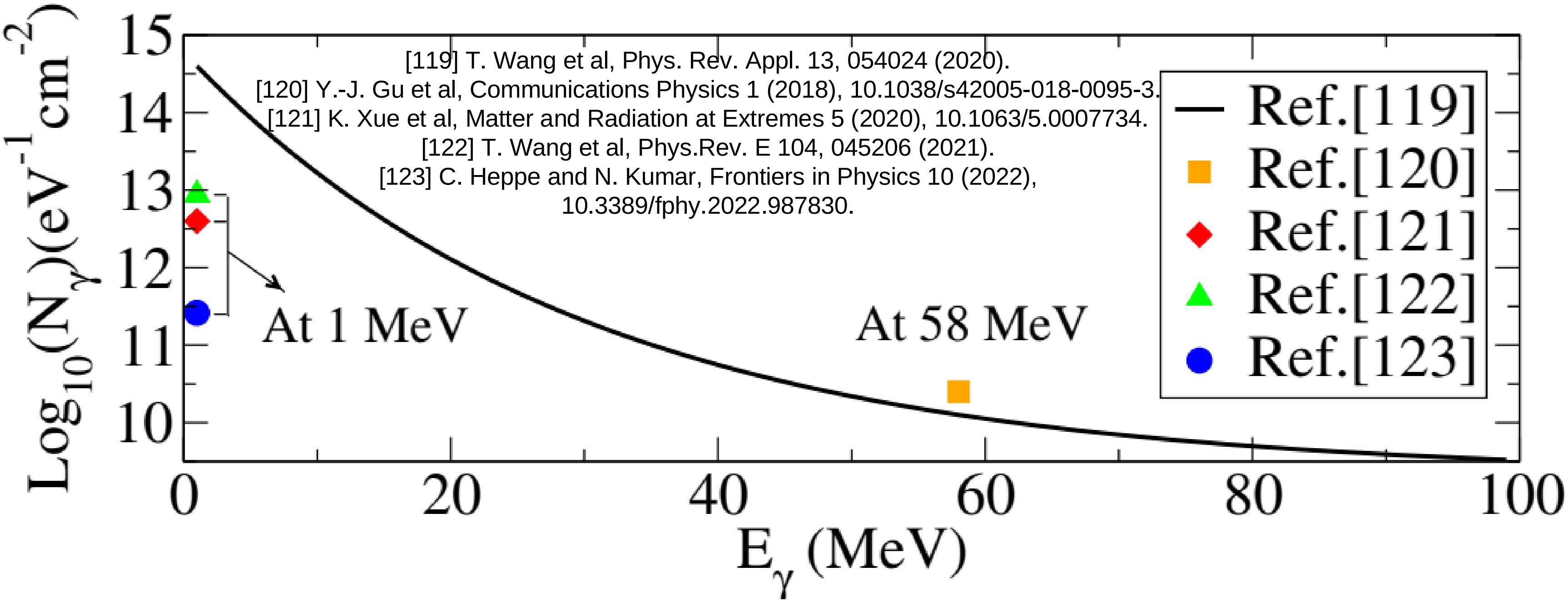
Grow with $I_{2..n}$

2PA in nuclear case

So far not observed. ∵Lack of <u>intense enough γ beam</u>

(the reverse case, 2-photon emission has been observed).

Could HPLS + laser-matter interaction provide that?



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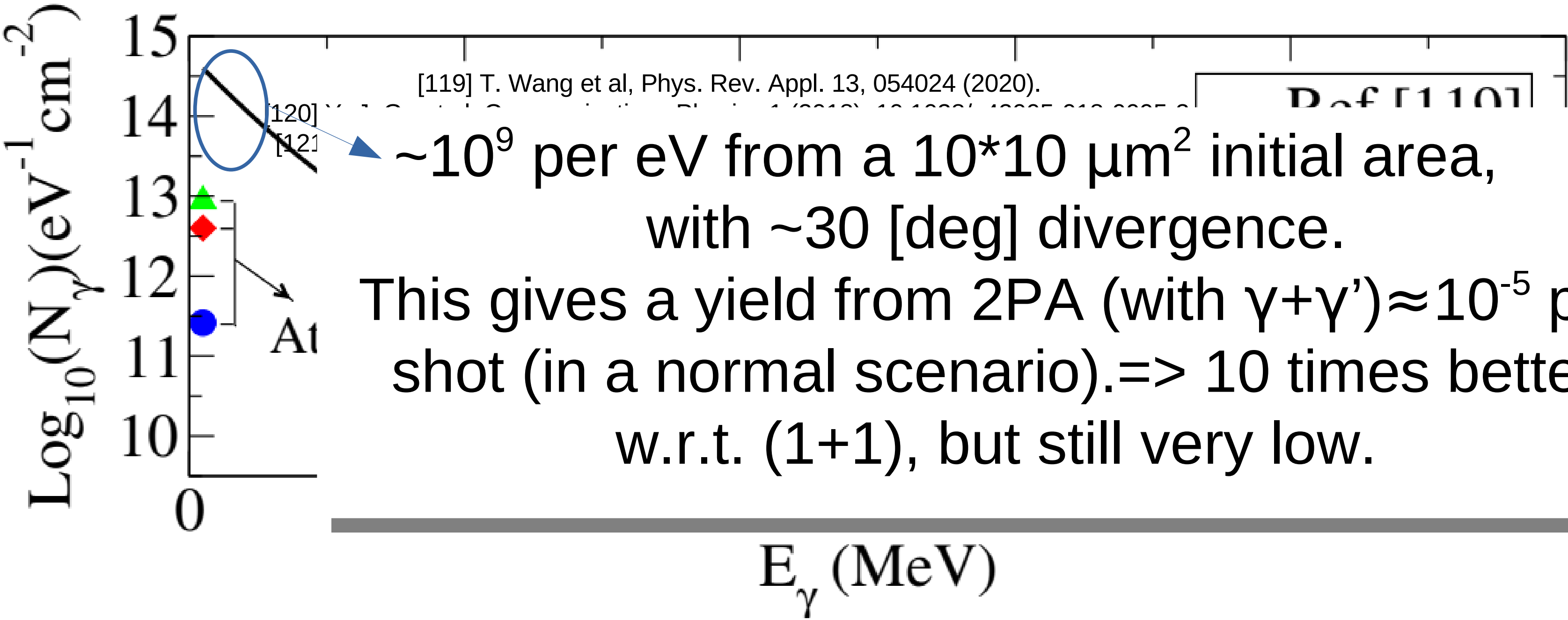


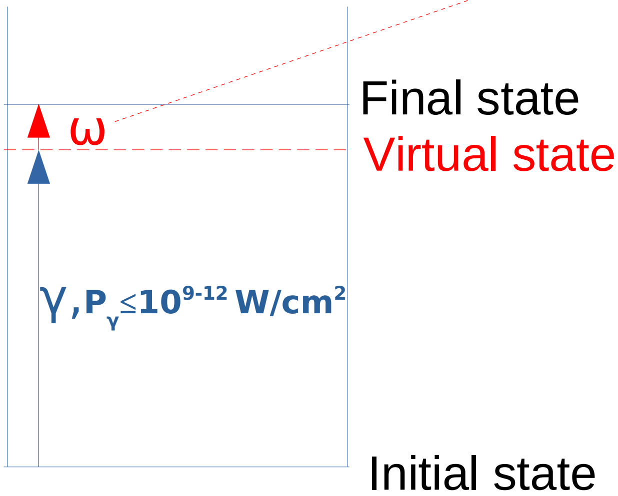
~10^9 per eV from a 10*10 μm^2 initial area, with ~30 [deg] divergence.

