ECT* Workshop “Nuclear Physics under the low-energy, high intensity frontier”

Messages from the organizers

- Please feel free to present ***whatever*** ideas you have. We don’t want *perfect* presentation, we want discussion.

- Don’t have to “***think through***” it in all aspects, practicability verification will be the task of discussion sections (end of each day).

- To theorists: we encourage insights/inspirations/suggestions:

  New, but immature ideas >> boring calculations/results

  don’t be afraid to think/propose something new!

- To experimentalists: We also want ideas regarding future prospects if possible.

What opportunity can HPLS bring to nuclear and particle theory?

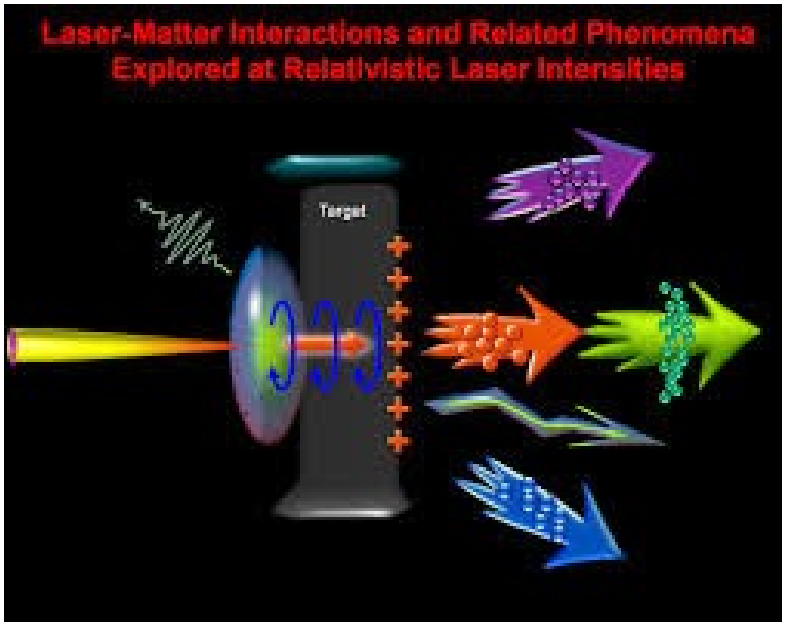
ECT* Workshop “Nuclear Physics under the low-energy, high intensity frontier”

Chieh-Jen (Jerry) Yang

August 10, 2026



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



https://www.icuil.org/

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

10~50 fs 3~100 μm

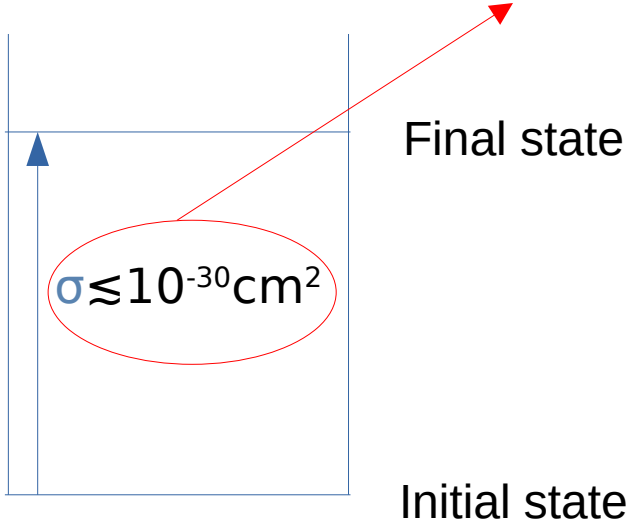
Motivations I

(from a practical aspect)

One main **obstruction** for femto-technology/nuclear photonics

Question: σ for the required transition is too small, what can we do?

e.g.,



Conventional solution for rare events:
Just shot with more γ (continuously), but it's inefficient...

Is there other ways?

If one follows strictly the diagram specified in the previous page

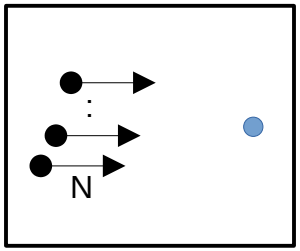


No, because the cross section (or the probability) of a given transition is a constant.

(these are solid math, cannot do anything about it.)

However, there are **more than 1 way** to achieve a given transition.

Quantum events



Each ● can take **more than** 1● => a strike difference w.r.t. classical cases

$$\text{Yield} \propto N\cdot\sigma_1 + N(N-1)\cdot\sigma_2 + N^3\cdot\sigma_3 + \ldots$$

The leading term (under low N) is linear

Non-linearity ⇒ N choose 2 N choose 3

Reasons:

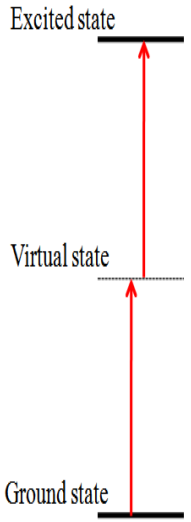
1. Could have **intrinsic 3^+-body** forces.
2. Even without 3^+-body forces, **uncertainty principle** still permits more-to-one to occur.

This has consequences under the **intense-limit**

More is different P.W. Anderson

2 Photon absorption (2PA)

https://www.youtube.com/watch?v=Uxc5H5Ui1n0



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

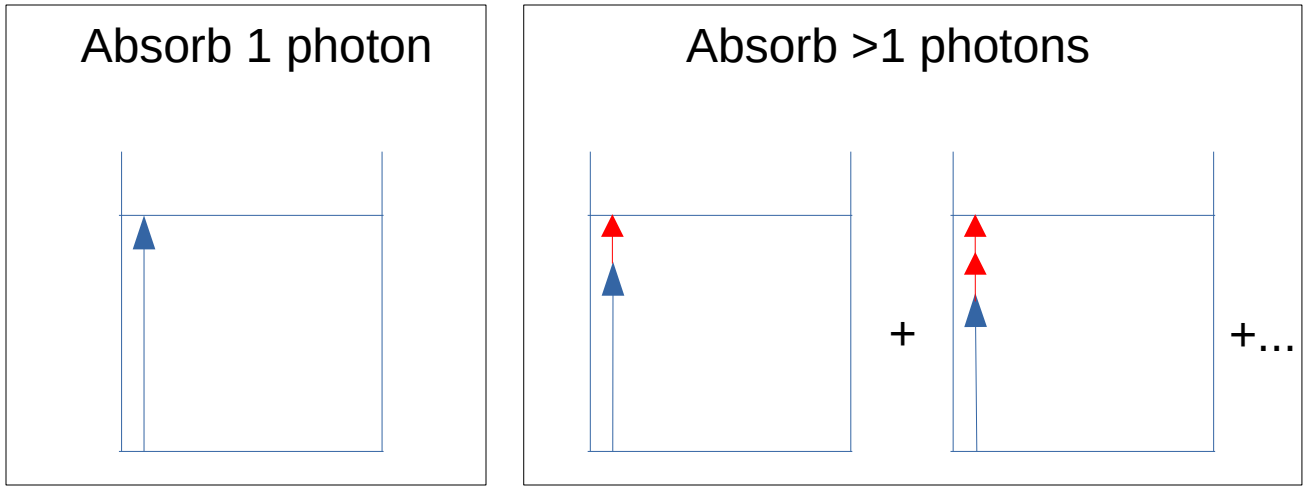
2PA first observed in atomic/molecule cases 1961.

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 grows with I^2.

Single- v.s. multiple-processes

E.g.,



linear

non-linear

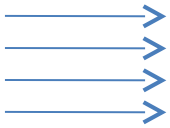
Physical meaning of non-linearity:

With the same incoming I, the number of trials $\sim I$ for 1PA, $\sim I^2$ for 2PA, etc.

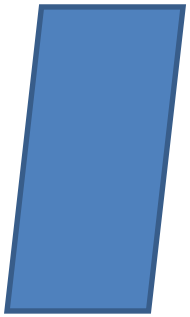
This is simply due to a combinatorial argument.

If each nucleus only takes 1 photon

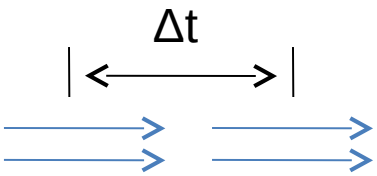
N: number density

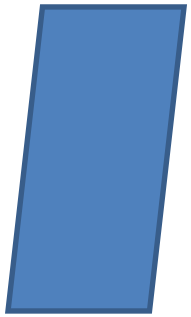


N possible way of scattering



=



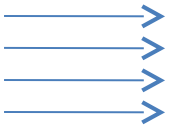


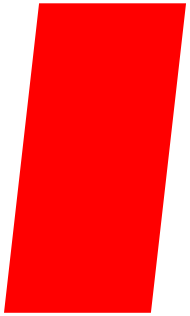
If Δt ≤ decay time

If each nucleus takes 2 photons

Choose by pairs

12
13
14
:
23
:

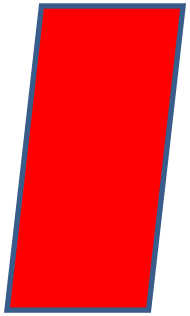




If Δt ≤ transition time

=





N*(N-1) ~N² possible way of scattering

Question:
Can 2PA (which comes with smaller transition probability) dominates over 1PA?

Yields v.s. probability

Observation of a rare-event

$(\text{Yield}_{\text{rare}}) \propto$ (more # of trials)*(smaller probability)
$\equiv T_A$

$(\text{Yield}_{\text{normal}}) \propto$ (less # of trials)*(larger probability)
$\equiv T_B$

If want $\text{Yield}_{\text{rare}} \gtrsim \text{Yield}_{\text{normal}}$ (i.e., to promote rare events), then the (# of trials) must be different => $T_A \gg T_B$

How to achieve $T_A \gg T_B$ efficiently to probe rare events?

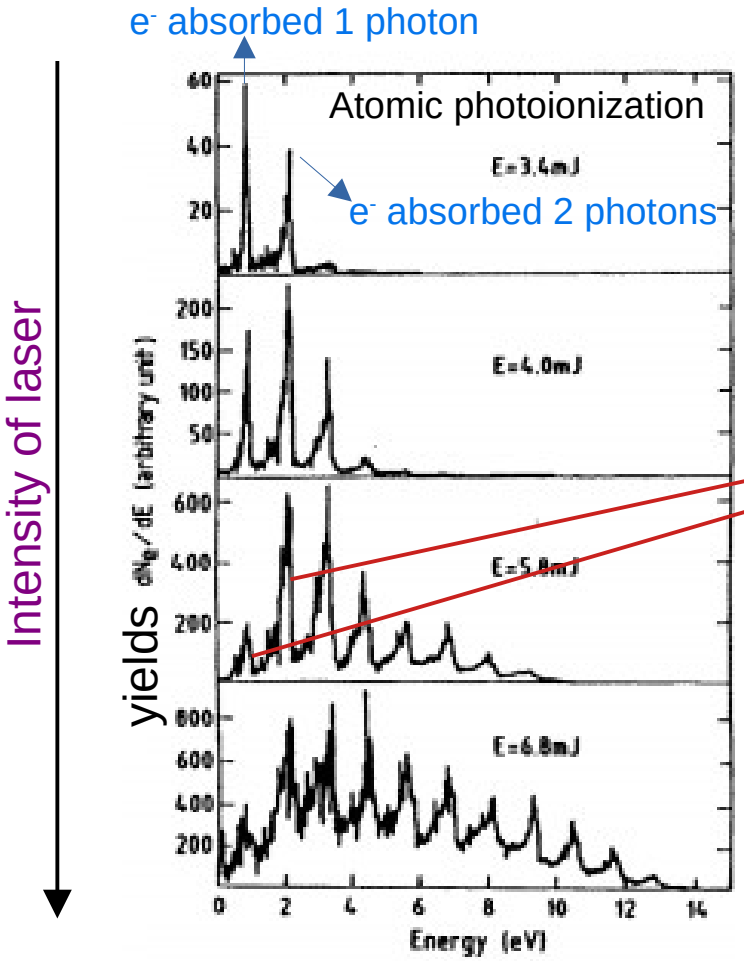


By increasing I, so that: $I^2 * \sigma^{2PA} >> I * \sigma^{1PA}$

Experimental evidence

of yields from nPA >> (n-1)PA

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



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

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

$I^2 * \sigma^{2PA} \gg I * \sigma^{1PA}$

(occurs when $I \gg \sigma^{1PA}/\sigma^{2PA}$) → fixed number

Achieved via lasers with $P \equiv I E_\omega \approx 10^{12\text{-}13}$ W/cm^2

Fundamental reason

(more # of trials)*(smaller probability)

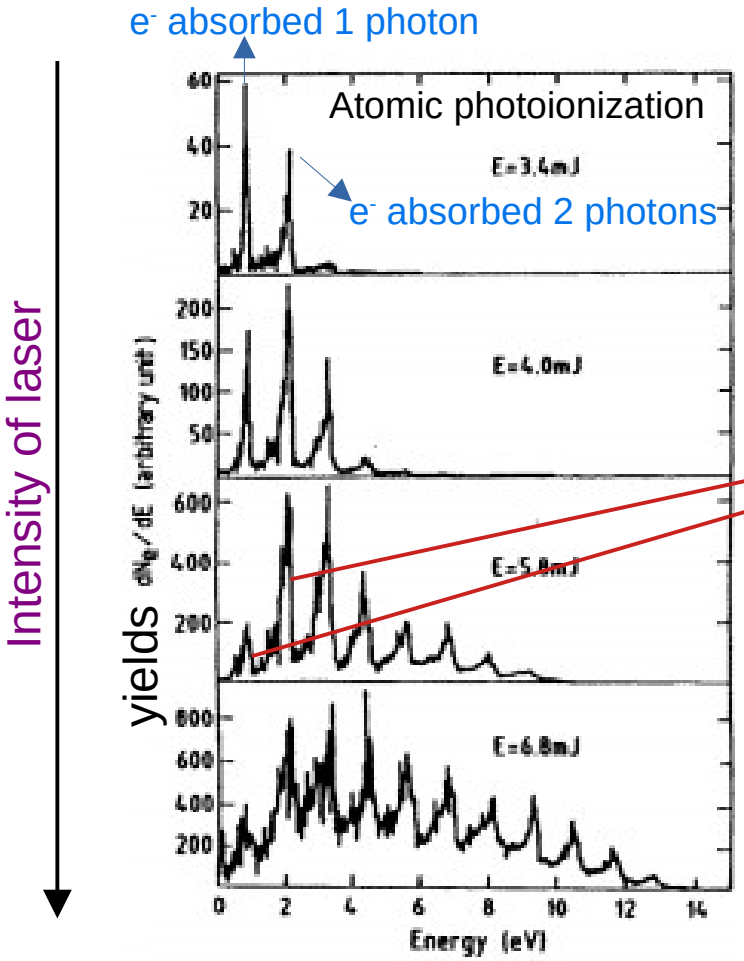
⩡

(less # of trials)*(larger probability)

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

Under intense limit:
# of trials ≠ total incident particles
(it's much greater than that!)

