Non-adiabatic laser-nucleus interaction with nucleon emission

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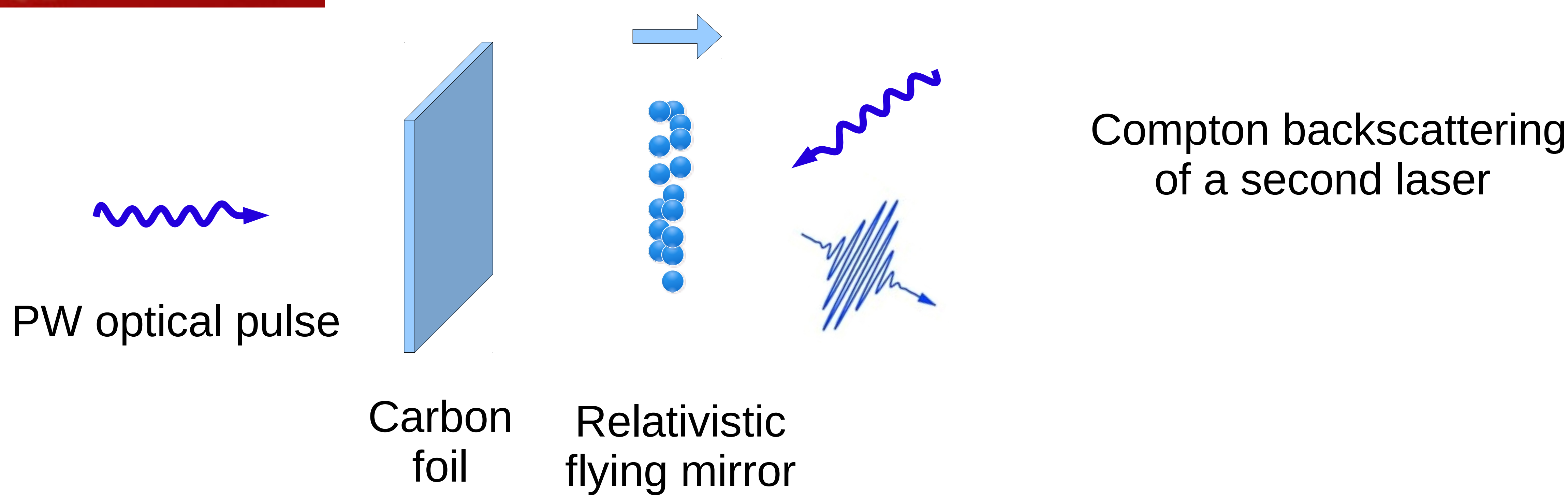
ELI-NP prospects

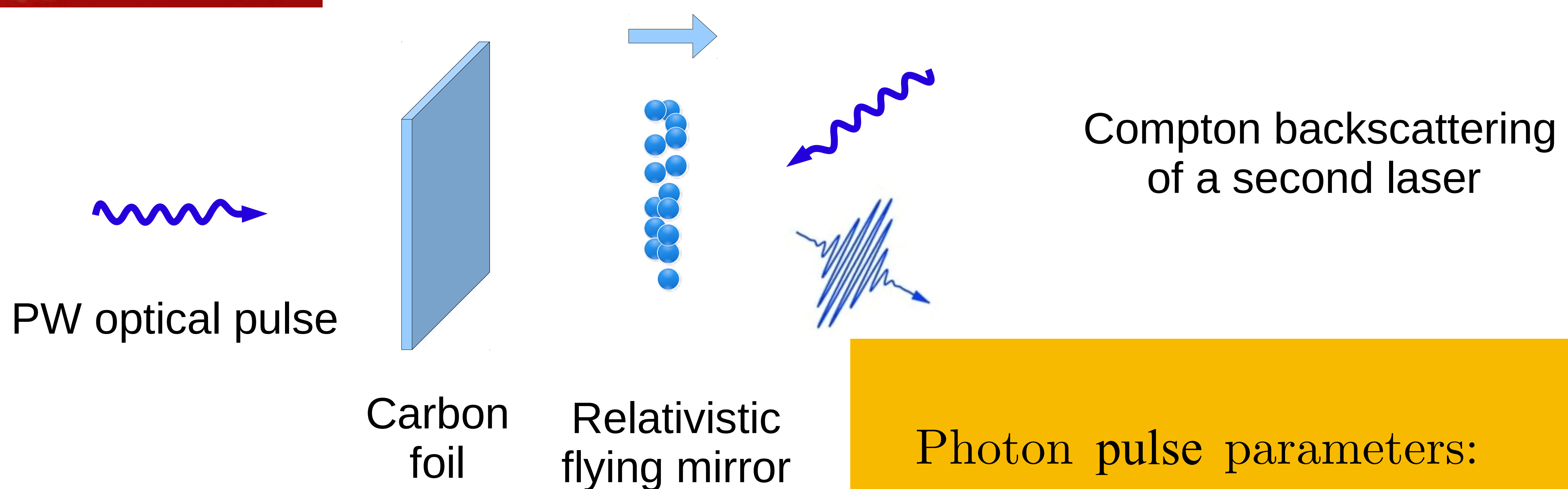
Extreme Light Infrastructure – Nuclear Pillar