This gives a yield from 2PA (with γ+γ')≈10^{-5} per shot (in a normal scenario).=> 10 times better w.r.t. (1+1), but still very low.

But, there's a trick

C.-J. Yang, K. M. Spohr, M. Cernaianu, D. Doria, P. Ghenuche, V. Horny, arXiv:2404.07909 [nucl-th]

- Photons participate 2PA (or nPA) **doesn't need to be in equal energy**.
- Consider (eV-level≡ω-photon)+(γ-photon), where ω can be provided by HPLS, and make very intense (up to 10^{23} W/cm^2).



$$R_{2pa} = \frac{e^4 \mathcal{E}_1^2 \mathcal{E}_2^2}{16\hbar^4} |\mathcal{M}|^2 2\pi \delta_t(\omega - \omega_1 - \omega_2),$$

$$\mathcal{M} = \sum_m \left[\frac{\langle f|\hat{H}_2|m\rangle\langle m|\hat{H}_1|i\rangle}{\omega_1 - \omega_{mi}} + (1 \longleftrightarrow 2) \right],$$

ω

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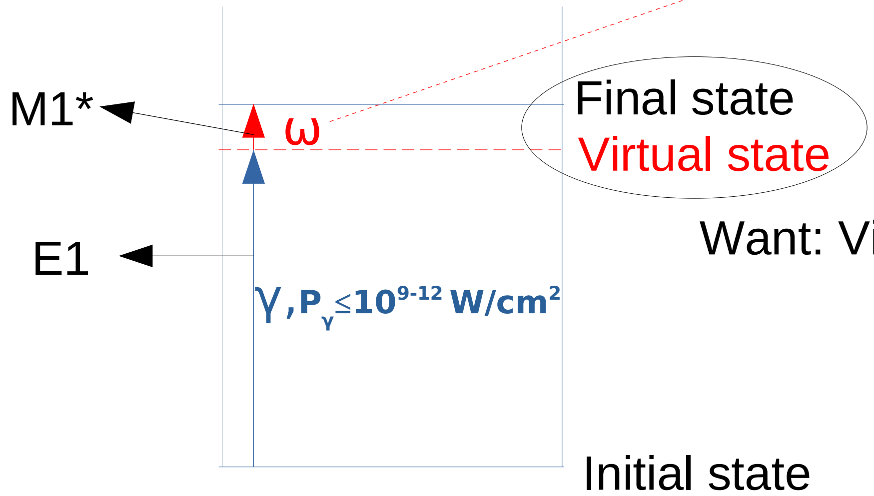

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Want: Virtual state to resonance with physical state

$$\mathcal{M} = \sum_m \left[\frac{\langle f|\hat{H}_2|m\rangle\langle m|\hat{H}_1|i\rangle}{\omega_1 - \omega_{mi}} + (1 \longleftrightarrow 2) \right],$$

ω: gap b/w v.s and phy.s

* unless there's a closer phy.s for it to resonance with.

Practical number (via Weisskopf estimate)

Effective cross section [unit: cm2] feel by each γ.

First derived by: C. B. Collins, S. Olariu, M. Petrascu, and I. Popescu, Phys. Rev. Lett. 42, 1397 (1979).

$$\sigma_{eff}^{2pa,E1+E1} \approx 3\cdot 10^{-51}\frac{E_\gamma}{w_>}\mathcal{P}_2\frac{A^{4/3}}{(\Delta E)^2}G,$$

$$\sigma_{eff}^{2pa,M1+E1} \approx 5\cdot 10^{-51}\frac{E_\gamma}{w_>}\mathcal{P}_2\frac{A^{2/3}}{(E_2)^2}G,$$

TABLE I. Summary of cross sections calculated for the absorption of γ radiation induced by the fields associated with an optical power density of 10^{10} W/cm^2 by model nuclei of mass $A\sim 200$ having nearly degenerate excited states separated in energy from each other by ΔE and from the ground state by 0.1 MeV. The widths Γ correspond to the lifetimes of the final state of the two-photon absorptions as determined by single-photon spontaneous emissions of the multipolarity indicated.

Multipole type	Γ (Hz)	ΔE (eV)	σ (cm^{-2})
$E1$	1.1×10^{12}	21	10^{-32}
$M1$	1.0×10^{10}	22	10^{-30}
$E2$	2.8×10^{5}	42	10^{-28}

If $P_2=10^{10}$ W/cm^2, $\sigma_{eff}\approx 10^{-26}\sim 10^{-32}$ cm^2.

With HPLS we may have $\sigma_{eff}\approx 10^{-21}$ cm^2

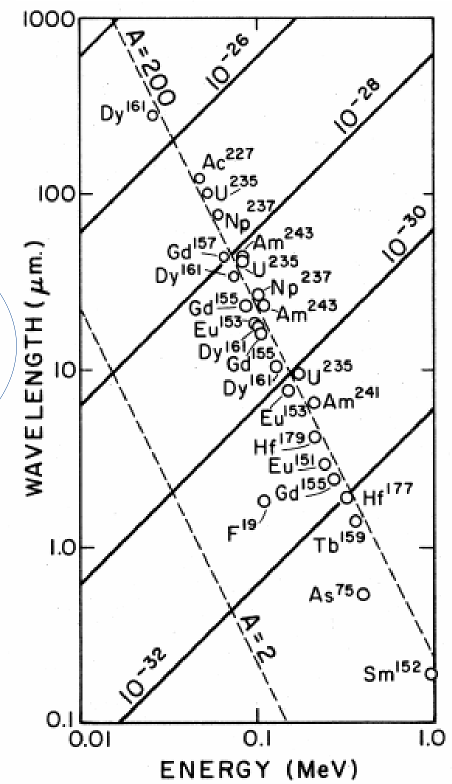

FIG. 1. Domains of the energies of γ radiations and of the wavelengths of laser photons compensating the recoils, associated with the nuclear emission and absorption of the γ photons induced by intense optical fields. Heavy lines locate parameter values at which the cross sections shown might be achieved in optical fields of 10^{10} W/cm^2. Dashed lines locate the domains of parameters corresponding to the induced absorption by nuclei of the mass numbers given. 0: tabulated transitions satisfying the necessary selection rules for the nucleus indicated.