Fundamental reason

(more # of trials)*(smaller probability)
⩛
(less # of trials)*(larger probability)

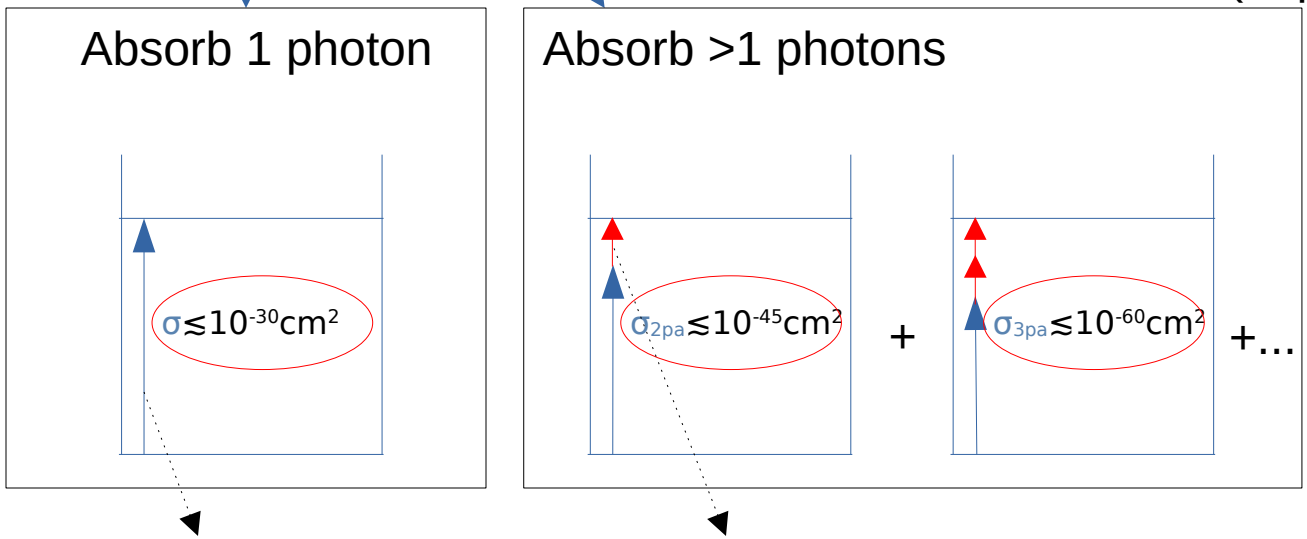
Nuclear case: 1PA v.s. nPA

γ+ω scheme (inhomogeneous 2PA)

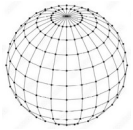
Yield per dz in the target

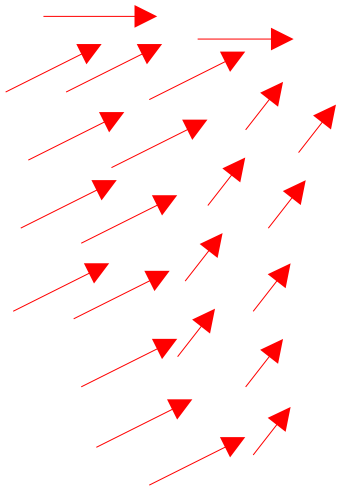
$$\frac{dY_{all}}{dz} = \frac{d(Y_{1pa} + Y_{2pa} + ... + Y_{npa} + ...)}{dz} = N \cdot (I_1\sigma_{1pa} + I_1 I_2 \sigma_{2pa} + ... + I_1 I_2 \cdot ... \cdot I_n \sigma_{npa} + \text{more})$$

Fixed value (dep. on nuclear structure)

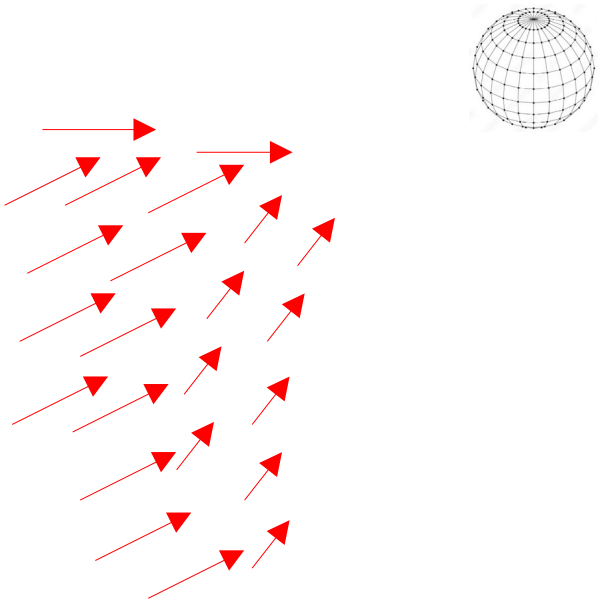


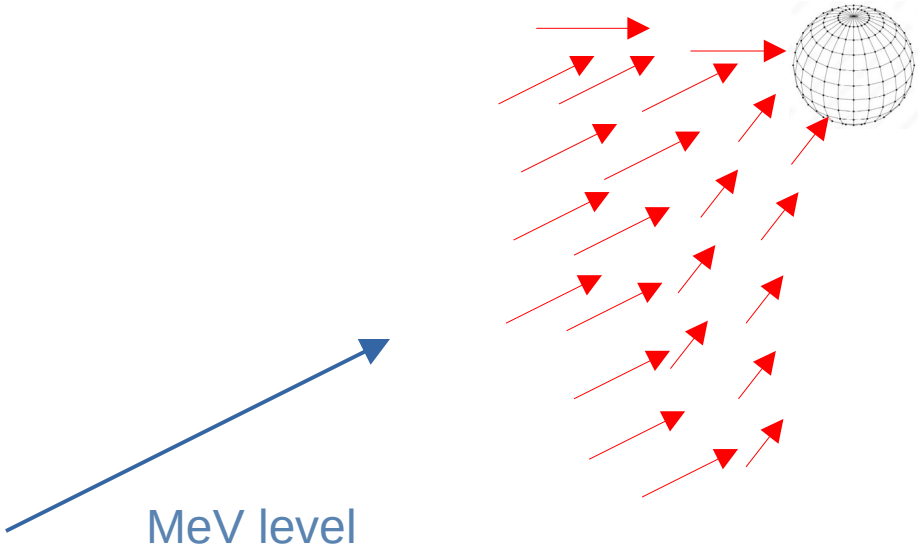
Thus, at the ***intensity regime (I_i>>1)***, one must have: $Yield_{nPA}$>>$Yield_{1PA}$.



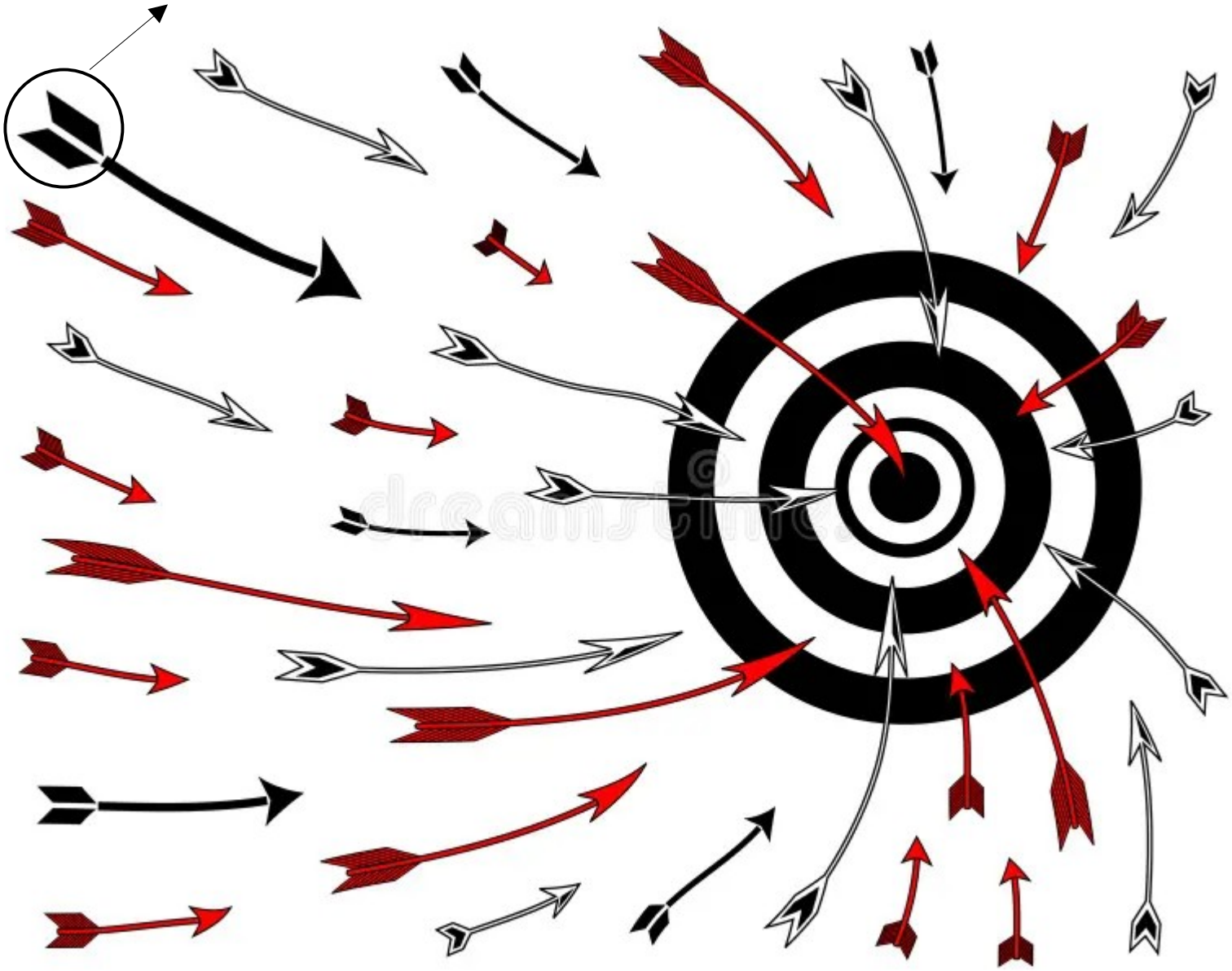


eV level



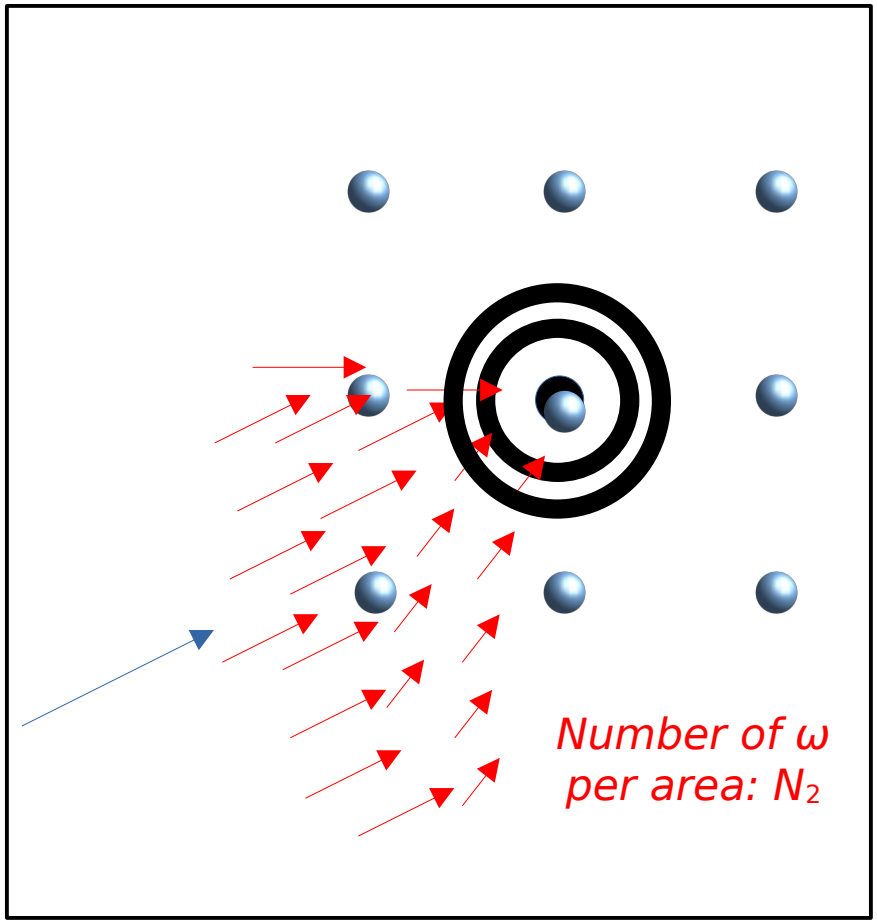

MeV level

Each end serves as a new target for the γ-photon to combine with!

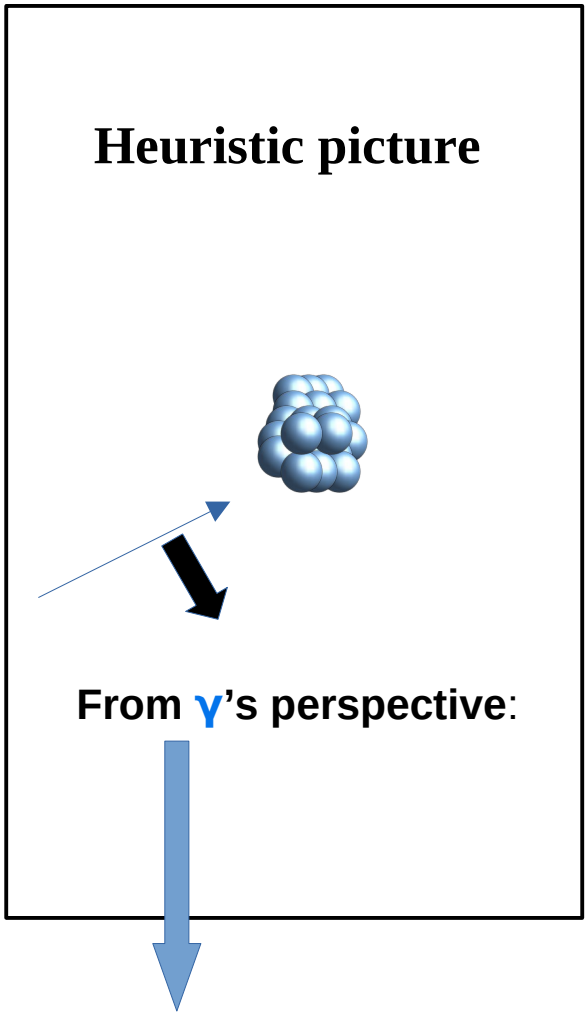


Copyright: Maigi | Dreamstime.com

Or, alternatively:

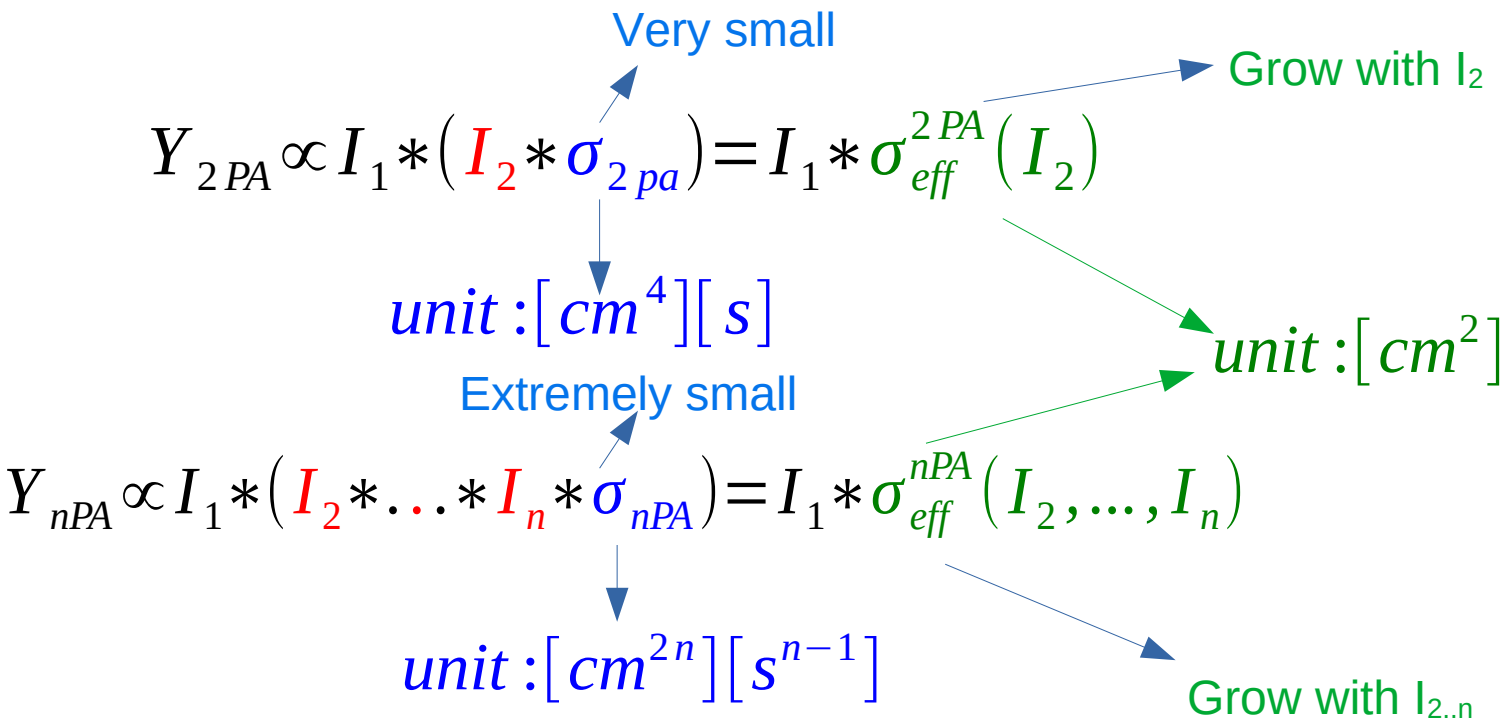


=
(can be seen as)



New number density of target$\propto(\sigma^{2PA})*N_2$*number density of nuclei

Mathematical formulation



Intensity is the curial thing!
(absolute total number are important, but not that crucial).