G. Mourou and T. Tajima, Science 331 (2011) 41

ELI-NP prospects

Extreme Light Infrastructure – Nuclear Pillar

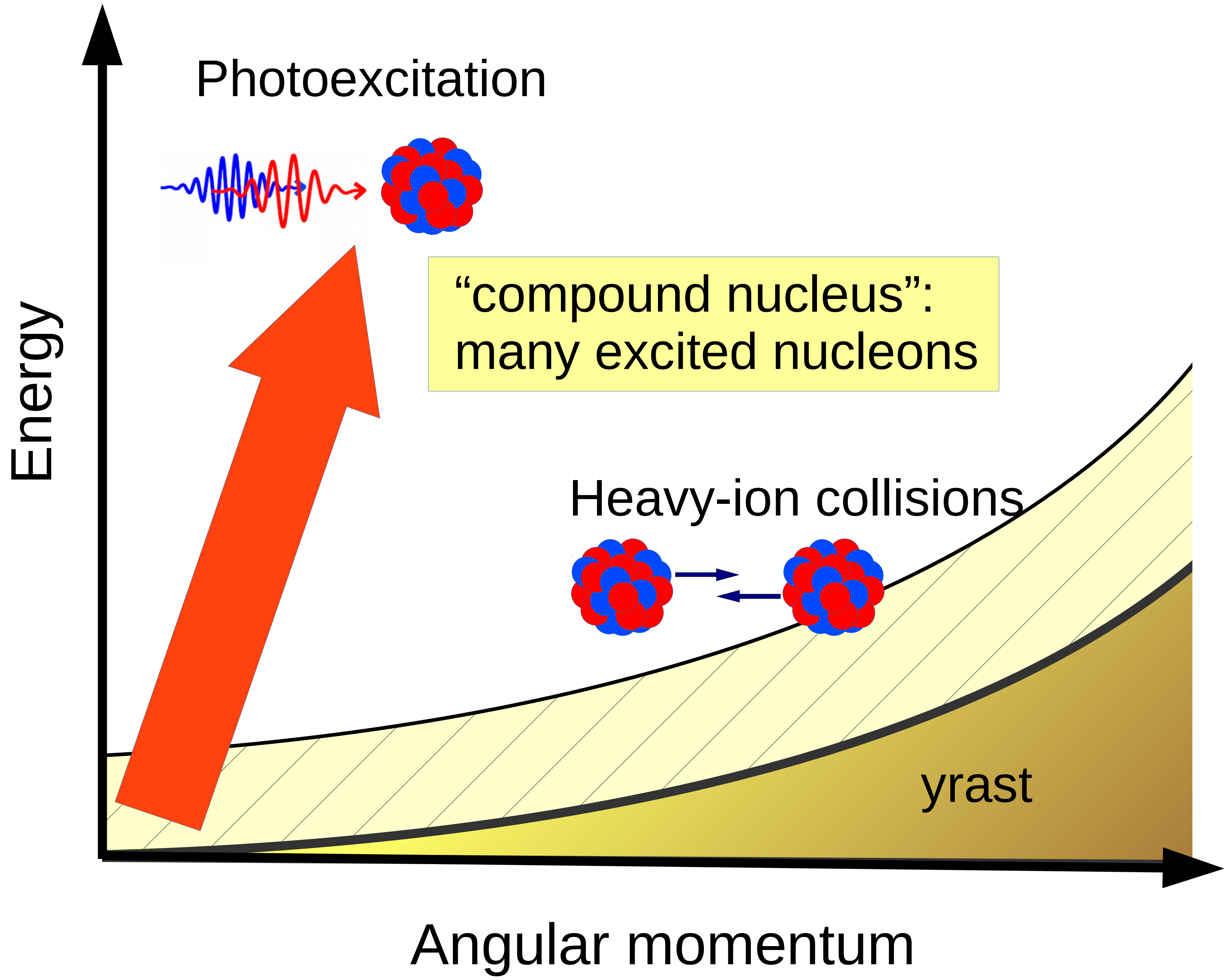


G. Mourou and T. Tajima, Science 331 (2011) 41

Photon **pulse** parameters:

- $N \sim 10^3 - 10^4$ coherent photons
- $E_L \sim 5 - 10$ MeV per photon
- $\sigma \sim 50$ keV: Zeptosecond pulse