nPA generalization:

$$R_{npa}=\frac{e^{2n}\mathcal{E}_1^2\cdots\mathcal{E}_n^2}{4^n\hbar^{2n}}|\mathcal{M}^{(n)}|^2 2\pi\delta_t(\omega-\omega_1\cdots-\omega_n)$$

$$\mathcal{M}^{(n)}=\sum_{m_2}\cdots\sum_{m_n}\left[\frac{\langle f|\hat{H}_n|m_n\rangle\cdots\langle m_3|\hat{H}_2|m_2\rangle\langle m_2|\hat{H}_1|i\rangle}{(\omega_1-\omega_{m_2 i})(\omega_2-\omega_{m_3 m_2})\cdots(\omega_{n-1}-\omega_{m_n m_{n-1}})}+\text{(all permutation)}\right]$$

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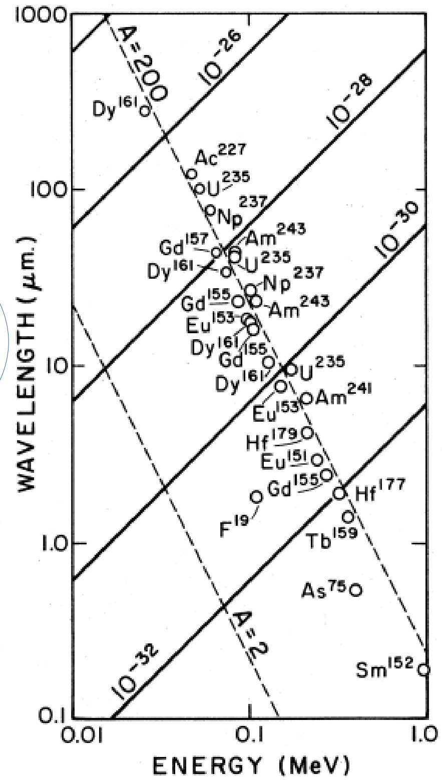

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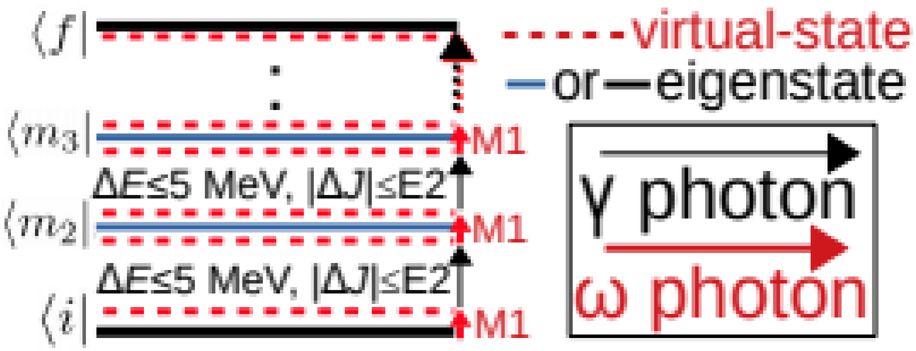

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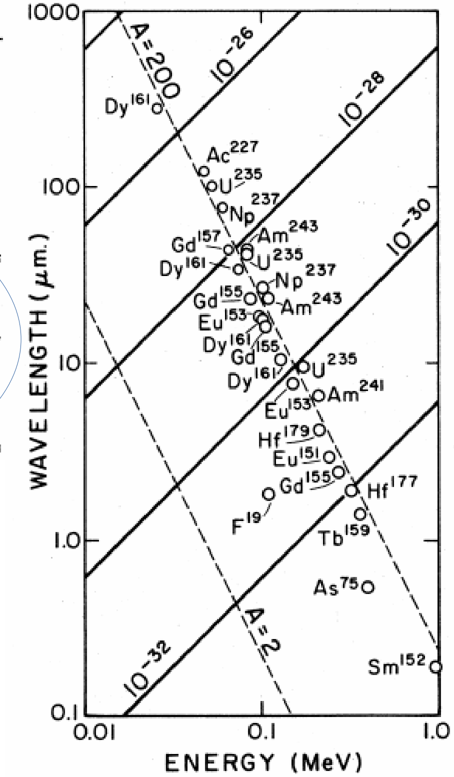

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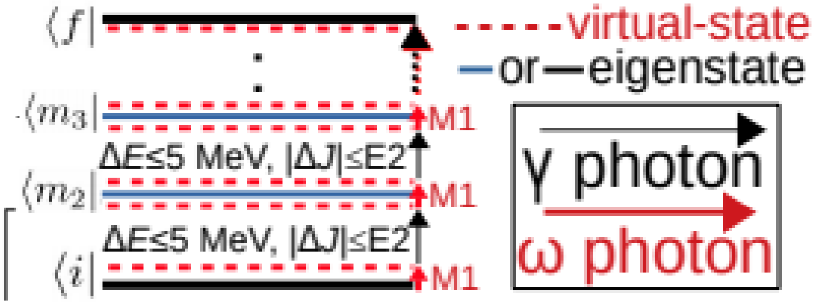


$$\mathcal{M}^{(n)} = \sum \cdots \sum \left[\cdots \right] \text{(all permutation)}$$