This is exactly what HPLS provides

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

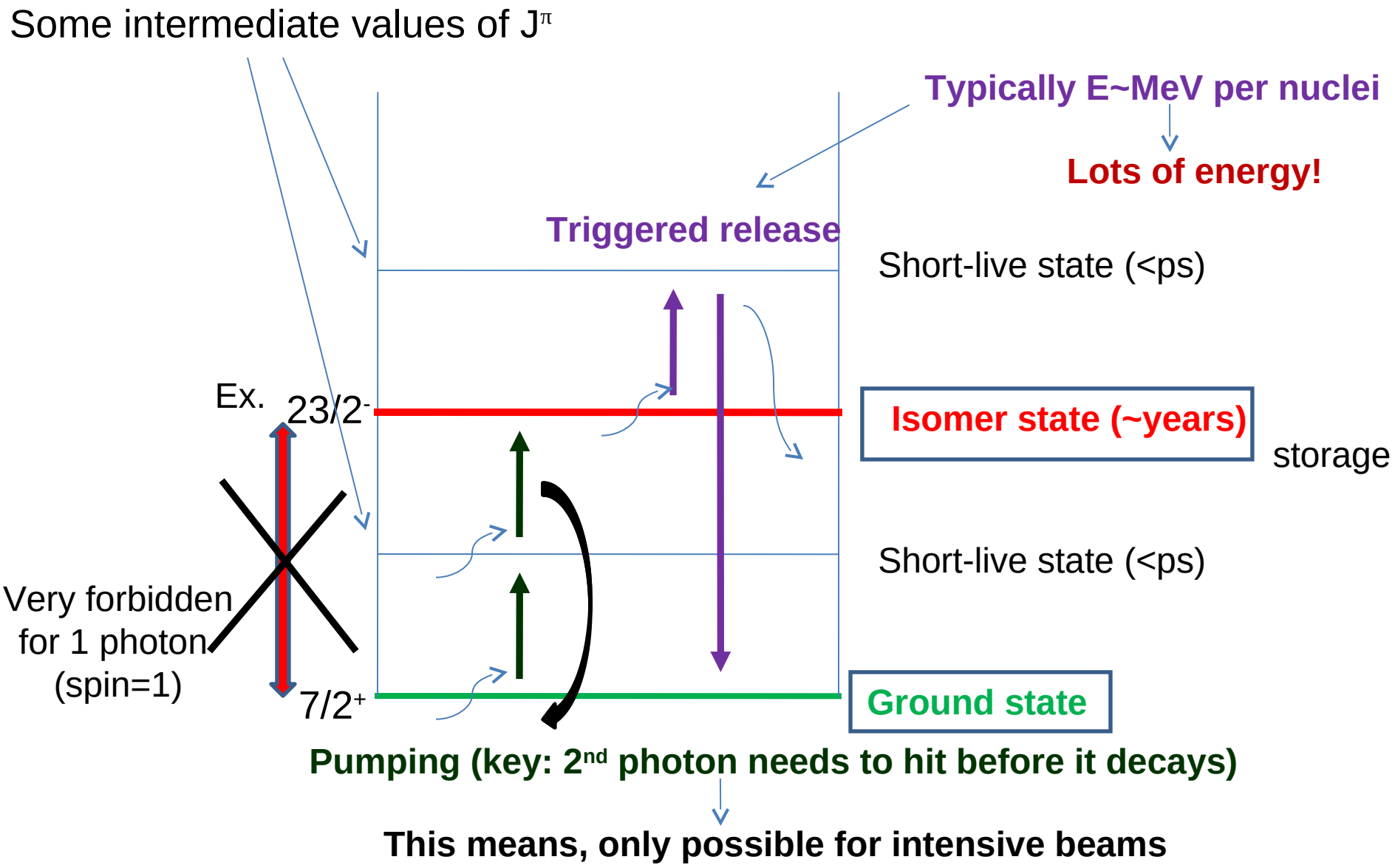
This is unique for us (not for traditional accelerators).

Application & experimental ideas

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.

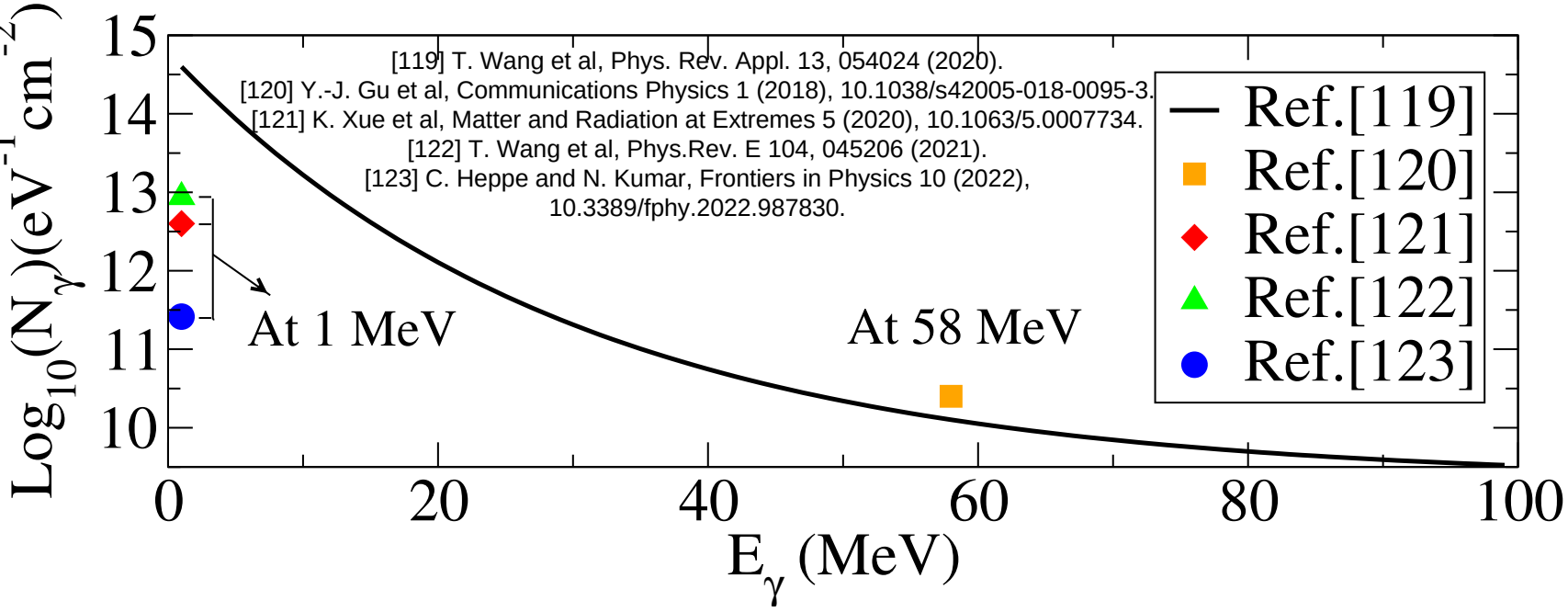

Some intermediate values of Jπ
Typically E~MeV per nuclei
Lots of energy!
Triggered release
Short-live state (<ps)
Ex. 23/2-
Isomer state (~years)
storage
Short-live state (<ps)
Very forbidden
for 1 photon
(spin=1)
7/2+
Ground state
Pumping (key: 2nd photon needs to hit before it decays)
This means,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

2PA solely from a γ-flash

So far not observed. ∵Lack of intense enough γ beam

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

Could HPLS + laser-matter interaction provide that?

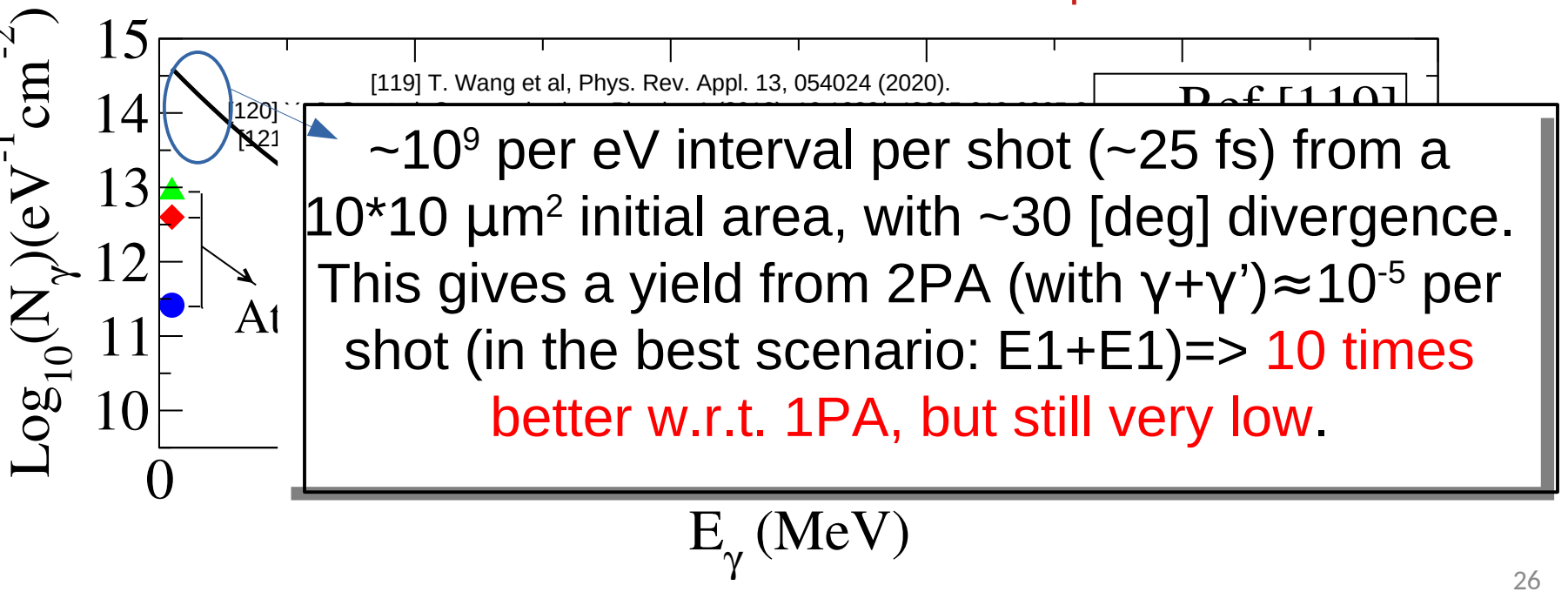


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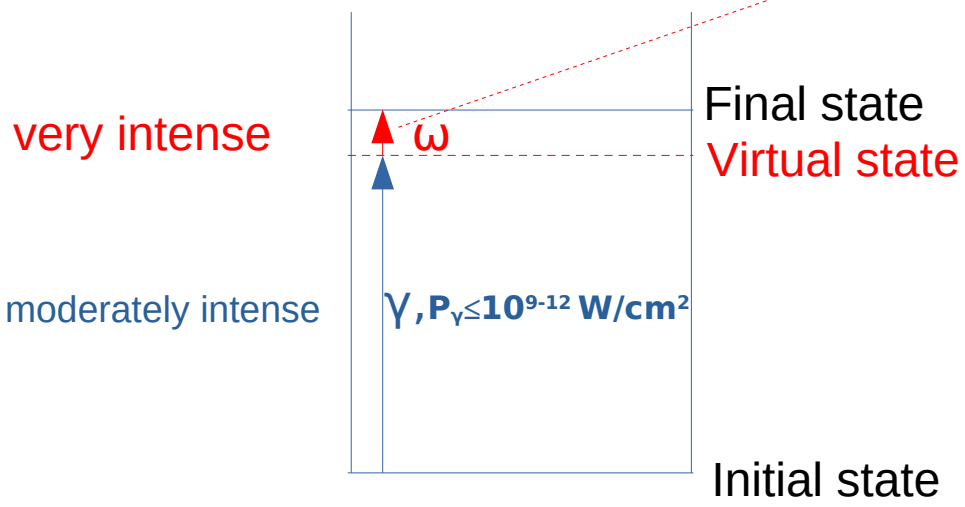


~10^9 per eV interval per shot (~25 fs) from a 10*10 μm² initial area, with ~30 [deg] divergence. This gives a yield from 2PA (with γ+γ')≈10^{-5} per shot (in the best scenario: E1+E1)=> 10 times better w.r.t. 1PA, but still very low.

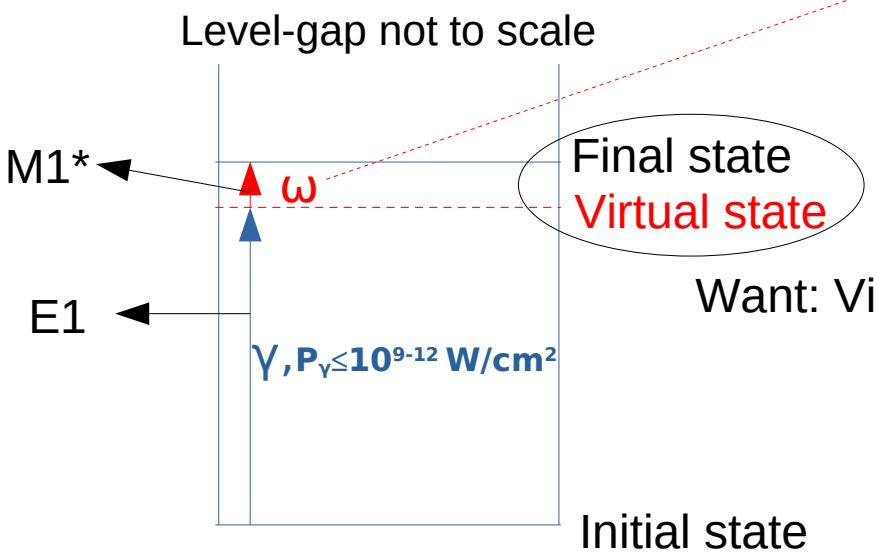
γ+ω scheme (inhomogeneous 2PA)

C.-J. Yang, K. M. Spohr, M.Cernaianu, D. Doria, P. Ghenuche, V. Horny, Matter Radiat.Extremes 10 (2025) 5, 057201

- 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).