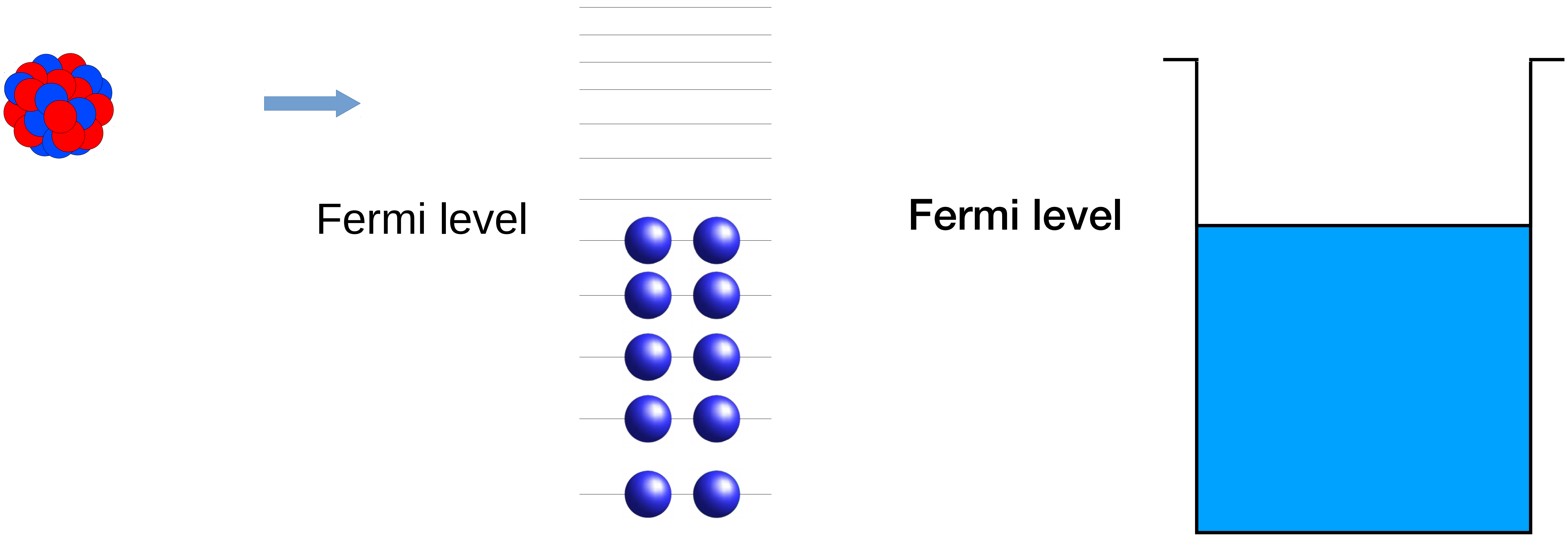
Exciting nucleus with laser



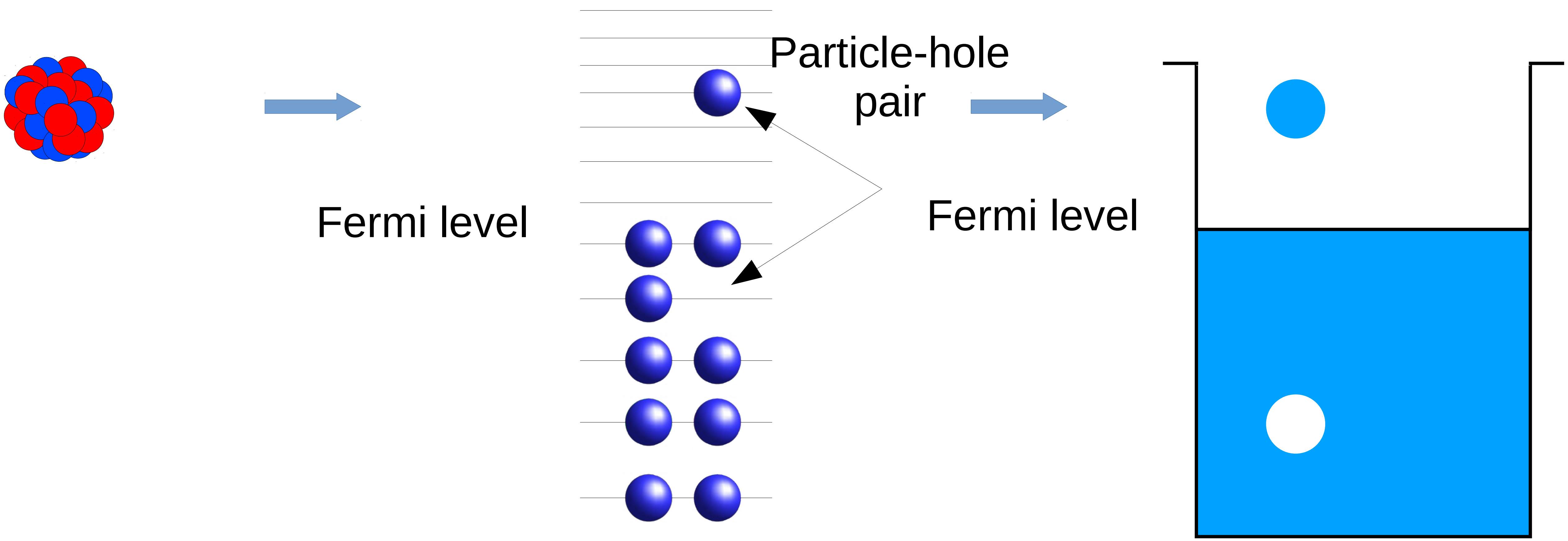
- **Completely unexplored new parameter regime for compound nucleus**
- **Which reactions to expect?**

Contents:

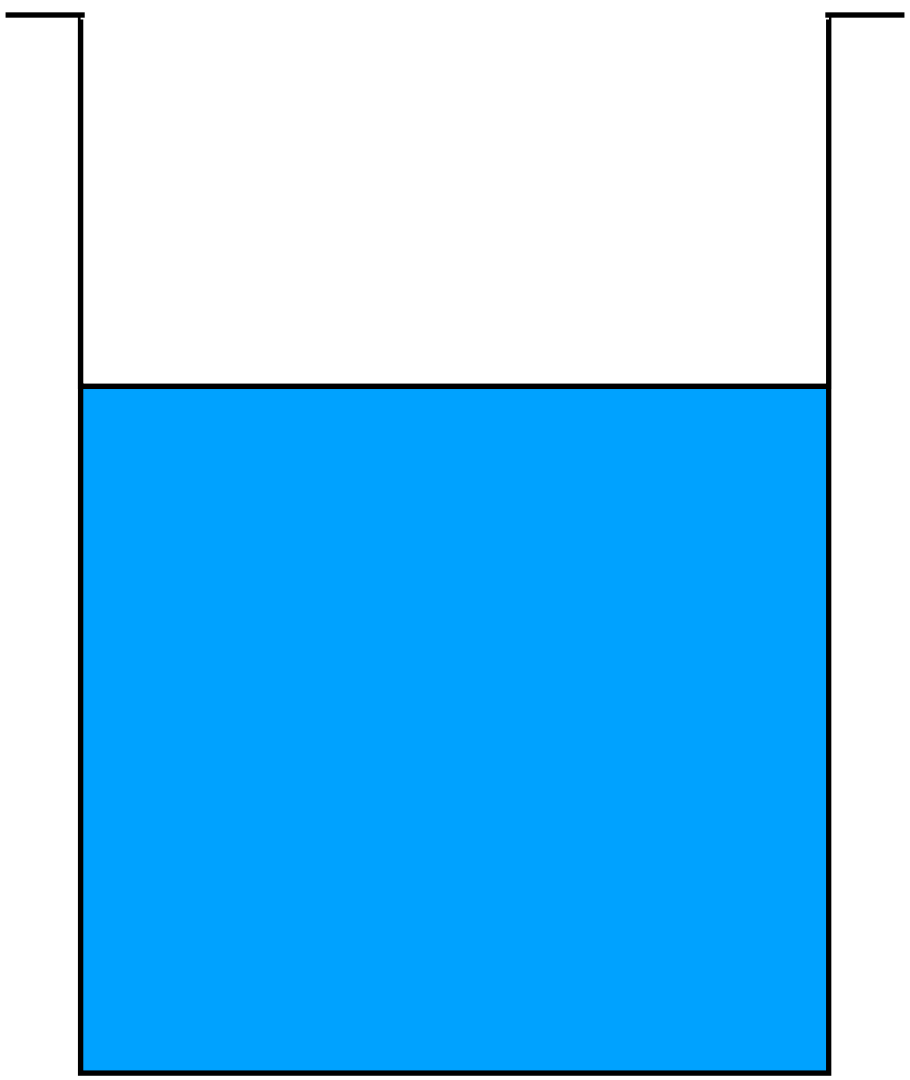
Nucleus as a many-body system



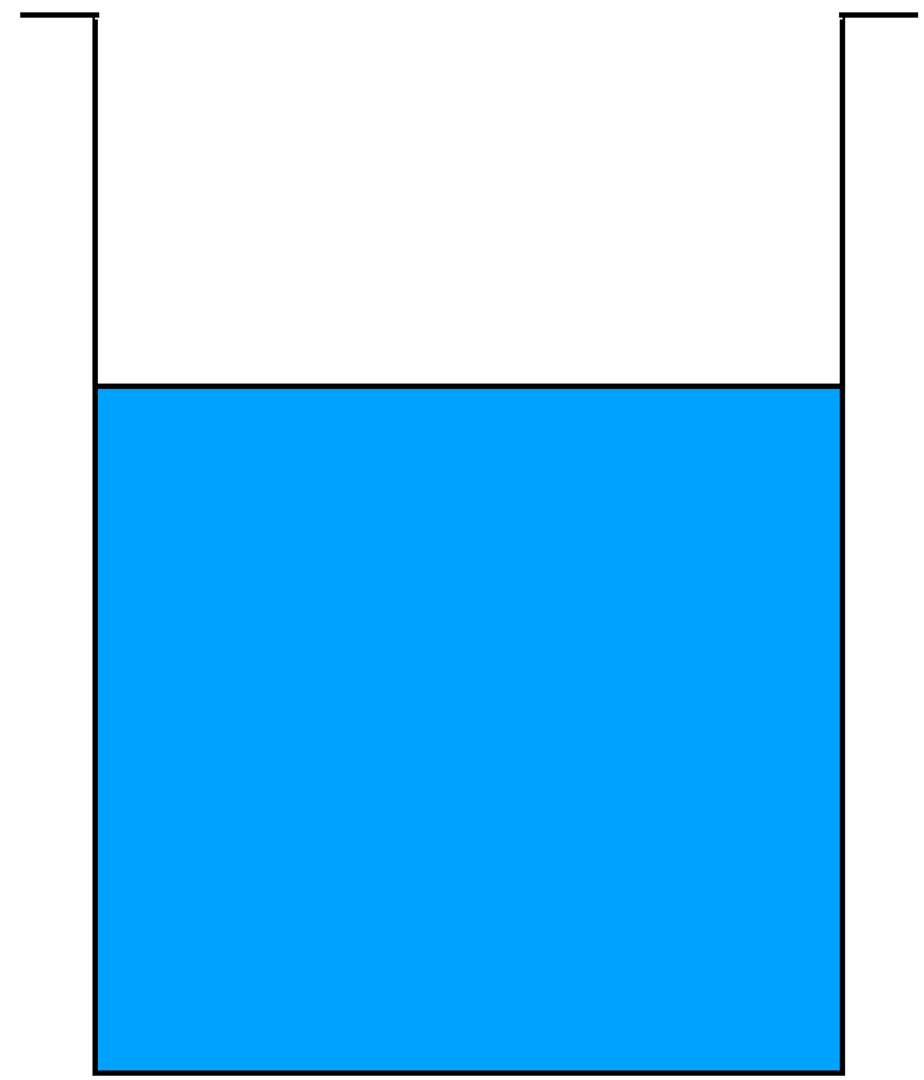
Nucleus as a many-body system



Laser-nucleus interaction and nuclear equilibration