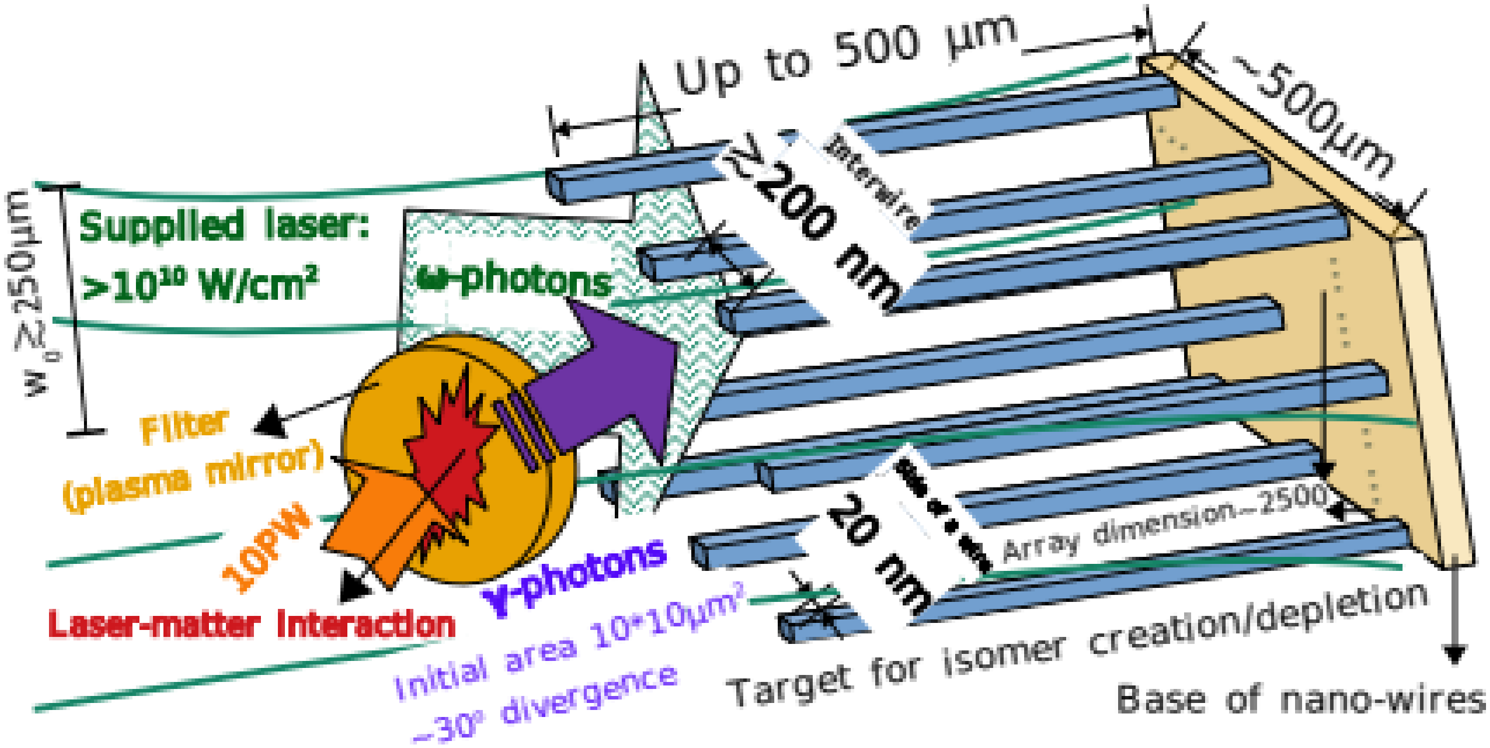
$\sigma_{eff} \geq 10^{-25}$ cm^2 realizable for 4PA in a multi-PW site!

- With such an effective cross section for 4PA (**$\sigma_{eff} \geq 10^{-25}$ cm^2**), one can already manipulate the transitions (≤E4) for lots of isomers with $t_{1/2}$>1 year in 1 HPLS shot (yield~10^6-10^9).

- Lessons:

1. At least some old people already knew the idea, but not gamma-flash then.
2. It's important to investigate another field. This is a nice demonstration how Laser-Plasma Physics impacts Nuclear Physics

Detail: one practical way to pump/deplete isomers



C.-J. Yang, K. M. Spohr, M. Cernaianu, D. Doria, P. Ghenuche, V. Horny arXiv:2404.07909 [nucl-th]

Nuclear gamma-ray laser (graser)

Beating Einstein's detail-balancing

spontaneous emission coefficient

stimulated emission coefficient

$$A = B\frac{8\pi h\nu^3}{c^3}.$$

A. Einstein, Deutsche Physikalische Gesellschaft 18, 318 (1916).

Beating Einstein's detail-balancing

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A grows quickly with (photon energy released)^3

In general, excited states releasing higher energy tend to have shorter life.

Harder to reach population inversion for graser (need elusive pumping power)!

Beating Einstein's detail-balancing

spontaneous emission coefficient

stimulated emission coefficient

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For nuclear, long-lived states (aka, isomers) exist. => **A** can be made small (via special spin/isospin/J arrangement), but then **B** is even smaller.

This then hinders the amplification process.

There's no escape! The so-called **graser dilemma !**

Beating Einstein’s detail-balancing

However, the derivation of the previous equation assumes yield is linear to I, and the stimulated emission ∈ 1PA.

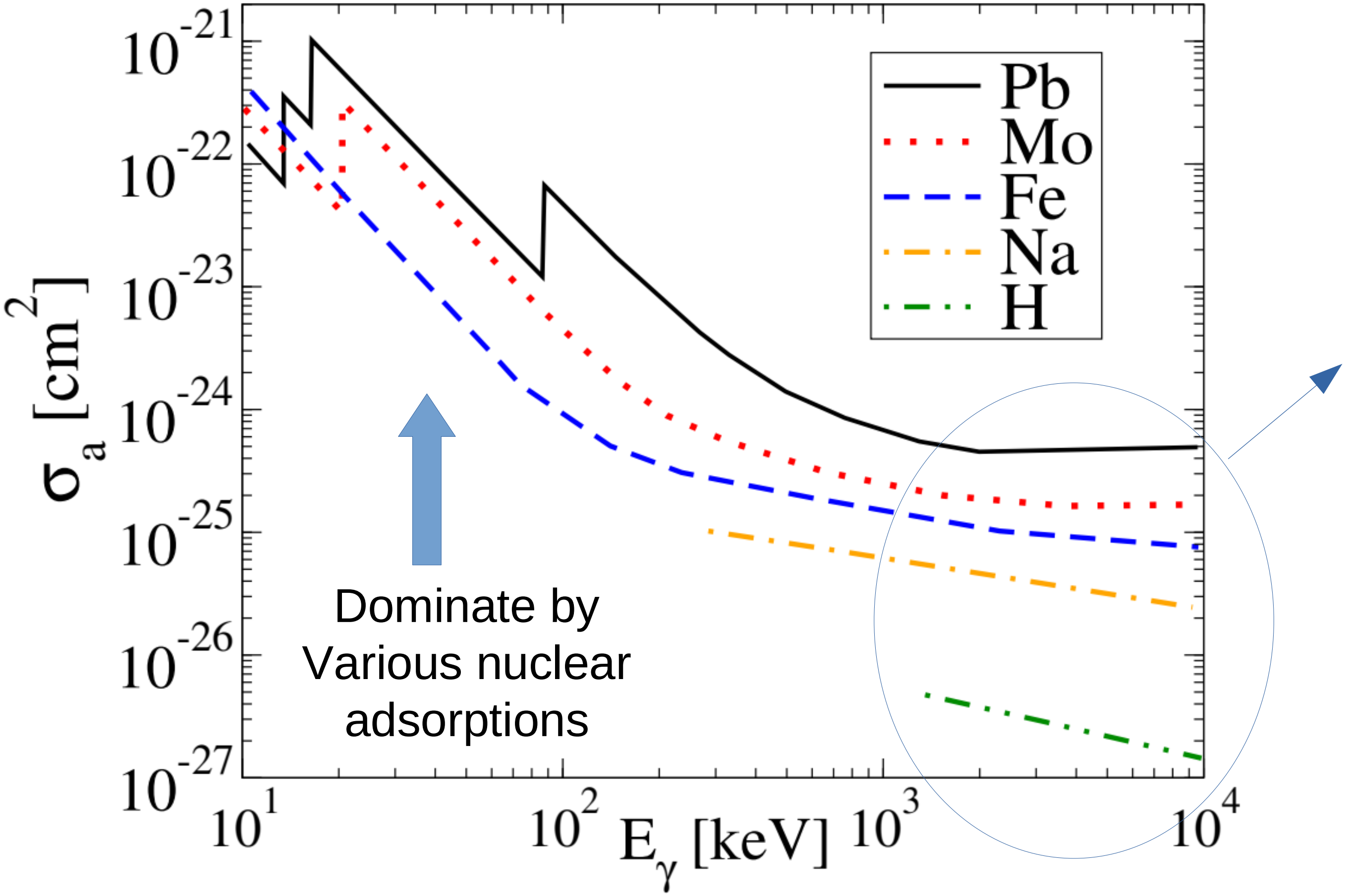
For nPA, the combinatorial enhancement kicks in.