- 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).



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

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.

THz source would be excellent!

Practical number (via Weisskopf estimate)

Effective cross section [unit: cm^2] feel by each γ.

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

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

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

If P_2=10^{10} W/cm^2, σ_{eff}≈10^{-26}~10^{-32} cm^2.

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~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^{-26}

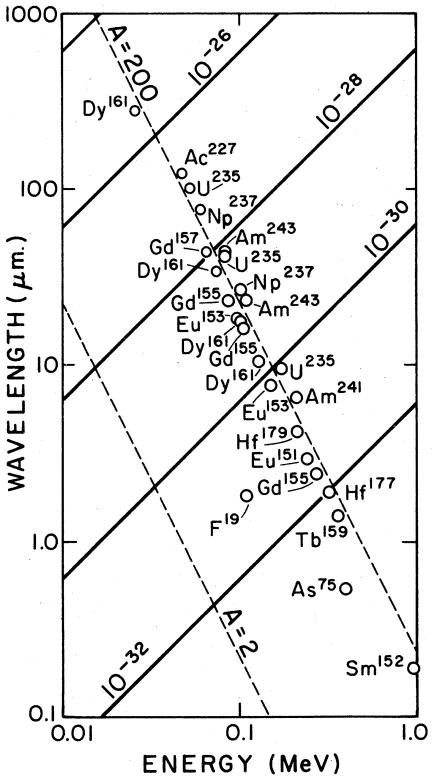


FIG. 1. Domains of the energies of γ radiations and of the wavelengths of laser photons compensating the recoils, associated with the nuclear emission and absorption of the γ photons induced by intense optical fields. Heavy lines locate parameter values at which the cross sections shown might be achieved 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.

Limitations in 1979 (or before PW-class lasers)

1. $E_\gamma + E_\omega$ has to match E_{gap} exactly (up to the width of |f⟩), but E_{gap} varies between states across nuclei.

2. ω-photons mostly need to resonate with |i⟩ or |f⟩ itself, this means that the virtual state will have the same J^π as the state to which it resonates. Thus the enhancing mechanism through 2PA can only be realized for |f⟩ separated from |i⟩ by at most E2.

Practical number (via Weisskopf estimate)

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If P_2=10^{10} W/cm^2, σ_{eff}≈10^{-26}~10^{-32} cm^2.

With HPLS we may have σ_{eff}≈10^{-21} cm^2

Moreover, E_γ spectrum is intense and continuous.

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~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.

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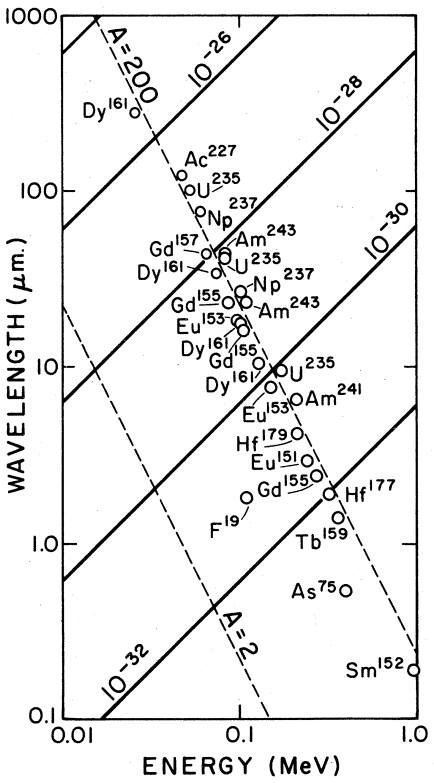
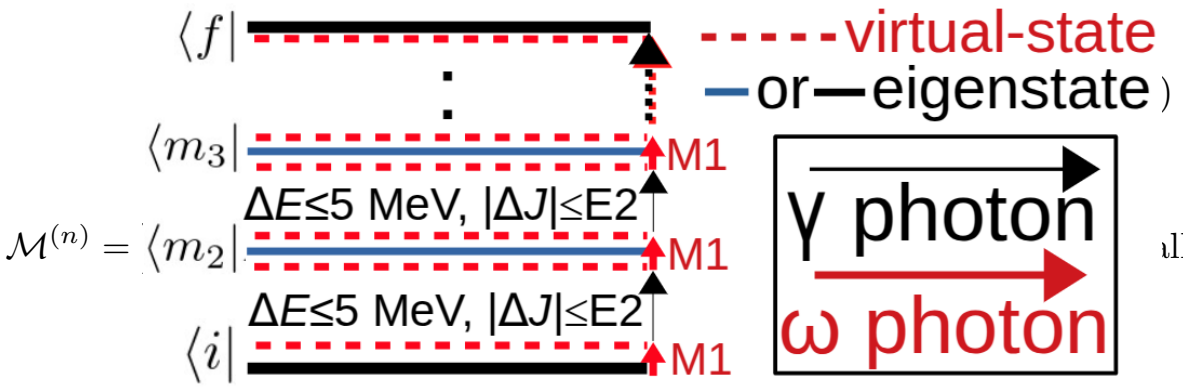


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nPA generalization:



$\mathcal{M}^{(n)} = \langle m_2|$ ... all permutation)

Practical number (via Weisskopf estimate)

Effective cross section [unit: cm^2] feel by each γ.

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

$\sigma_{eff}^{2pa,E1}$

$\sigma_{eff}^{2pa,M1}$

Improve with more refined nuclear structure Calculations (e.g., large-scale shell model) In progress...(thanks to ELI-RO/2024/AMAP)

If P_2=10^{10} W/cm^2, σ_{eff}≈10^{-26}~10^{-32} cm^2.

With HPLS we may have σ_{eff}≈10^{-21} cm^2

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ned by single-photon
polarity 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^{-26}

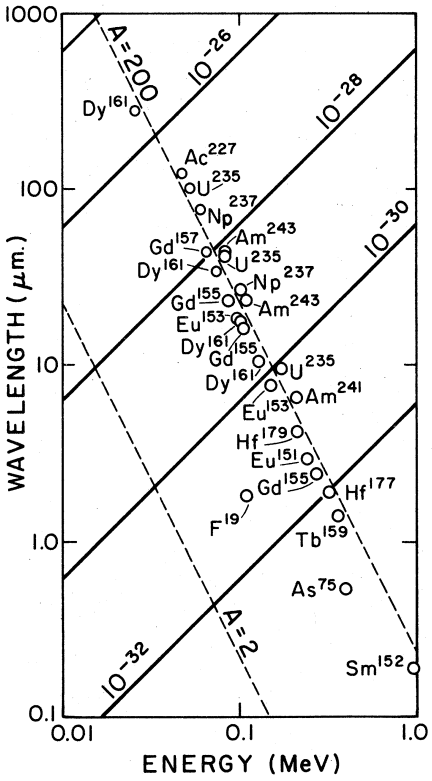
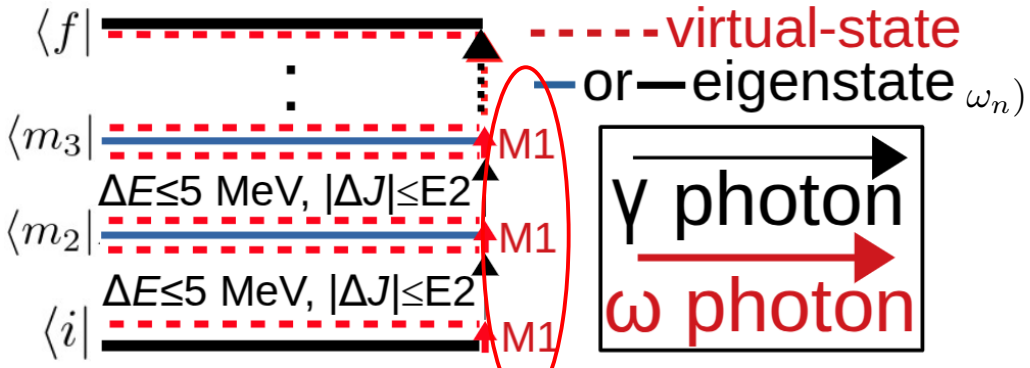


FIG. 1. Domains of the energies of γ radiations and of the wavelengths of laser photons compensating the recoils, associated with the nuclear emission and absorption of the γ photons induced by intense optical fields. Heavy lines locate parameter values at which the cross sections shown might be achieved 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

C.-J. Yang, et al, Matter Radiat. Extremes 10, 057201 (2025)



σ_{eff}≥10^{-25} cm^2 realizable for 4PA in a multi-PW site!

Practical number (via Weisskopf estimate)

Effective cross section [unit: cm^2] feel by each γ.

$\sigma_{eff}^{2pa,E1}$

$\sigma_{eff}^{2pa,M1}$

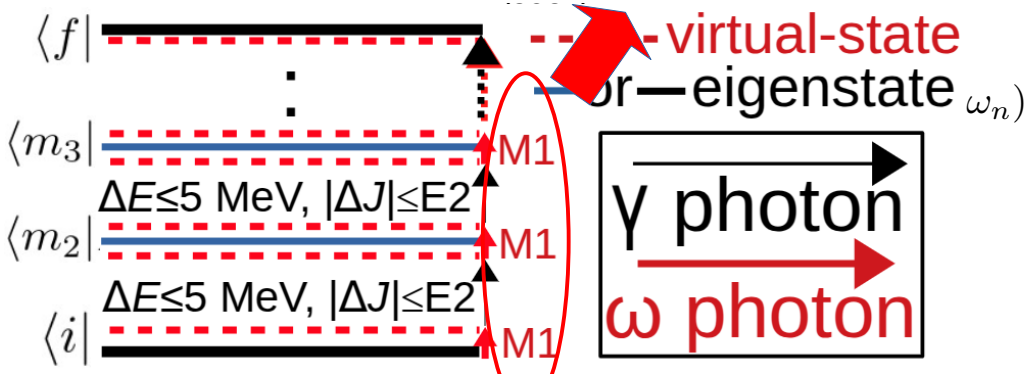
Improve with more refined nuclear structure Calculations (e.g., large-scale shell model) In progress...(thanks to ELI-RO/2024/AMAP)

If P_2=10^{10} W/cm^2, σ$_{ef}$

With HPLS we may h

Vortex ω photons are very desirable
(X10^2-10^3 per insertion, if tuned to maximize M1, instead of E1)
Will be investigated/provided by the experts in the team.
Experimental experts: D. Doria, M. Cernaianum
Theory expert: Y. Xu

C.-J. Yan



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

ctions calculated for
ed by the fields asso-
y of 10^{10} W/cm^2 by
g nearly degenerate
from each other by
1 MeV. The widths
e final state of the
ned by single-photon
polarity indicated.

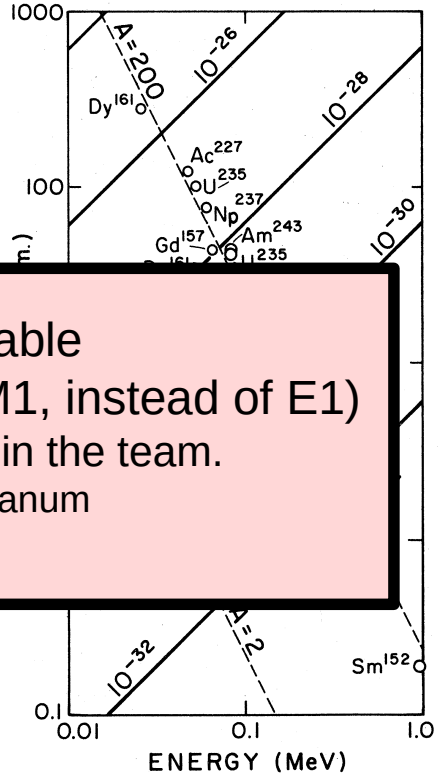


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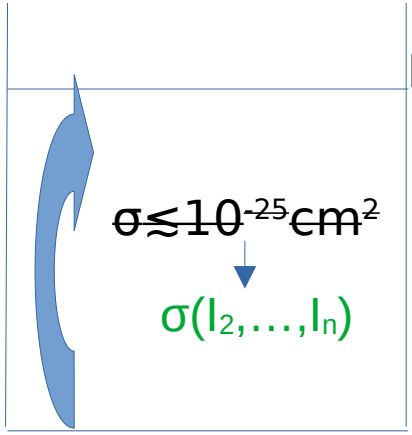
σ$_{eff}$≥10^{-25} cm^2 realizable for 4PA in a multi-PW site!

New opportunity

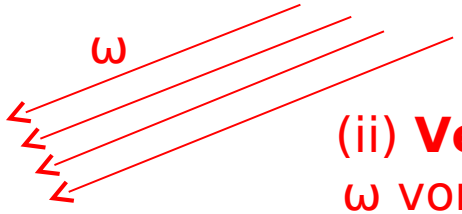
One main ~~obstruction~~ for femto-technology/nuclear photonics

σ for the required transition is too small, what can we do?

Tunable $\sigma(I_2,\ldots,I_n)$ through nPA enhanced by **HPLS**



(i) Intense γ-photon via HPLS-matter interaction



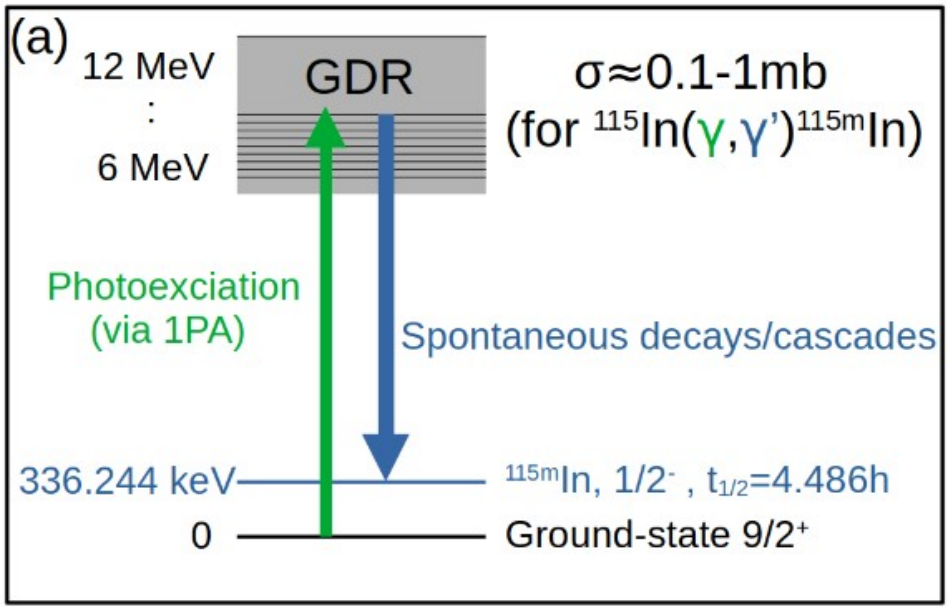
(ii) **Very intense** ω vortex photon (eV-level)

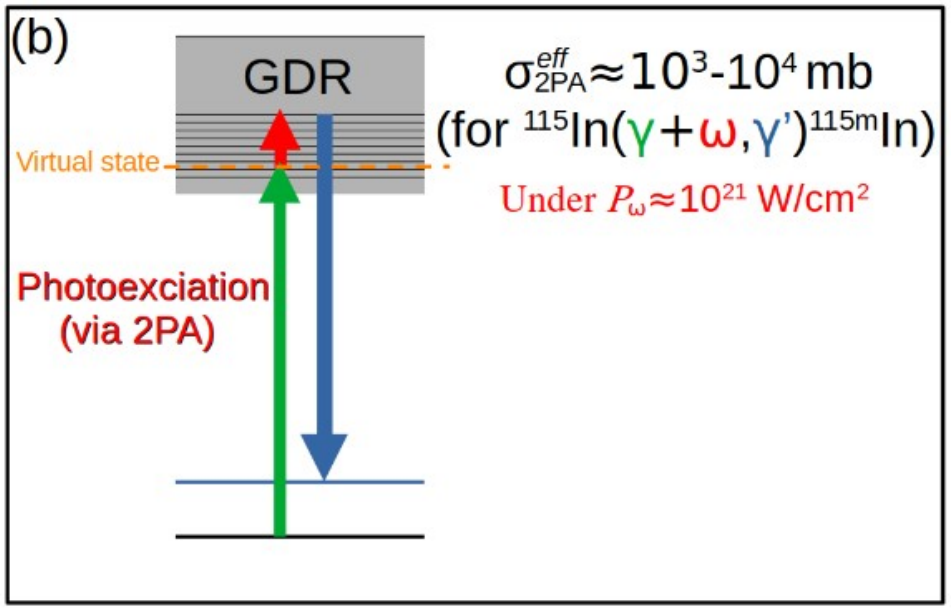
Nuclear photonics: This technique allows us to find some very hidden states also!