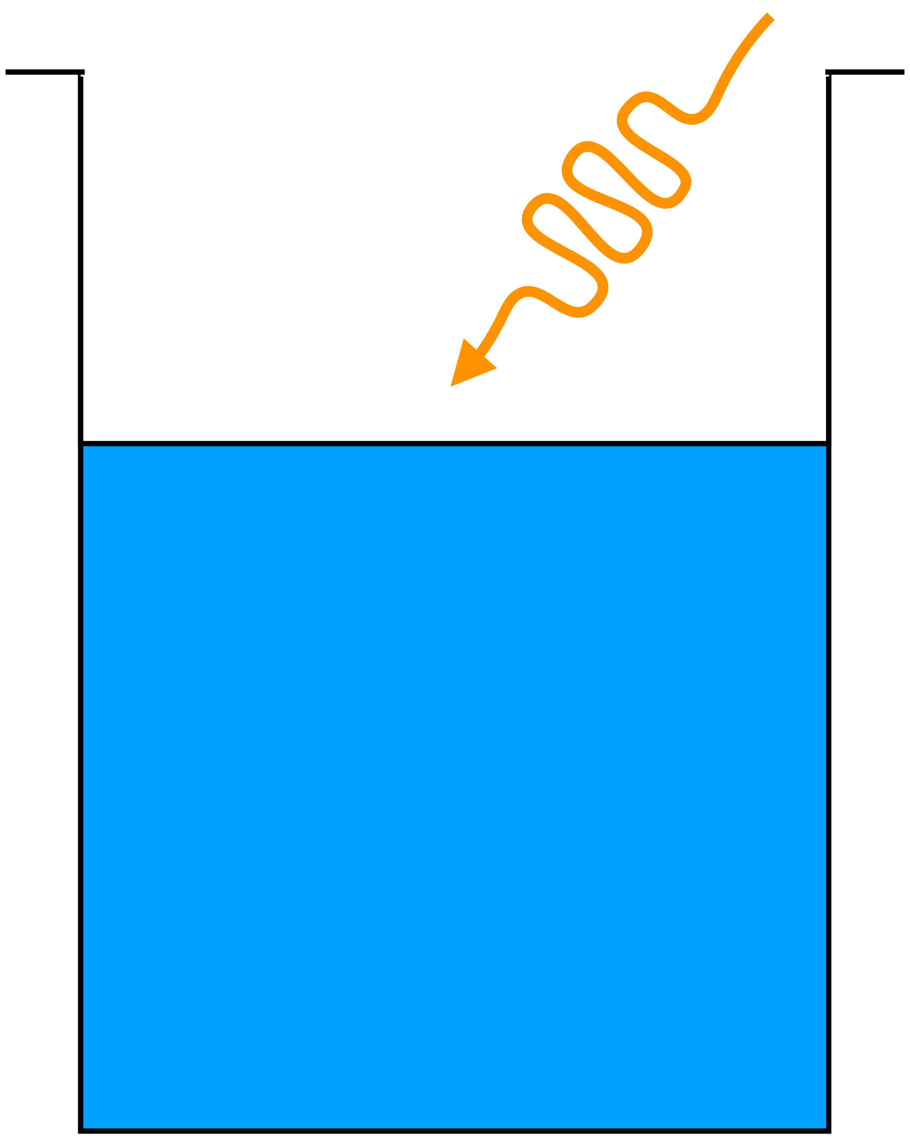


Photon excitation creates p-h pairs



Residual nuclear interaction redistributes energy over p-h pairs

Laser-nucleus interaction and nuclear equilibration