As demonstrated before, via (laser-matter interaction)+(supplied ω), one could manipulate isomers with a large effective cross section (via nPA), even when **B** is very small.

This provide a way to **circumvent** “graser dilemma” .

Detail 1

Requirement of minimum effective cross section
=> mainly from photon-removal effects



e^-e^+ pair production after Eγ ≳ 1 MeV, because electrons and positions interacting with the electric fields produced by the nucleus

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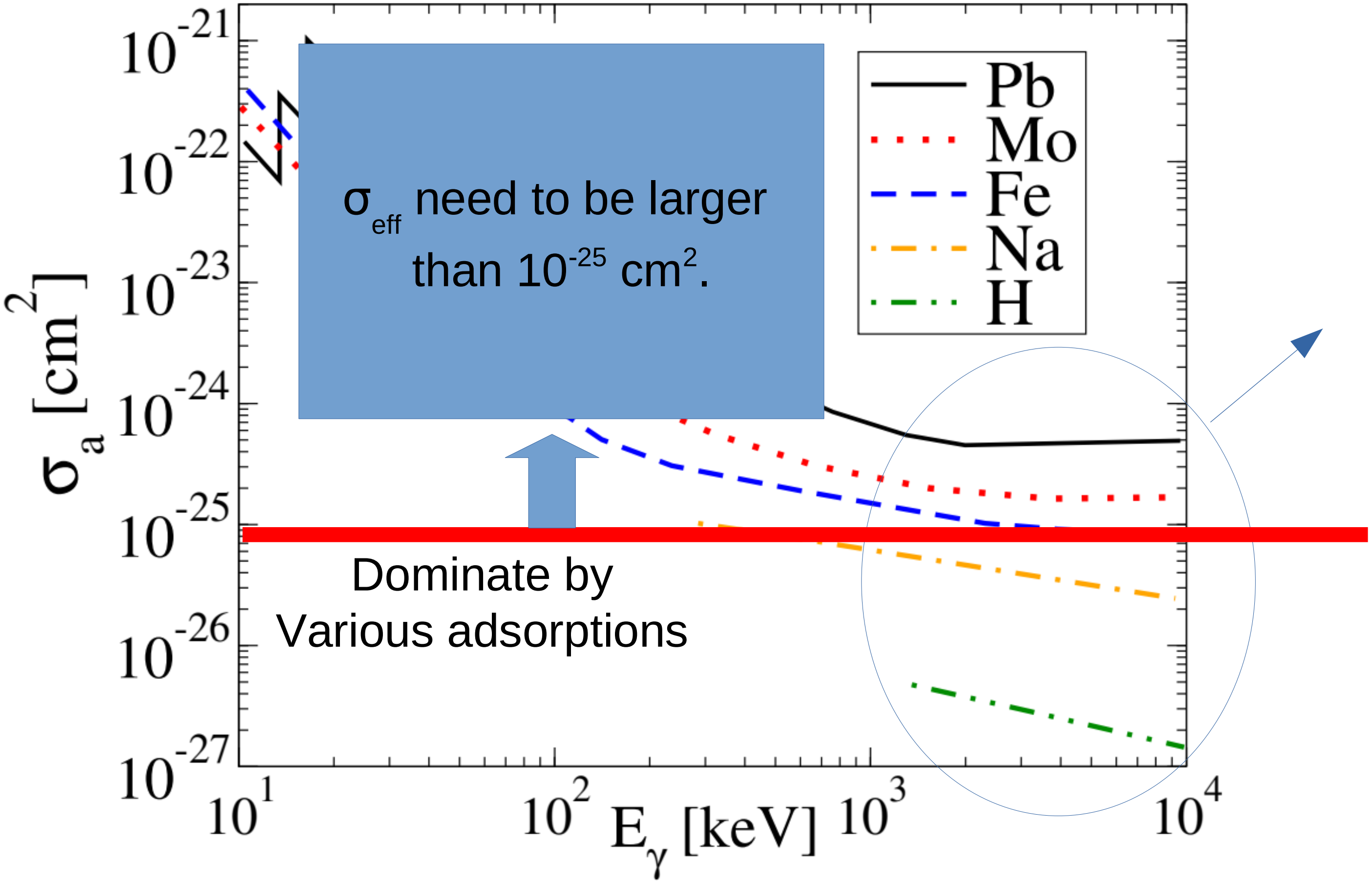