Easily missed in conventional exp. due to small σ

An experimental proposal

(^{115}In(γ,γ')^{115m}In v.s. ^{115}In(γ+ω,γ')^{115m}In)





C.-J. Yang K. M. Spohr P. Tomassini S. Balascuta, V. Horny, B. Maheshwari, P. Van Isacker, and P. M. Walker, in preparation.

Experimental design

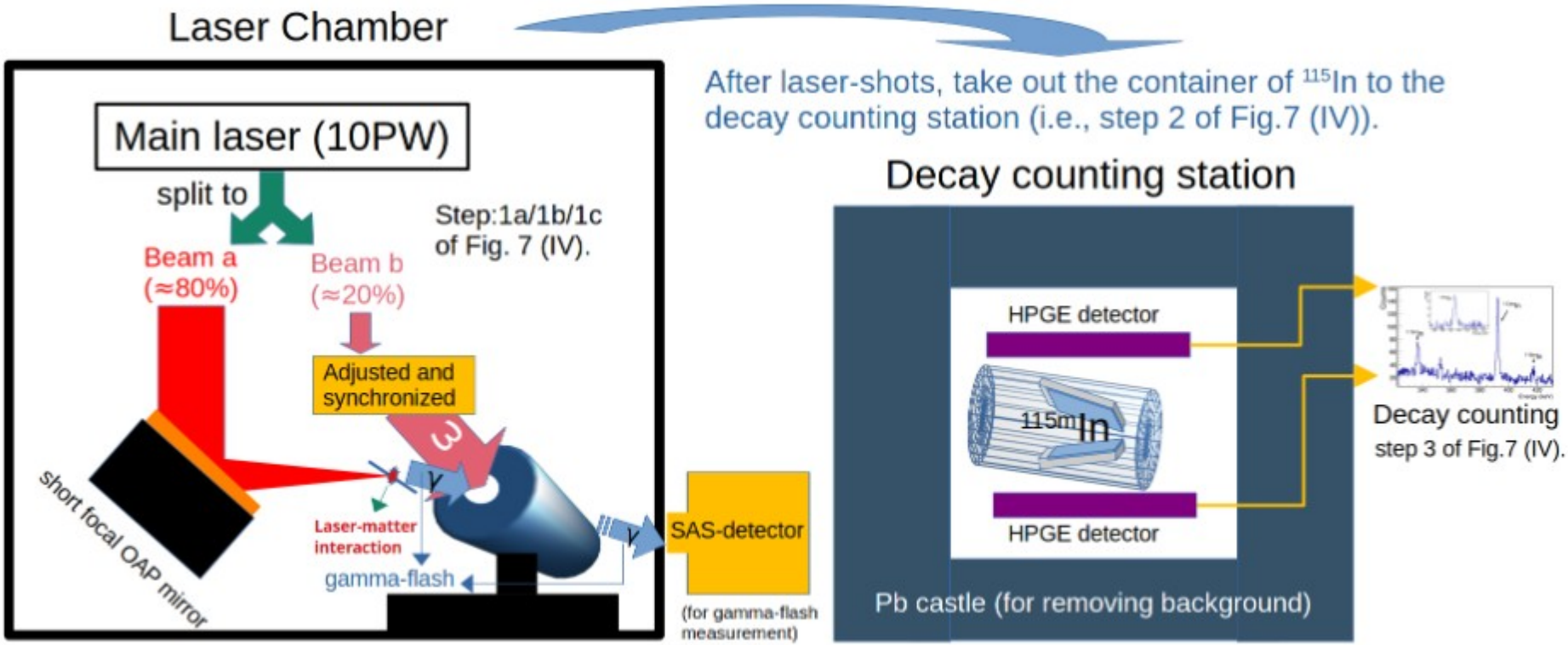
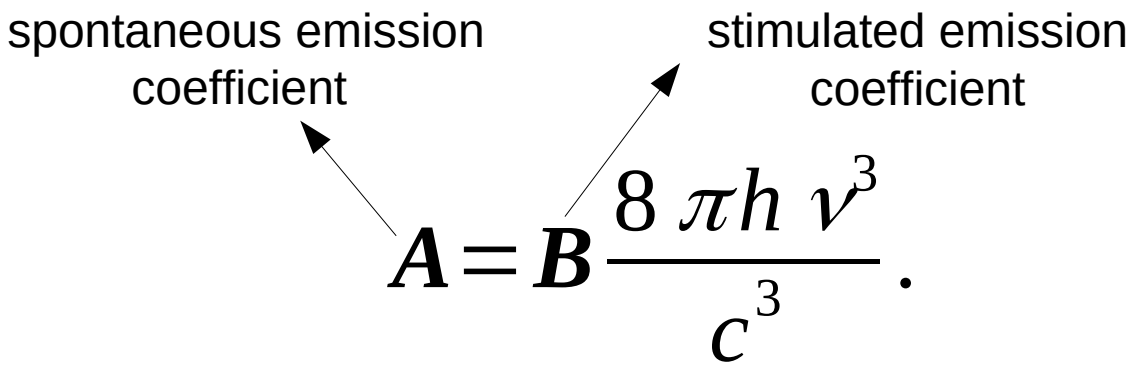


Figure 8. The drawing of the experimental layout.

Application II:
Nuclear gamma-ray laser (graser)

Beating Einstein's detail-balancing



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

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).

A grows quickly with (photon energy released)^3

In general, excited states releasing higher energy term 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

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

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

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

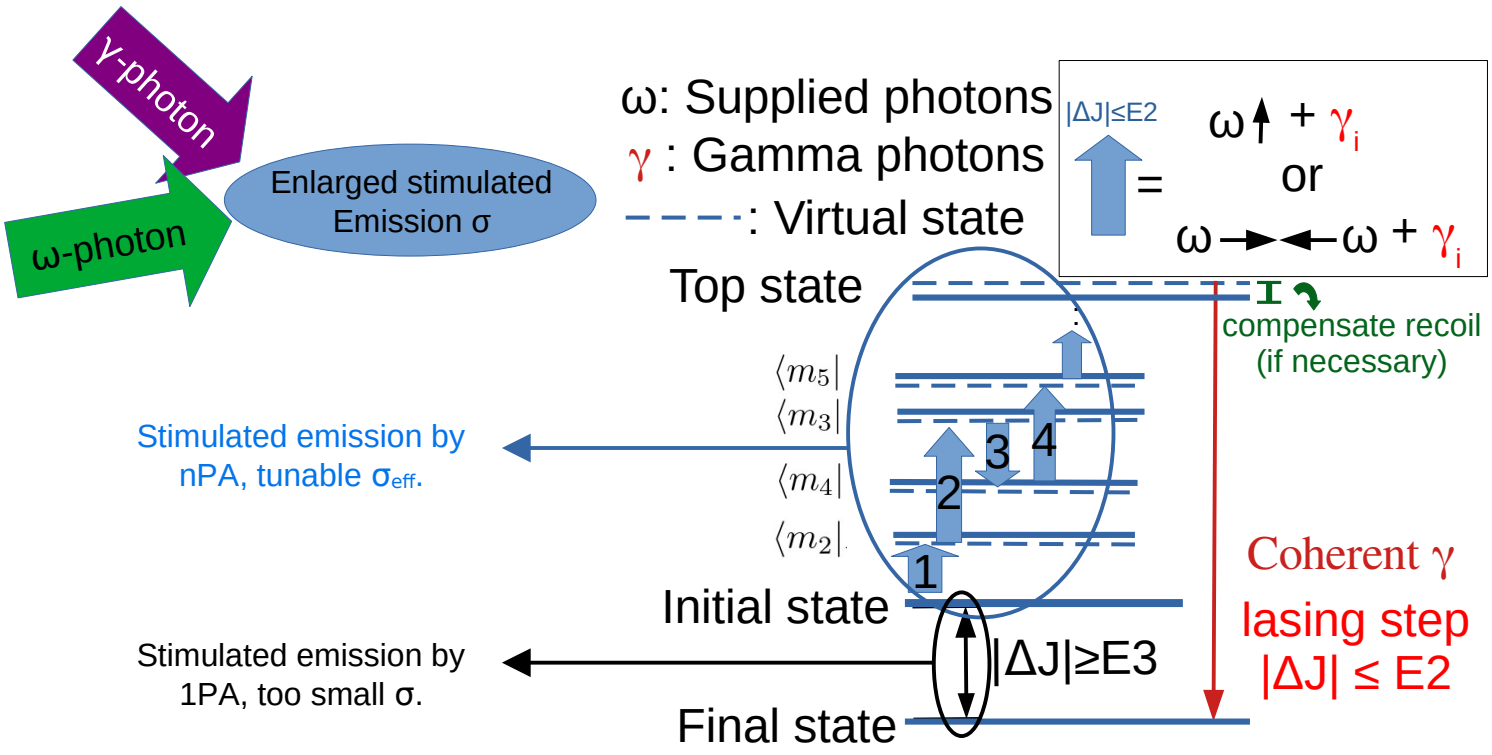
However, the derivation of the previous equation assumes yield is linear to I, and the stimulated emission ∈ 1PA.

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" .

General scheme



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

Application III:
A direct probe of three-Nucleon forces

Any physical problem

Need inputs: forces/interactions to start with.

Need to perform calculations/simulations for that system.

The Nuclear Force Problem: Is the Never-Ending Story Coming to an End?

R. Machleidt

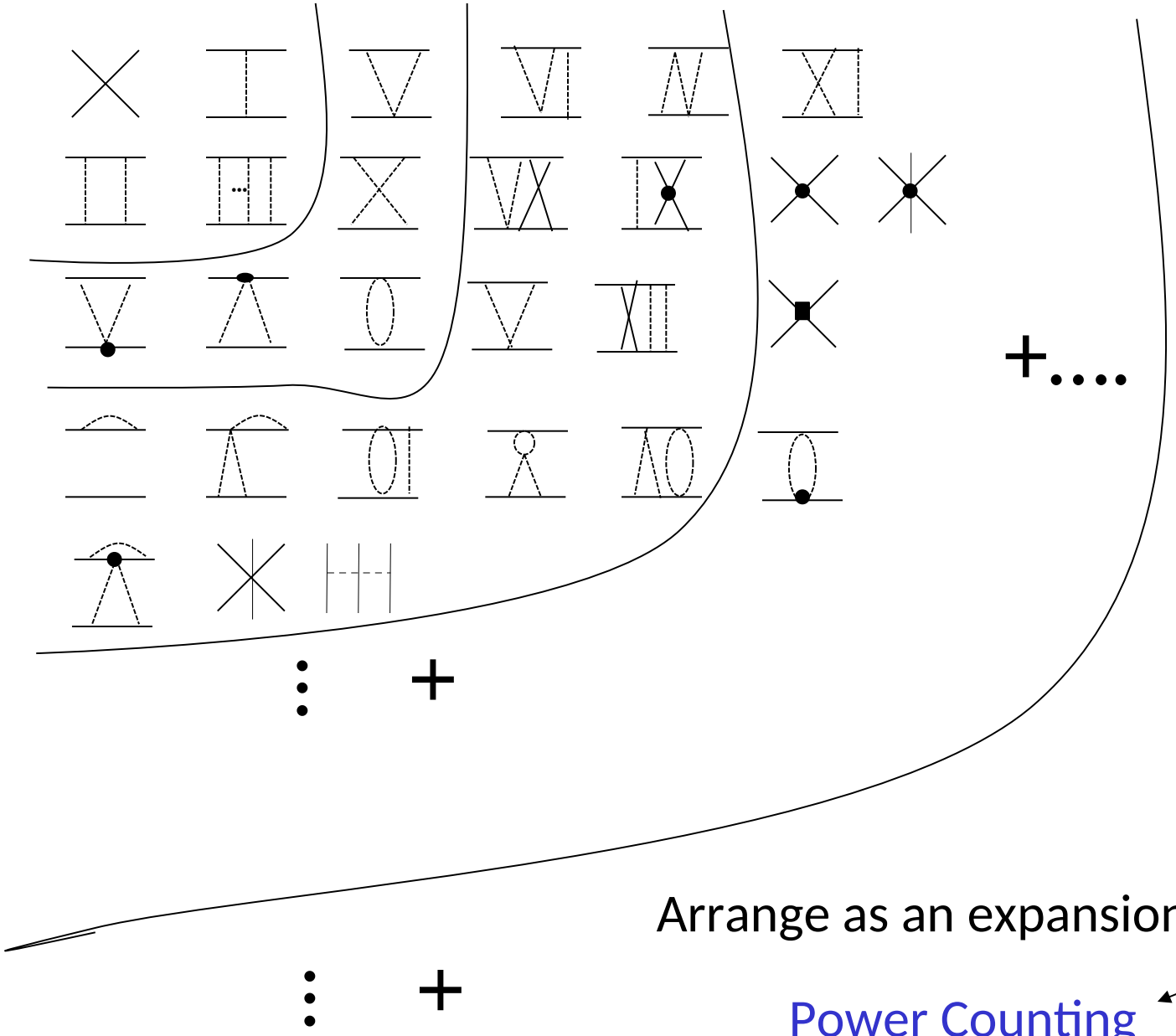
Department of Physics, University of Idaho, Moscow, Idaho, U.S.A.

Table 1. Seven Decades of Struggle: The Theory of Nuclear Forces

1935	**Yukawa: Meson Theory**
1950's	*The "Pion Theories"* One-Pion Exchange: o.k. Multi-Pion Exchange: disaster
1960's	Many pions ≡ multi-pion resonances: σ, ρ, ω, ... The One-Boson-Exchange Model
1970's	Refine meson theory: Sophisticated 2π exchange models (Stony Brook, Paris, Bonn)
1980's	Nuclear physicists discover **QCD** Quark Cluster Models
1990's and beyond	Nuclear physicists discover **EFT** Weinberg, van Kolck **Back to Meson Theory!** *But, with Chiral Symmetry*

Hans Bethe:
"more man-hours have been given to this problem than to any other scientific question in the history of mankind".