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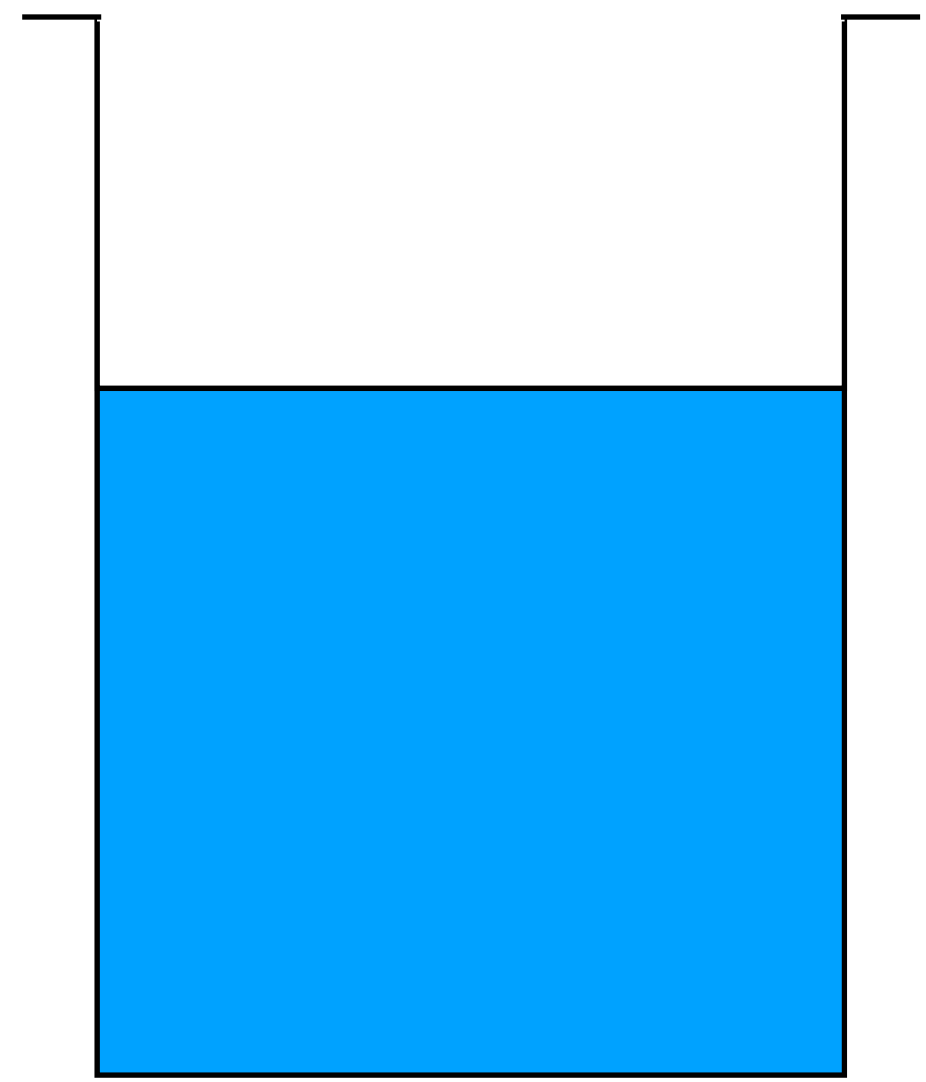

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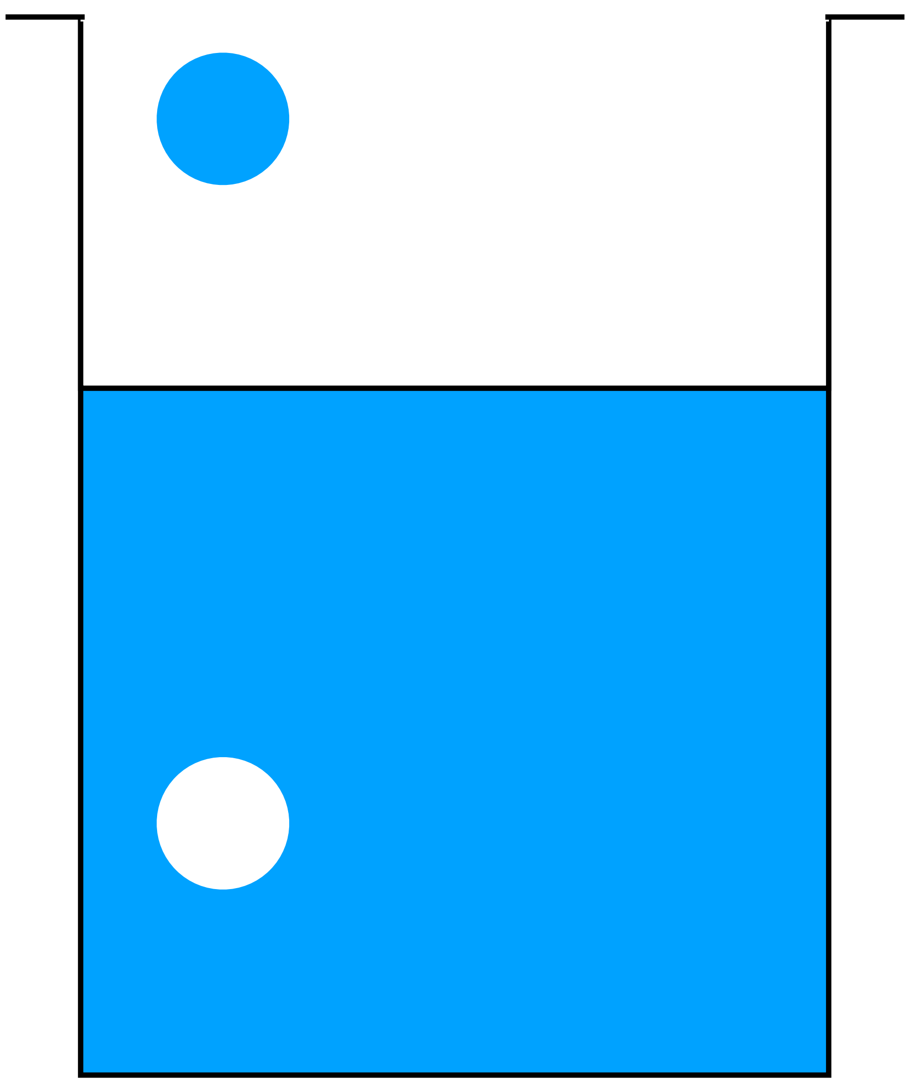