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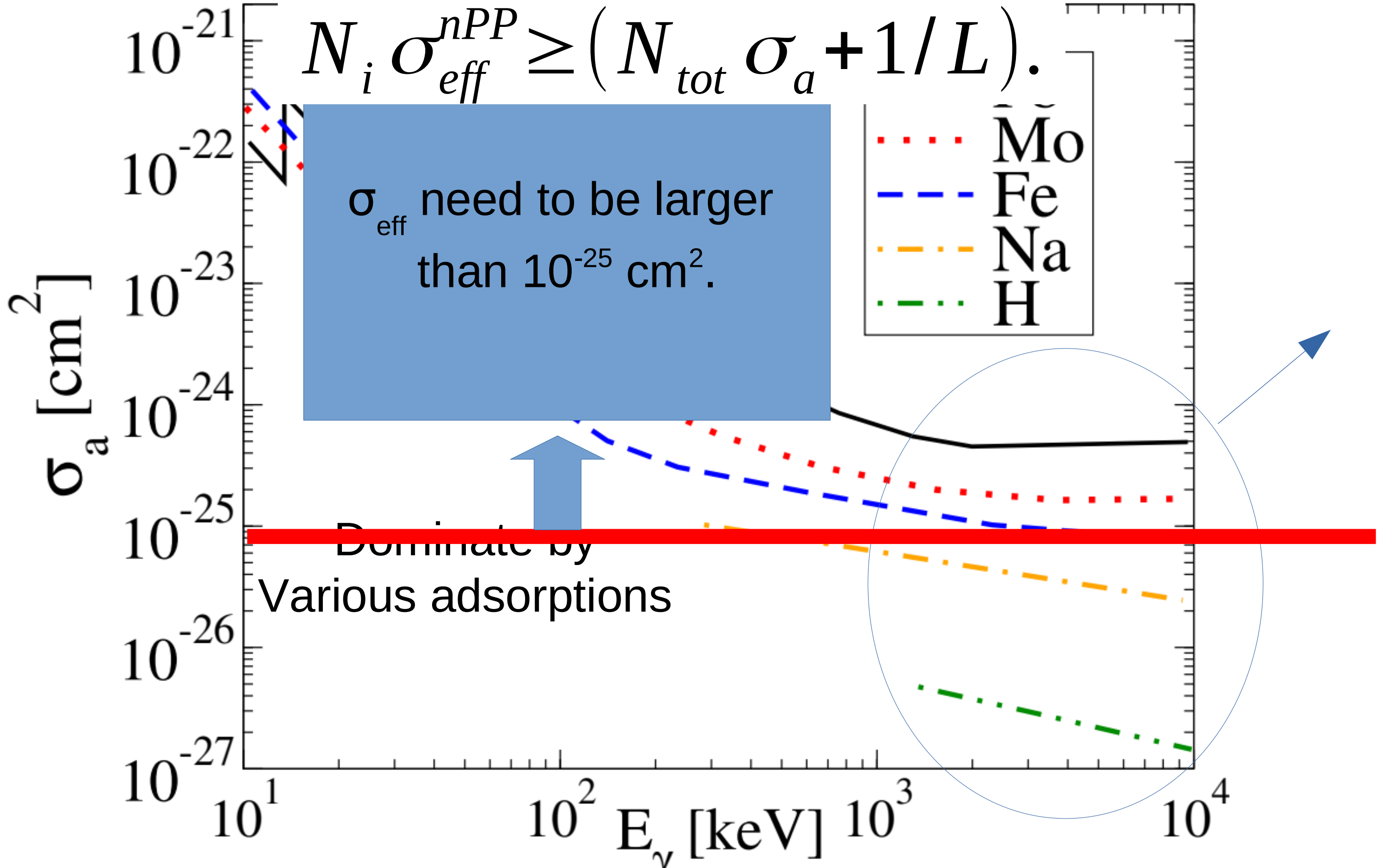
$$N_i \, \sigma_{eff}^{nPP} \geq \left(N_{tot} \, \sigma_a + 1/L \right).$$



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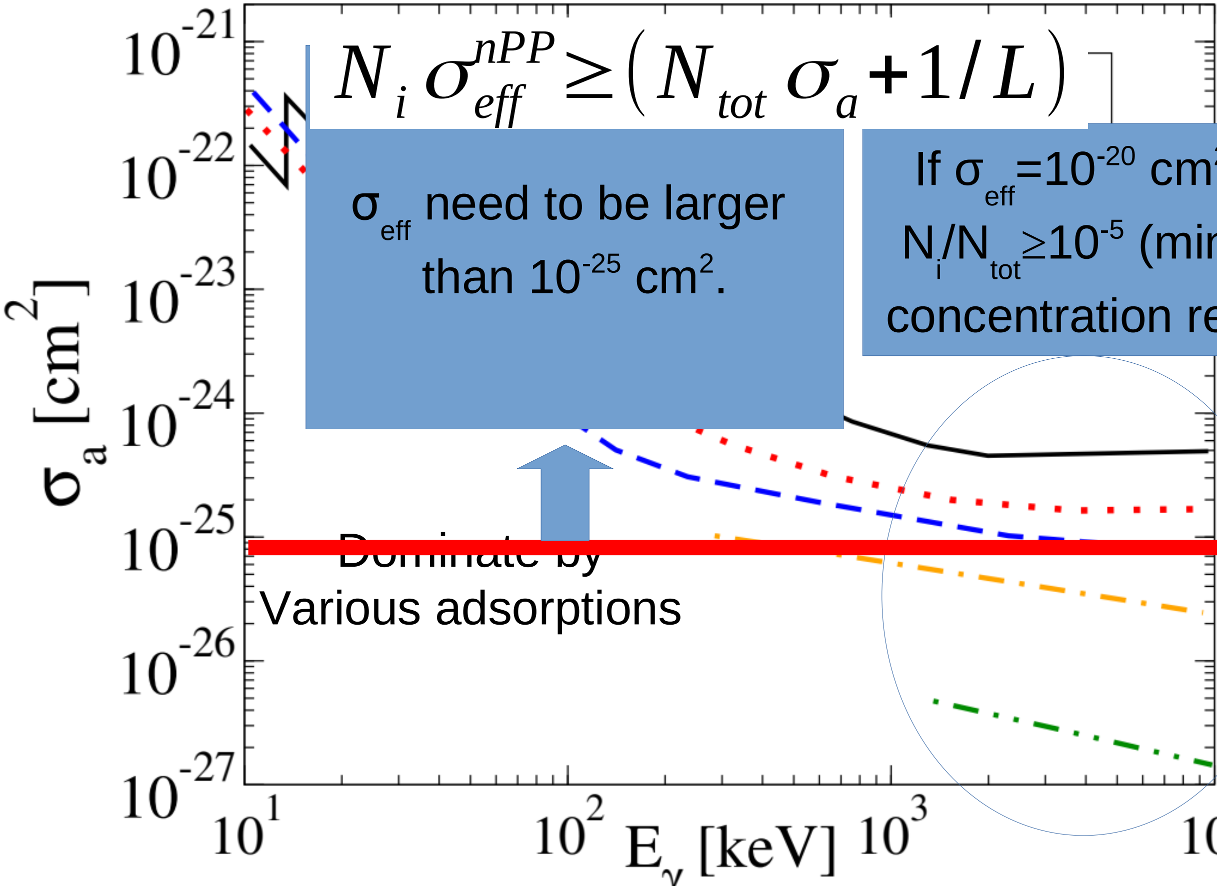
σ_{eff} need to be larger than 10^{-25} cm^2.

If $\sigma_{eff}=10^{-20}$ cm^2, then $N_i/N_{tot} \geq 10^{-5}$ (minimum concentration required)