Modern approach

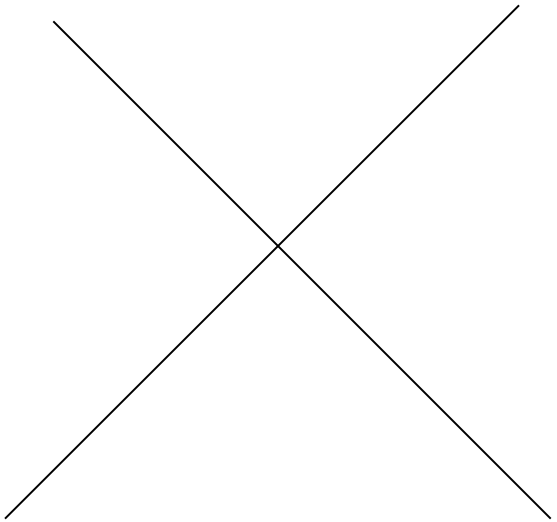


Arrange as an expansion of $\Sigma_n (M_{lo}/M_{hi})^n$

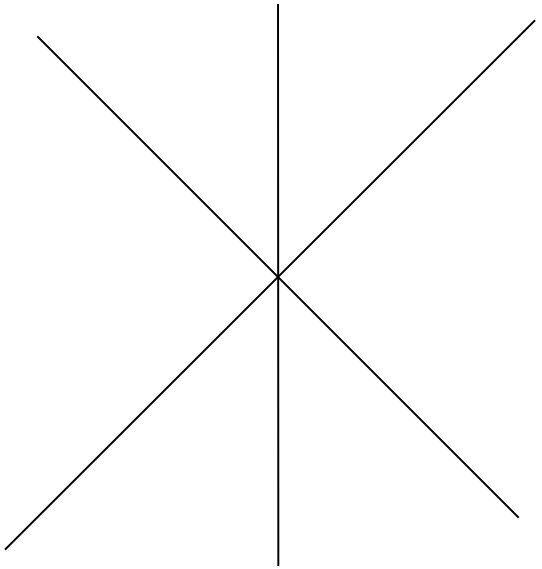
Power Counting

Weinberg's counting → naïve dimensional analysis

Naïve dimensional analysis (NDA)



2 nucleon force



3 nucleon force

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

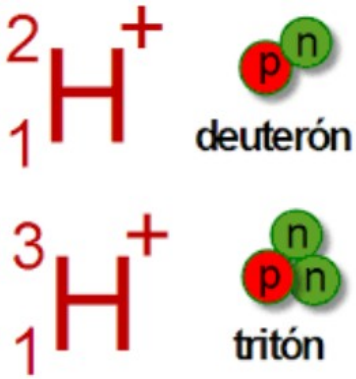
How to determine 3NF?

(what have been do so far)

1. Choose a 2NF, fit it to reproduce 2-body observables, e.g., nucleon-nucleon (NN) scattering data.

2. Do calculations on 3^{+}-body systems, see what's missing, then add and fit 3NF.

E.g.,



With 2NF → get E_b=2.21 MeV
(V_{2NF} fitted to NN phase shifts and E_b)

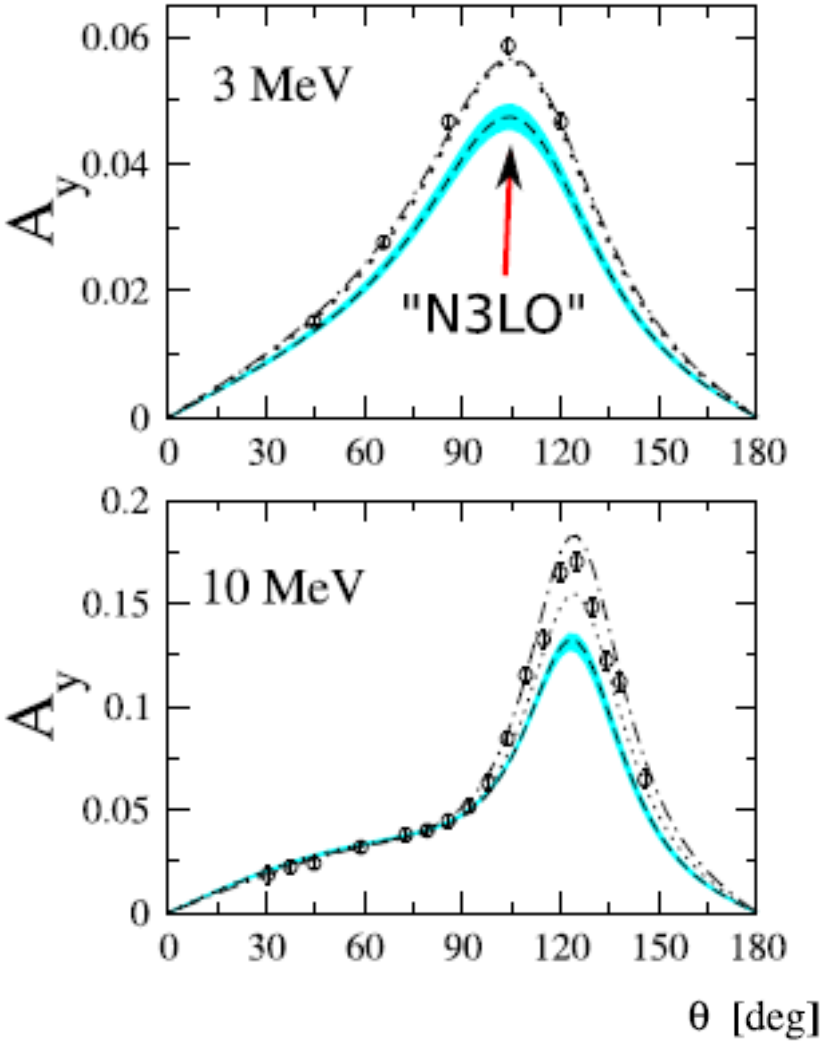
With 2NF → only get $E_b \approx 7.8$ MeV
Add 3NF to get to the exp. value E_b=8.48 MeV

Caveats and issues:

a) You might want to consider the impact of 4^{+}NF for $A \geq 4$ systems.
b) NN data only constraint the on-shell part ($k_{cm} \leftrightarrow k_{cm}$) of V_{2NF}, not the off-shell ($k \leftrightarrow k'$) part.
c) There are various ways to fit 2NF and 3NF (global fit, separate fit, Bayesian fit, etc), and they give very **different** results.

One example of the problems

Nd scattering (within the 3-body system)



A_y puzzle

Unsolved so far!

See, e.g.,
D. Huber and J. L. Friar, Phys. Rev. C, 58:674, (1998).
H. Witala, J. Golak, R. Skbinski, H. Sakai, K.S, Phys. Rev. C 111, 044003(2025).

There are more problems in 4^+-body systems.

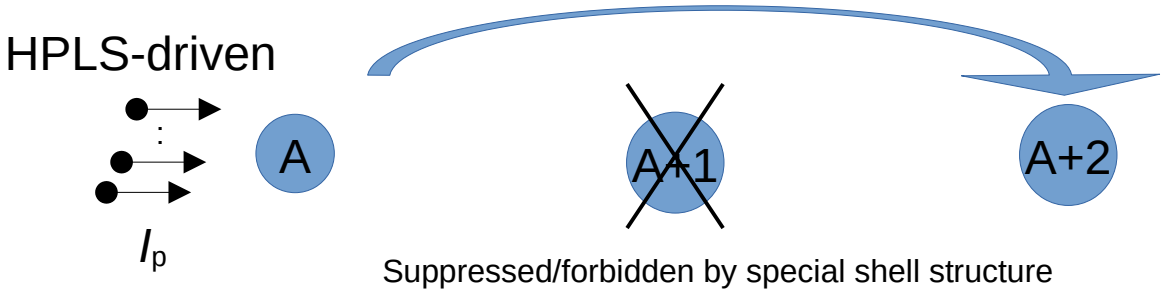
Root of the issue (largely due to 3NF)

There is **no observable** to **directly** pin down 3NF.

It's always treated as a residue of 2NF (with magnitude ranging from 1%~15%) and has the subtleties for being intertwined with the off-shell 2NF.

Our proposal

Two proton capture (A+p+p → ~~A+1~~ → A+2), with **intense** proton beam driven by HPLS.



Suppressed/forbidden by special shell structure
E.g., ^{45}Fe, ^{19}Mg, ^{48}Ni, ^{54}Zn, ^{67}Kr. The inverse process (two-proton decay) has been studied both in theo. and exp.

Only non-negligible if $I_p \gg 1$, i.e., HPLS-driven.

$$\text{Yield} \propto I_p \langle V_{pA} \rangle + I_p^2 \langle V_{3NF} \rangle$$

Through different dep. on I_p, we can differentiate the contributions and extract V_{3NF}.

See, e.g., S. M. Wang and W. Nazarewicz, Phys. Rev. Lett.,120:212502 (2018).
E. Olsen, M. Pfutzner, N. Birge, M. Brown, W. Nazarewicz, A. Perhac, Phys. Rev. Lett., 110:222501 (2013).

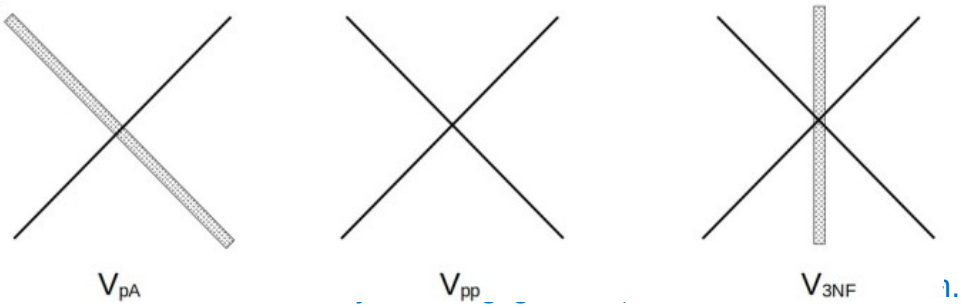
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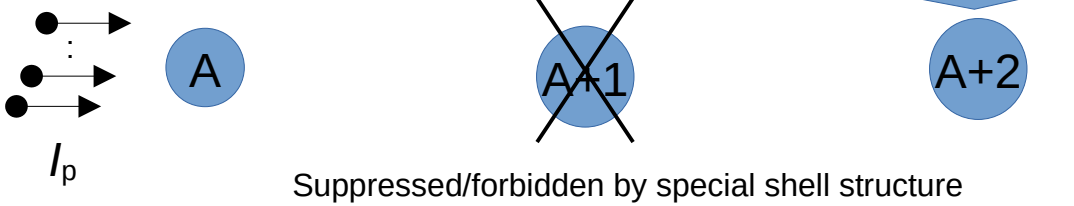
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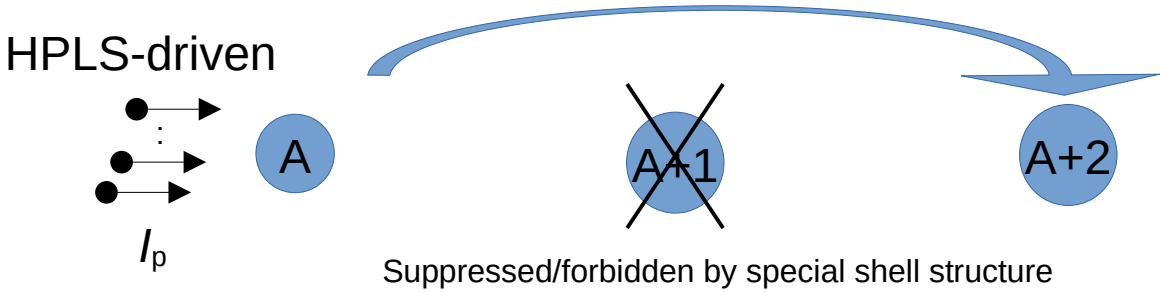
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Summary

New emerging field, with (nuclear) + (laser-plasma) community.

Exciting opportunity waiting us to explore !

Theory@LDED group

The group is part of the **LDED** (Department Head: **Domenico Doria**)

Group Coordinator
P. Tomassini



Paolo Tomassini
Head of Research



C-J Yang (Jerry)
Young Researcher



Vojtěch Horný
Young Researcher



Olimpia Budriga
Senior Researcher *

Performs theory and simulation (mostly) for LDED

- Nuclear Physics
- Laser Solid
- LWFA/DLA
- Radiation and secondary sources



Dragana Dreghici
Ph. D. student



Bogdan Corobean
Ph. D. student



Federico Avella
Ph. D. student **



Maxim Andronic
Master Student

* Part Time, **In Co-Tutoring

Acknowledgments

Romanian Ministry of Research and Innovation: PN23210105 (Phase 2, the Program Nucleu)

ELI-RO/RDI 2024 AMAP, ELI-RO RDI 2024 LaLuThe, ELI-RO RDI 2024 SPARC

Dr. LASER

“Medical applications of high-power lasers - Dr. Laser”

www.eli-np.ro/projects/drlaser/

SMIS Code: 326475

Project co-financed by the European Union and the Romanian Government within the Romanian Health Program

“This material does not represent the viewpoint of the European Union or the Romanian Government, neither of them being liable for the way the information contained in this presentation might be used.“

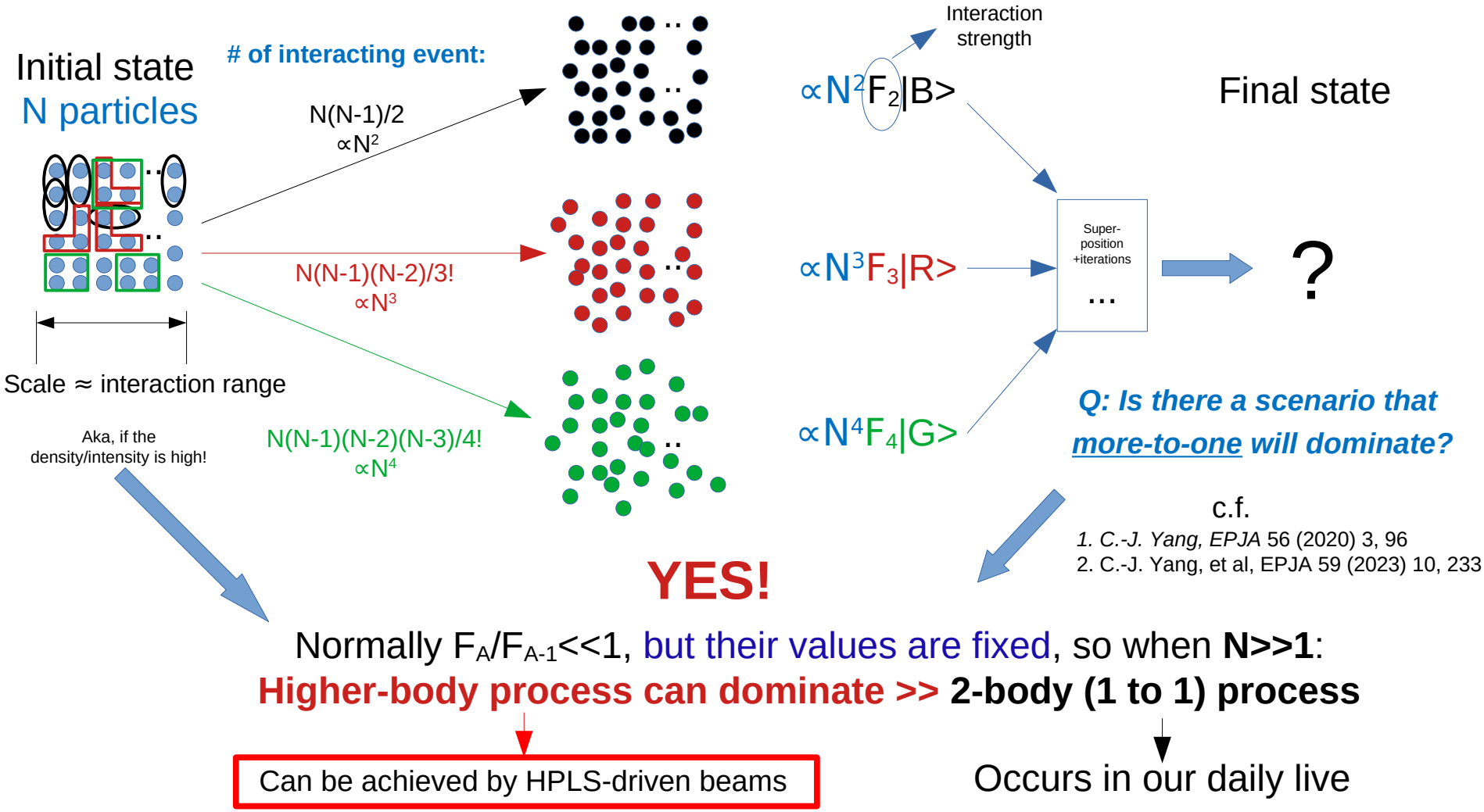
Cofinanțat de Uniunea Europeană

GUVERNUL ROMÂNIEI

Program Sănătate

Thank you!