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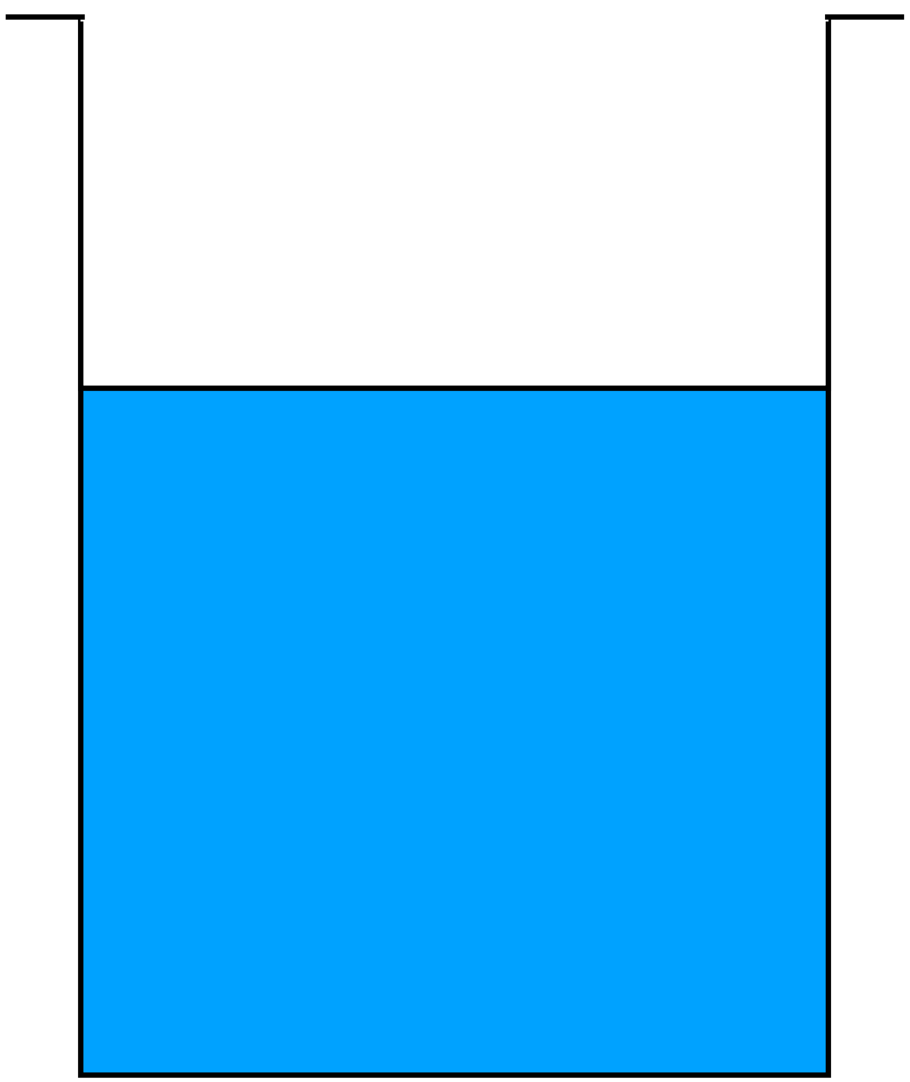