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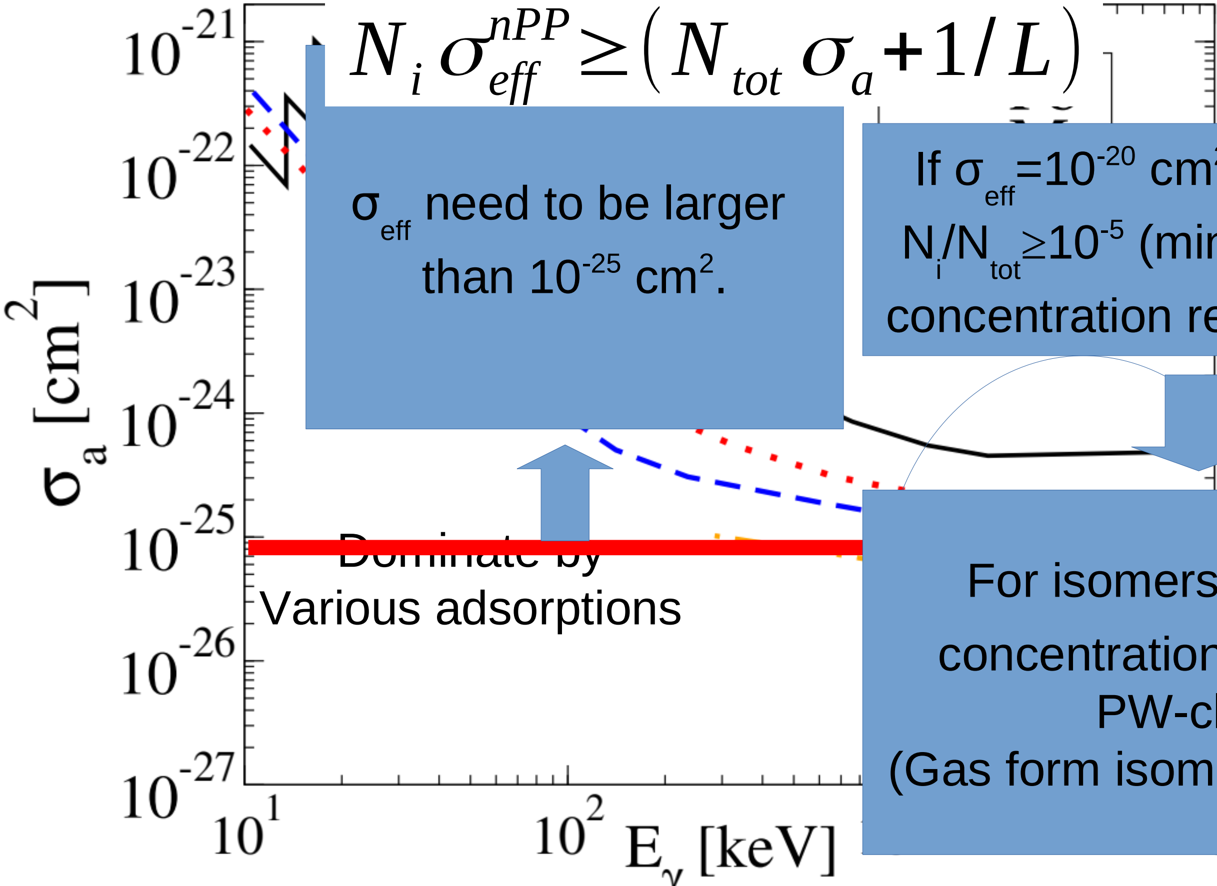

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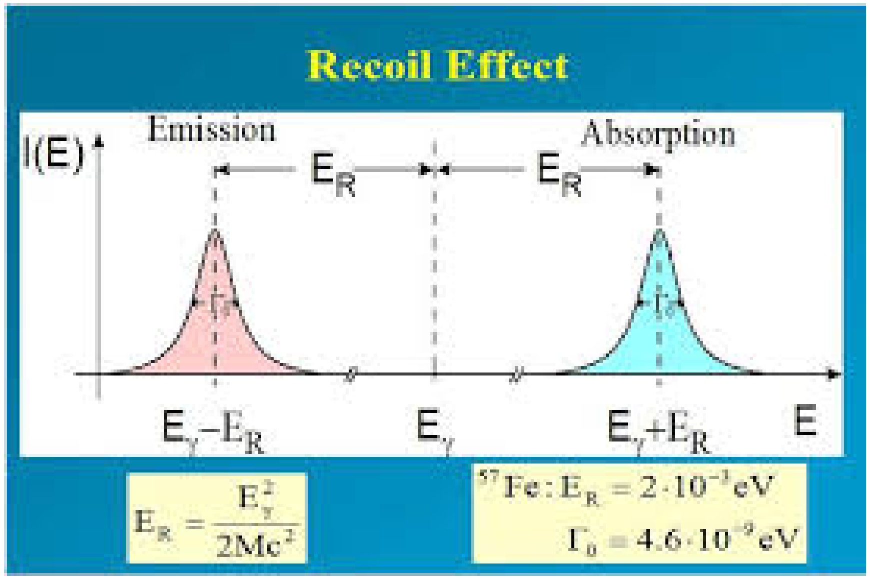
e^-e^+ pair production after Eγ ≳ 1 MeV, because electrons and positions

For isomers with $t_{1/2}$>30 days, this concentration could be reached in a PW-class HPLS site.
(Gas form isomers could be even better!)

Recoil: problem and solution

https://kanchiuniv.ac.in/coursematerials/Mossbauer%20Spectroscopy.pdf



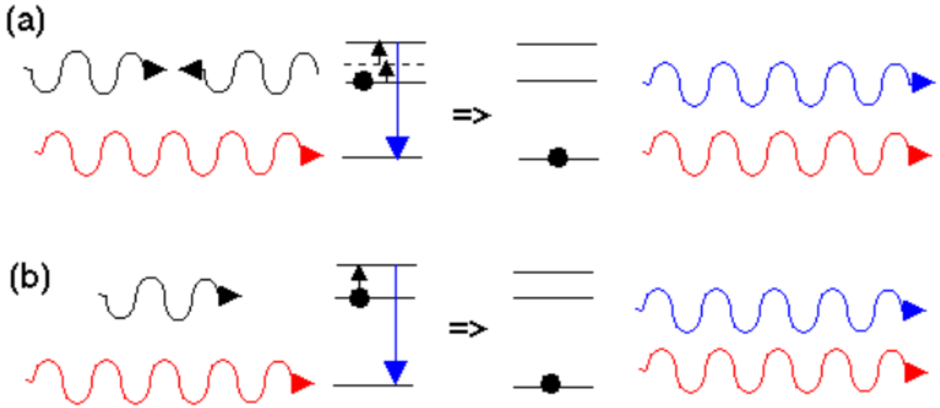
For γ>1 MeV, the stimulated process could loss (up to 5 eV in energy) >> (width of the lasing state≤10^{-3} eV)

⇩

This then kill the amplification process.

The supplied ω-photons plus its beam-width cover & compensate for the recoil loss.

2 ways:



This means:

No longer restricted to Mossbauer states

Broadening of the narrow absorption line breadth: problems and solutions

Natural width: $\Gamma_\gamma = \frac{\ln(2)\hbar}{t_{1/2}}, for\ t_{1/2} = 10\,s, \Gamma_\gamma = 3.7 * 10^{-17}\,eV.$

For non-Mossbauer nuclei, the natural width will be broaden by the "Doppler breadth", i.e.,

$$\Gamma \approx \Gamma_D \approx \frac{3.3}{\hbar}\sqrt{R_{loss} k_B \theta} \approx 0.3\,eV\ (for\ \theta = room\ temperature)$$

Bad news: 1 in 10^{16} chance for γ to meet another nucleus vibrate with suitable speed for the next stimulated emission!