More is different P.W. Anderson



A real example

(far from the best case, but with all exp. data relevant available)

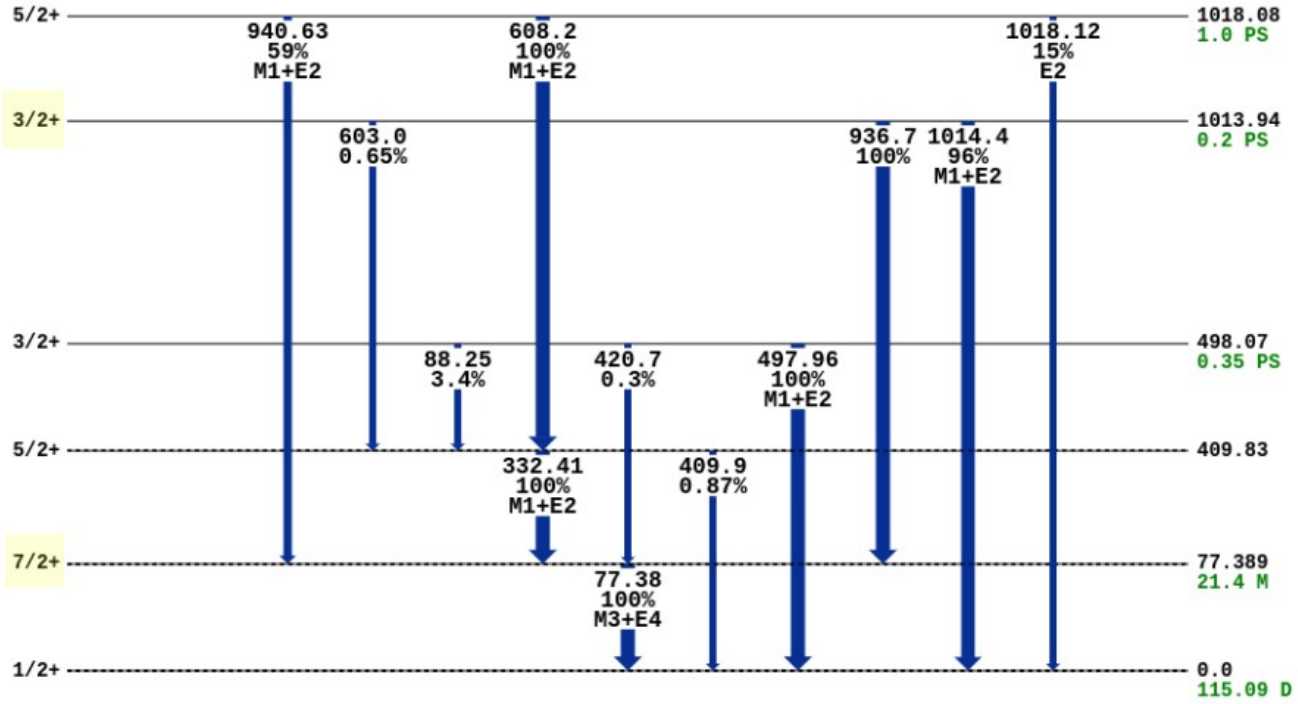
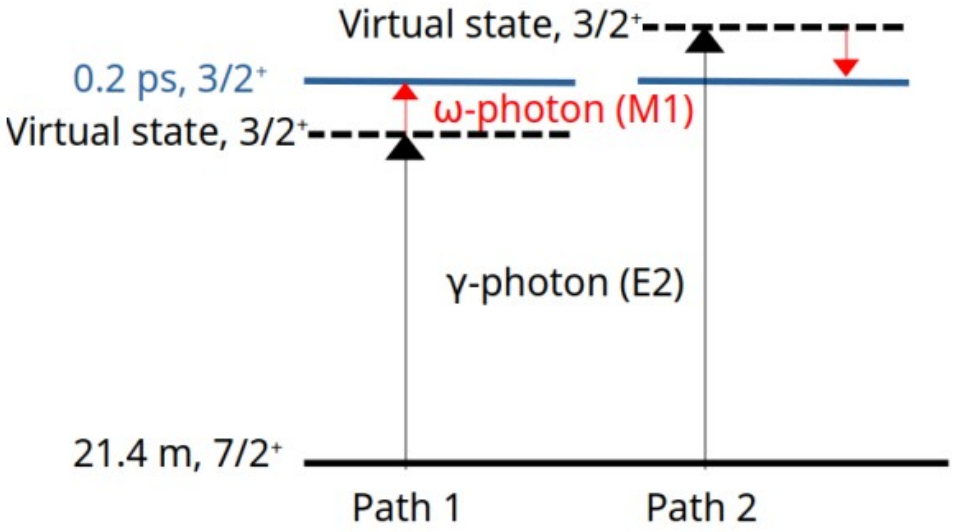


Figure 4. Level scheme of ^{113}Sn adopted from https://www.nndc.bnl.gov.

A real example

(far from the best case, but with all exp. data relevant available)



Gaps between states are not to scale. ($Gap_\omega/Gap_\gamma \approx 10^{-6}$)

$$\sigma_{\mathrm{eff}}^{2\mathrm{PA}} \approx 5.2 \times 10^{-48} \mathcal{P}_\omega \ \mathrm{cm}^2$$

σ felt by γ (which do E2)

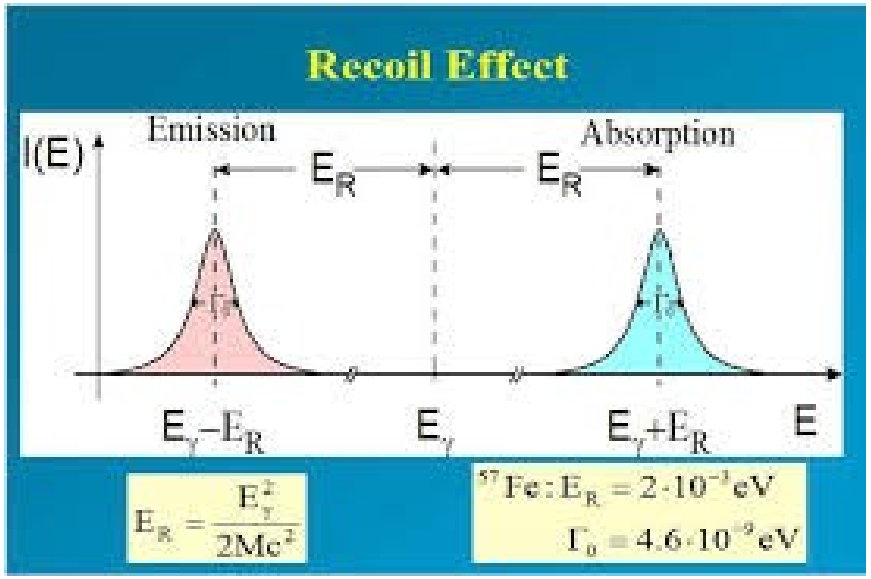
Intensity of ω (in unit of W/cm²)

0.1 barn if $\mathcal{P}_\omega \approx 10^{22}\ \mathrm{W/cm^2}$

Details in: C.-J. Yang, et al, Proc. SPIE 13535, 1353506 (2025), (arXiv:2503.15224 [nucl-th])

Recoil: problem and solution

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



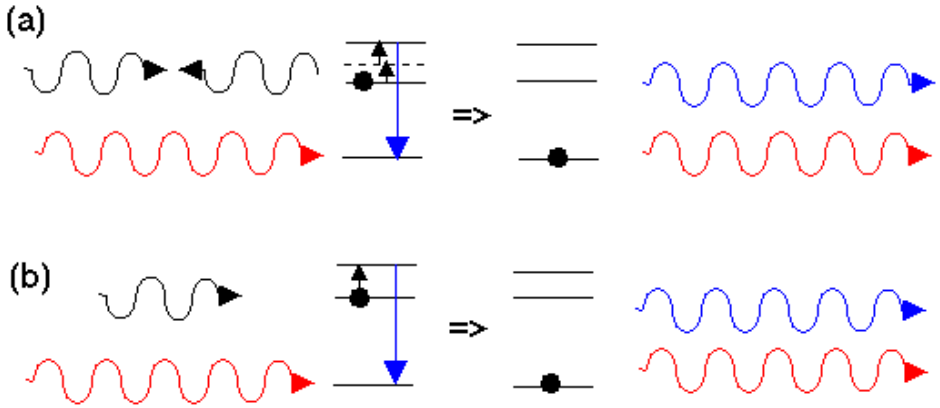
For γ>1 MeV, the stimulated process could loss (up to 5 eV in energy) >> (width of the lasing state)

⬇

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

Practical requirements
(sequential, 2 steps pumping)

To have ~1000 events of 1+1 steps pumping, it requires:

- Depositing all photons within ~ps.

=> not a problem for PW HPLS (each pulse ~20-50 fs)

- **10^{16}** photons (with E≈1 MeV) per 100 μm^2.

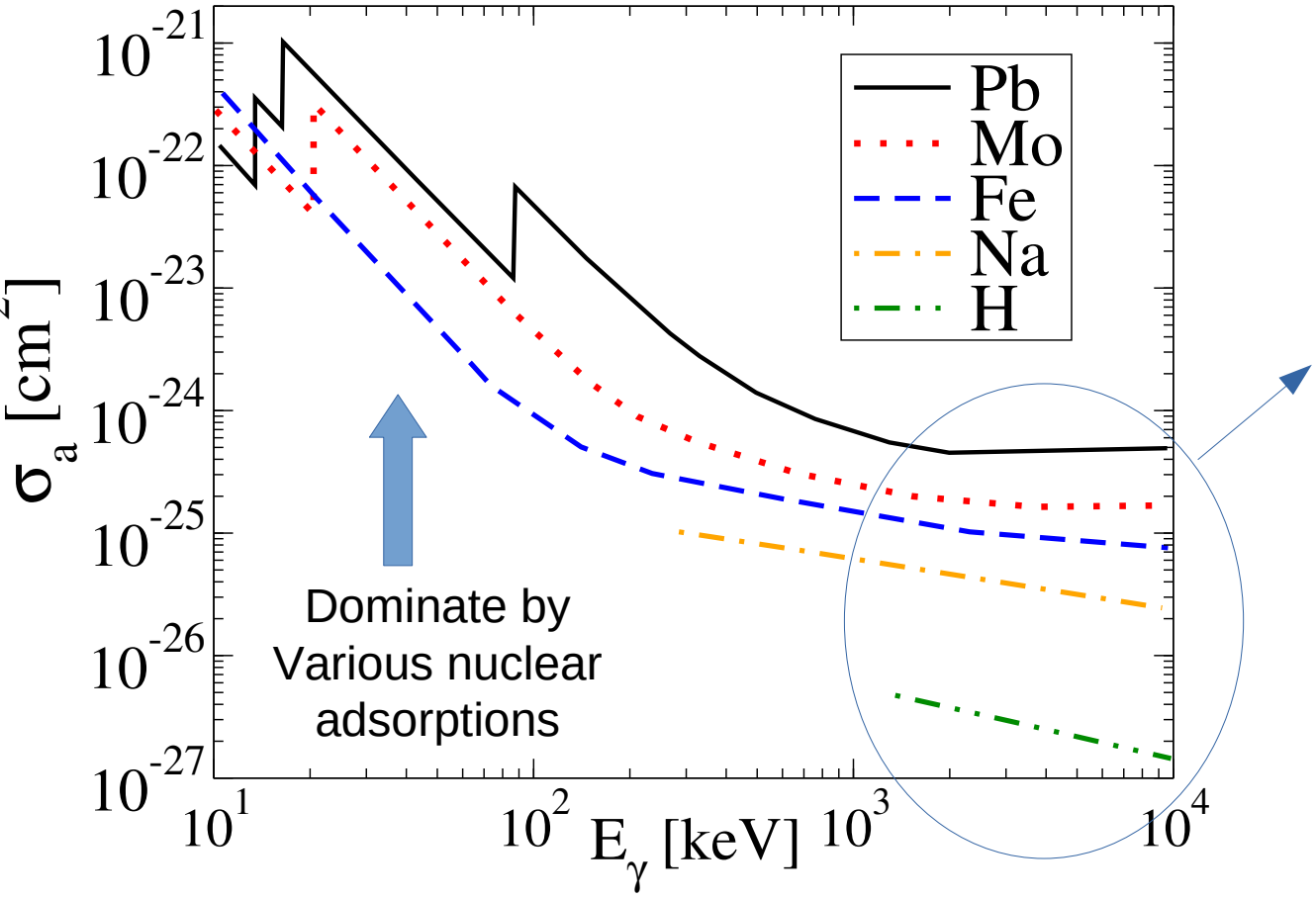
This is the problem! PIC simulations give at most **10^9 photons (within 1 eV BW)** at such energy.

* The number can varying ×/÷ 100 times dep. on the nuclei selected and detailed nuclear model used, but not 10^{16-9} times.

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

Detail 1

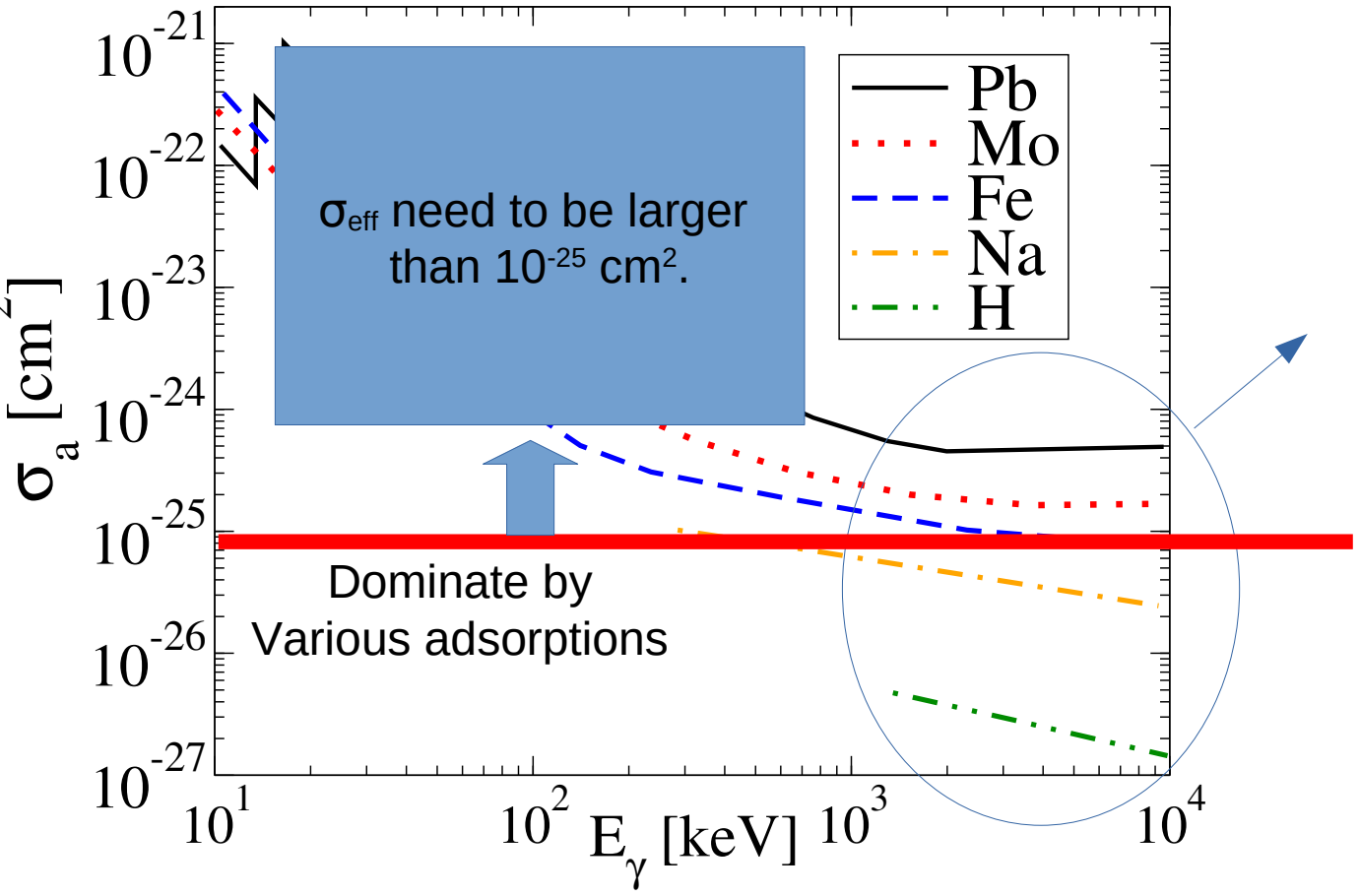
Requirement of minimum effective cross section => mainly from photon-removal effects



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

Detail 1

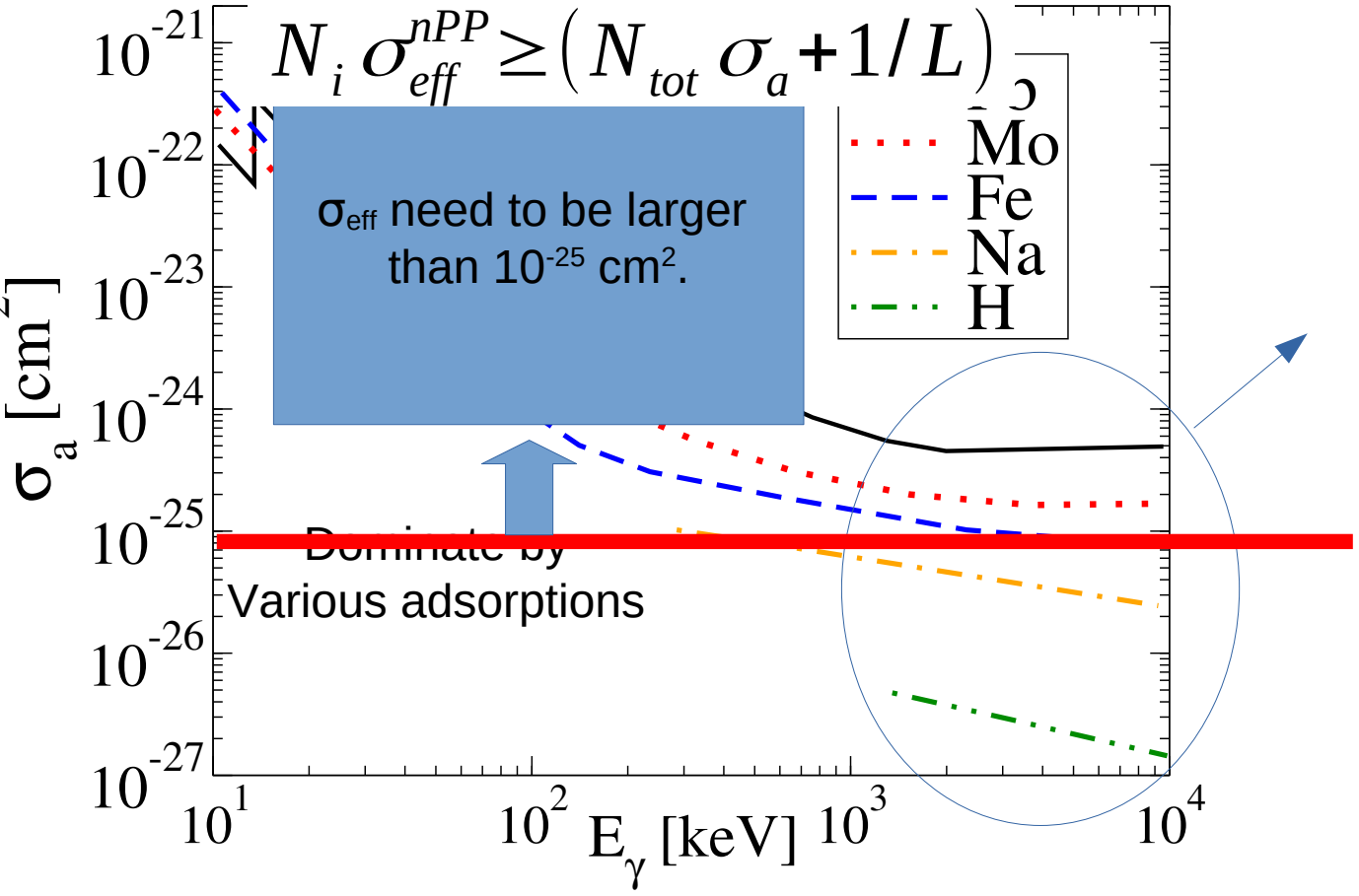
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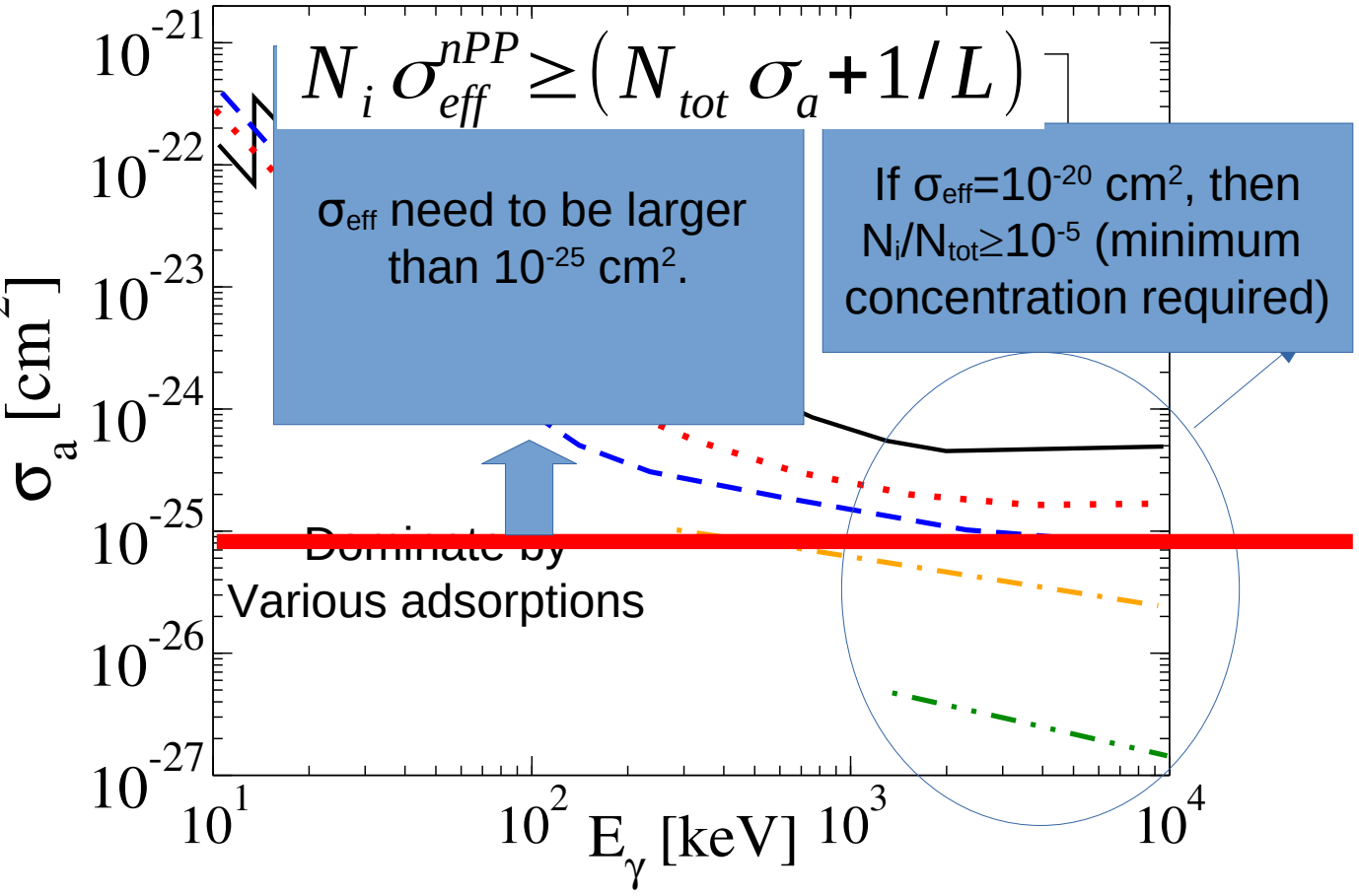
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Detail 1

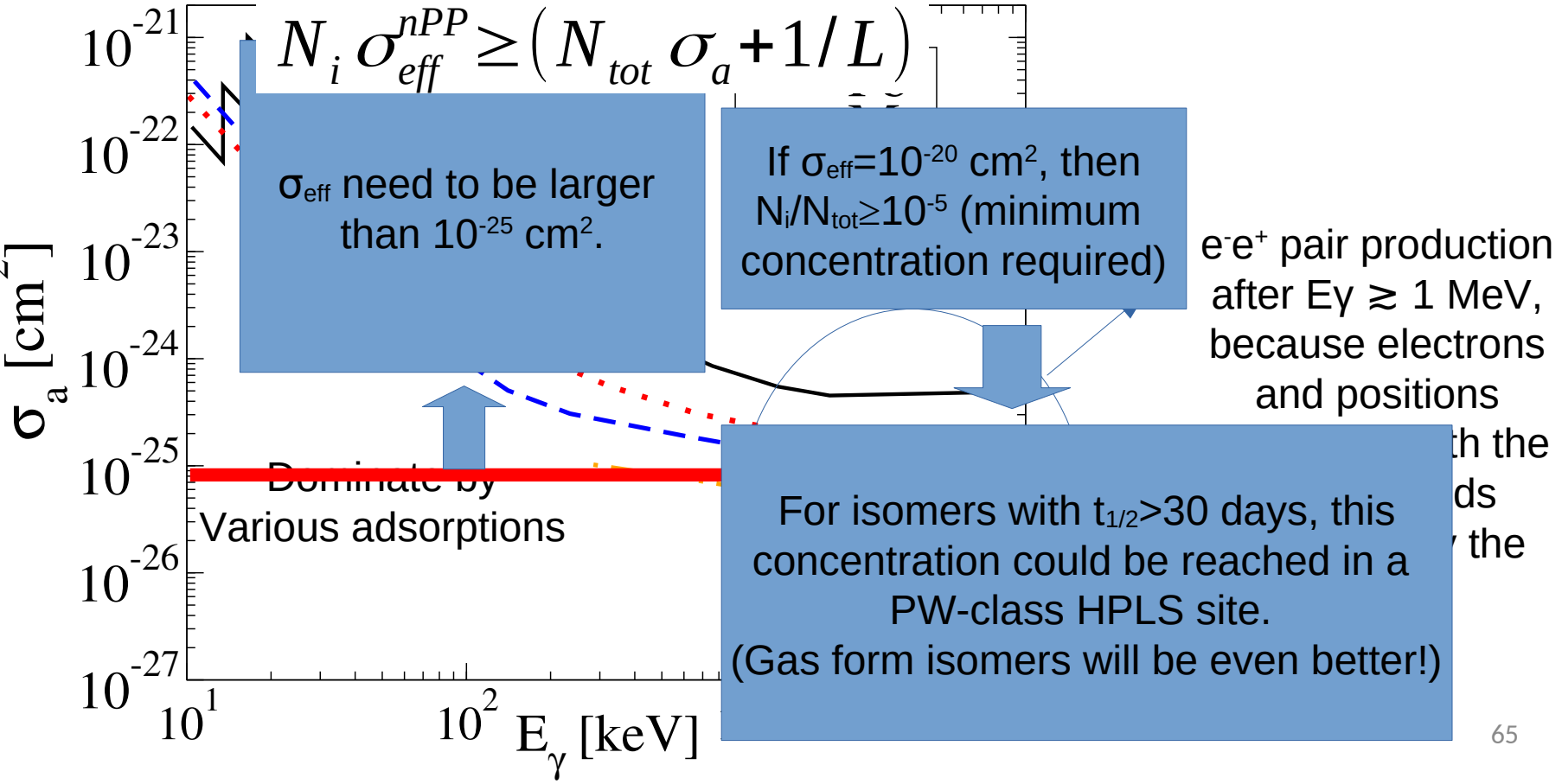
Requirement of minimum effective cross section => mainly from photon-removal effects



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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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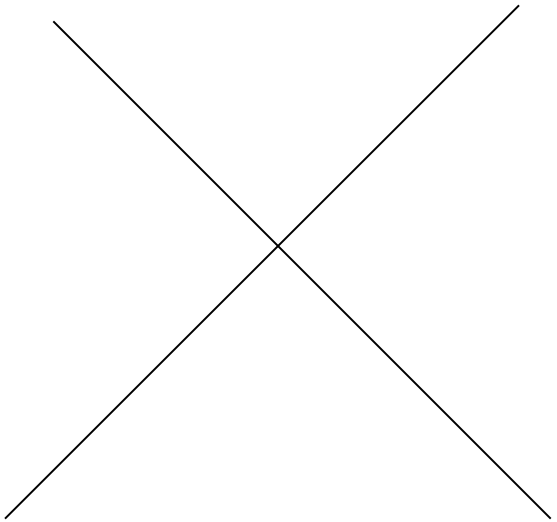
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Solution: Have the supplied ω-photon come with beam band-width ≥ 0.3 eV.

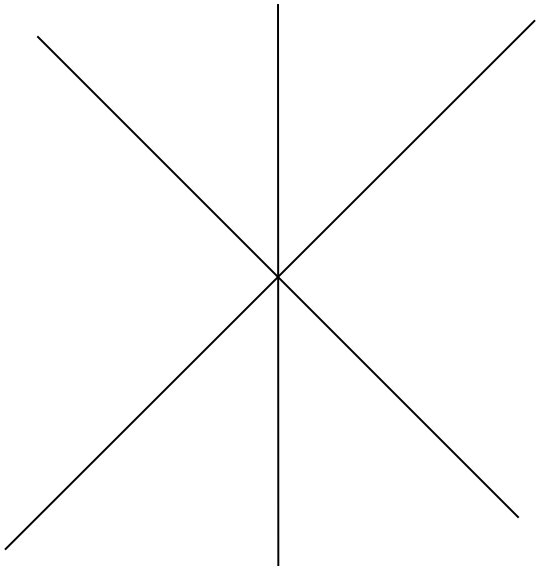
Many-body forces (e.g. NNN, NNNN, etc.)

- 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...