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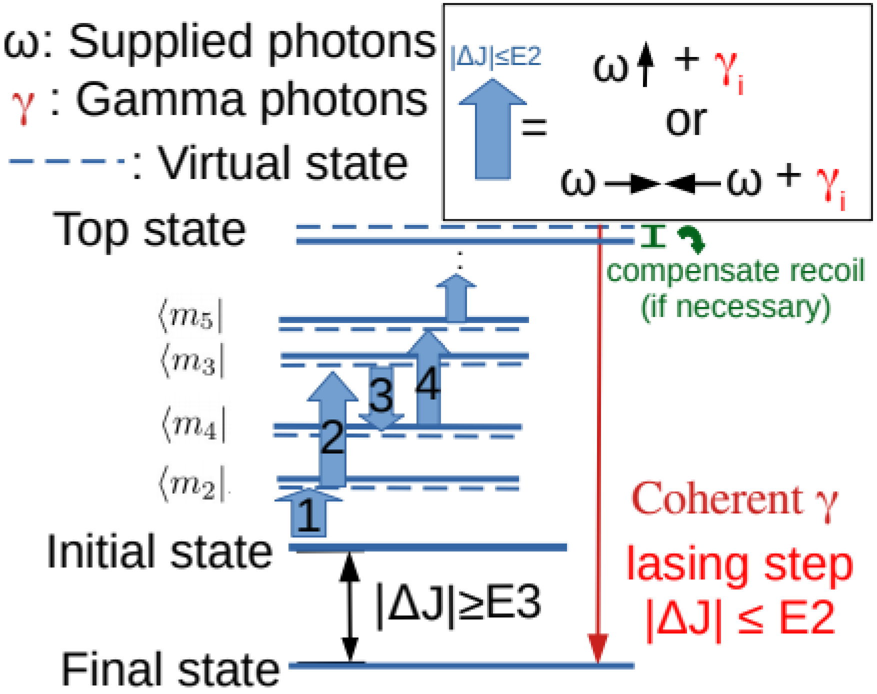
Solution: Have the supplied ω-photon come with beam band-width ≥ 0.3 eV. Then via nPA, this band-width is transferred to the graser band-width.

General scheme



C.-J. Yang, K. M. Spohr, D. Doria, arXiv:2404.10025 [physics.optics]

Summary

Beating Einstein's detail balance with combinatorial factor

=> exciting new emerging field, nuclear+laser-plasma community.

Exciting opportunity waiting us to explore !

Open issues/questions

1. Beam quality is crucial for non-linear effect, could it be 100 times better?

2. Instead of γ, if we could do the same for proton and/or neutron, it would be even more interesting (probe 3NF directly). Any trick?

3. Gas or liquid target seems very attractive, is there practical limitation on them?

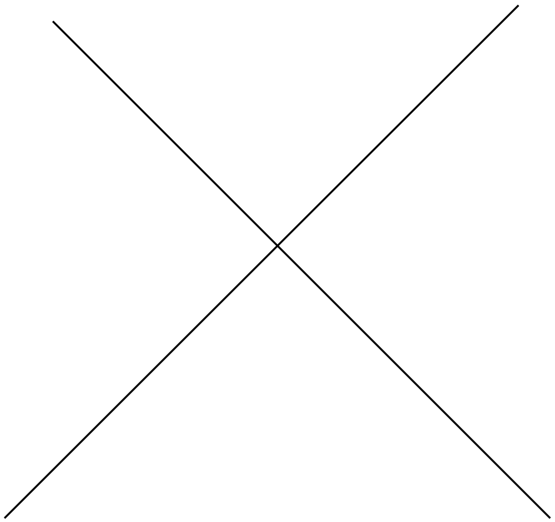
4. THz photon (i.e., $E \sim 10^{-3}$ eV) will improve the resonance of nPA a lot, any idea on generating them with $>10^{12}$ W/cm^2?

Thank you!

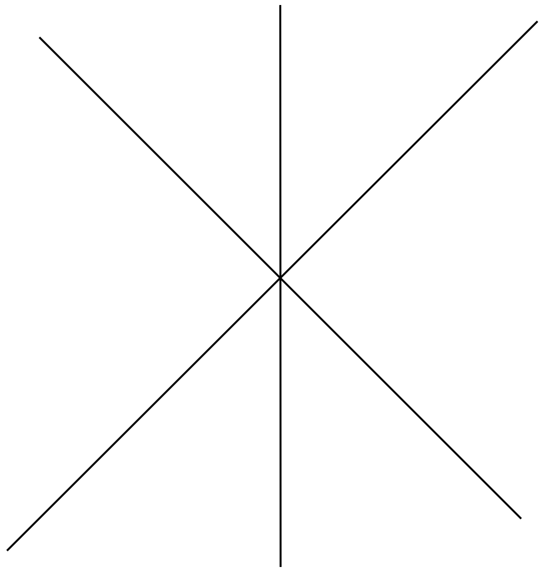
Many-body forces (e.g. NNN, NNNN, etc.)

- Higher-body forces, as long as allowed by relevant symmetries, exist in effective Lagrangian.
- Some of many-body couplings are genuine and unknown, i.e., cannot be derived from NN couplings.
- But their importance can be estimated by NDA.

Naïve dimensional analysis (NDA)



2 nucleon force



3 nucleon force

$$\text{3NFs/2NFs} \approx \frac{N^{+}N}{f_{\pi}^{2} M_{hi}} \approx \frac{\rho_0}{93^2 \cdot 500} \approx 0.28$$

Thus, 3^{+}-body forces are less important, which means they should appear later, i.e., accompanied with higher-order (next-to-next-to leading) 2nfs.

However, there are something very important missing…

If in the future, intense enough p/n beams come up, then
it would be extremely exciting!
=> A direct probe of 3NF.

Discussion

1. Trade off b/w E and I in laser-plasma part
2. 2NF v.s. 3NF
3. Note that already at the QED, I^2 case, if one does not know the 2PA mechanism but just interpret the yields by I*(cross section), then one will conclude that there must be a density-dependence in the 2-body force. In other words, at the intense-regime, higher-body effects are indistinguishable to intrinsic* n-body forces
4. Under field theory and standard model, it appears that everything can be described (or at least self-consistent) until Planck scale, though the intensive-limit has not really been probed as much as the High-E case experimentally

“A choose n” enhancements

$$C_n^A = \frac{A(A-1)(A-2)\ldots(A-n+1)}{n!}$$

- In a self-bound system, the above enhancement won’t be fully counted. For example, an n-body subset will have nearly zero contribution if its constituents span a distance much larger than the range of the n-body forces.→ density saturates, not $\to\infty$.

- On the other hand, those small contributions could still add up to become sizable, due to the fact that there are many of them.

- Thus, the growth of n-body forces in large systems depends on multiple factors such as the **range** and the **form** of interactions, the mass of particles, etc., ➔ **Require ab-initio calculations to know the PC.**