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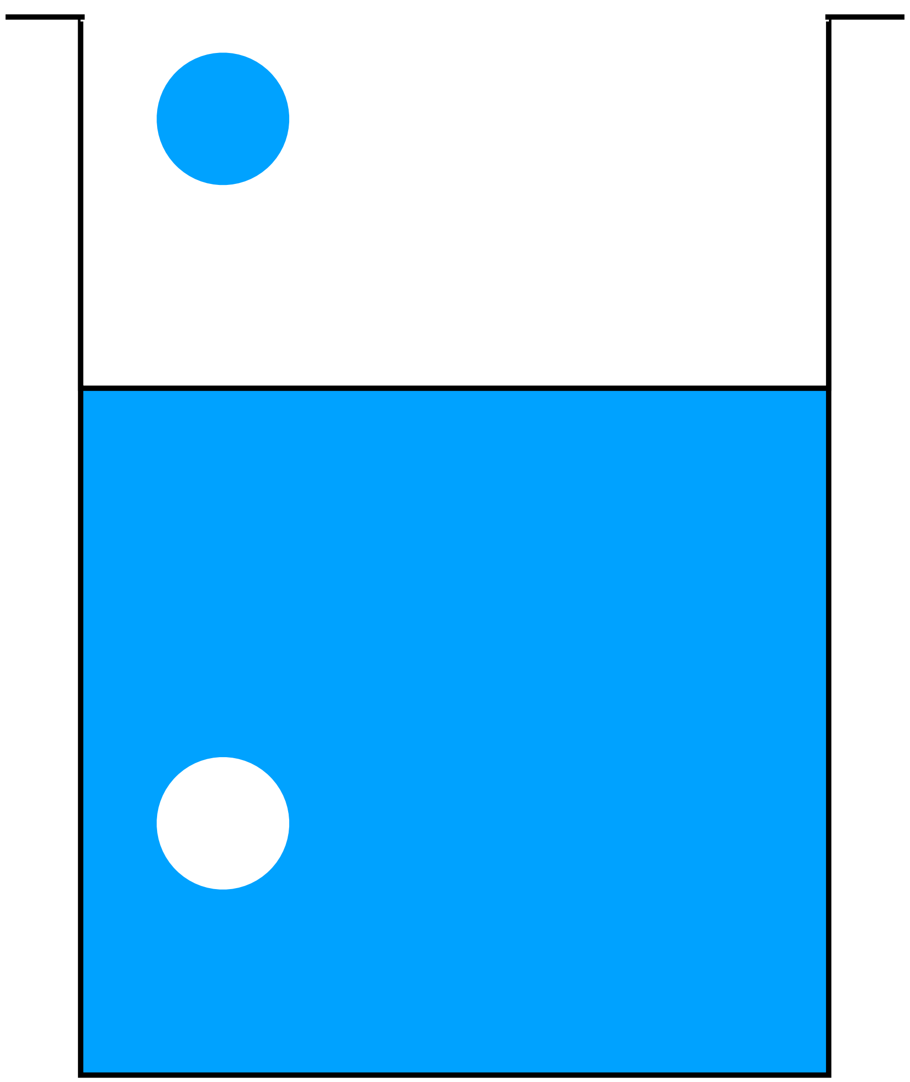

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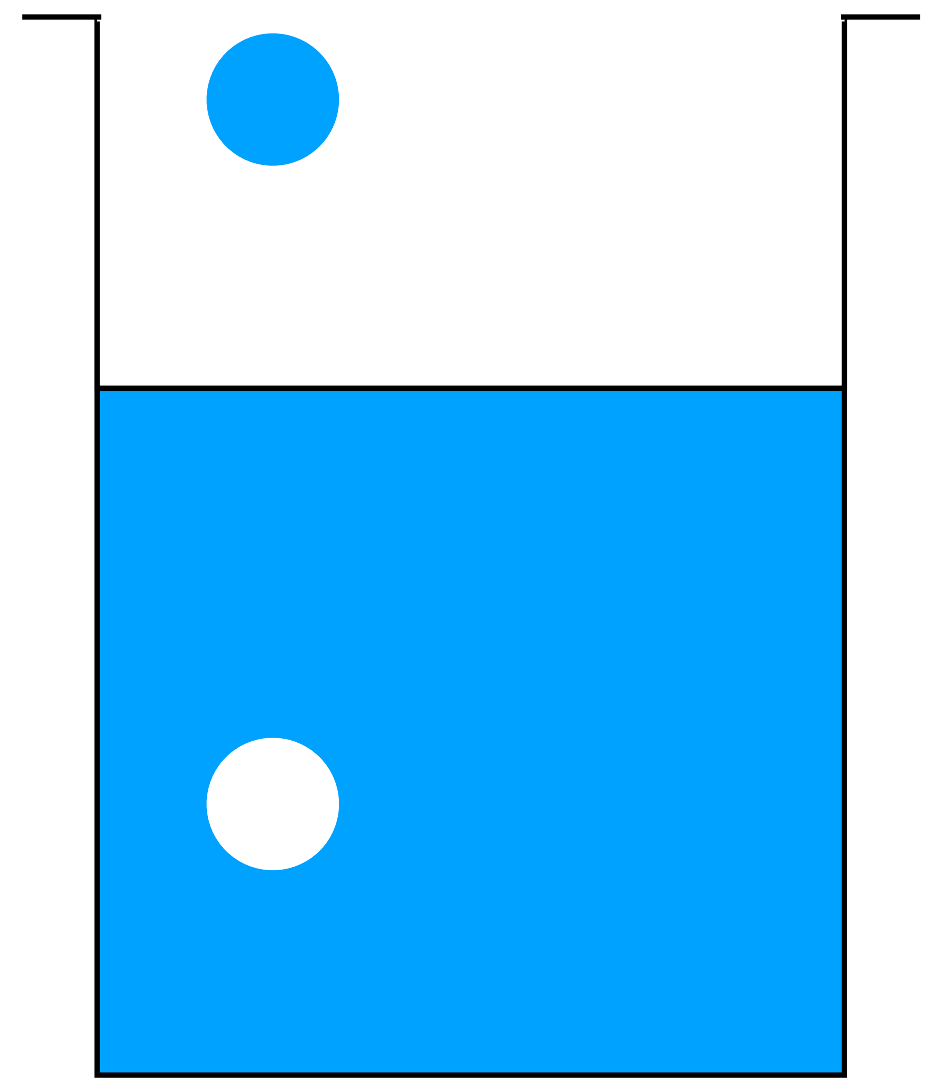

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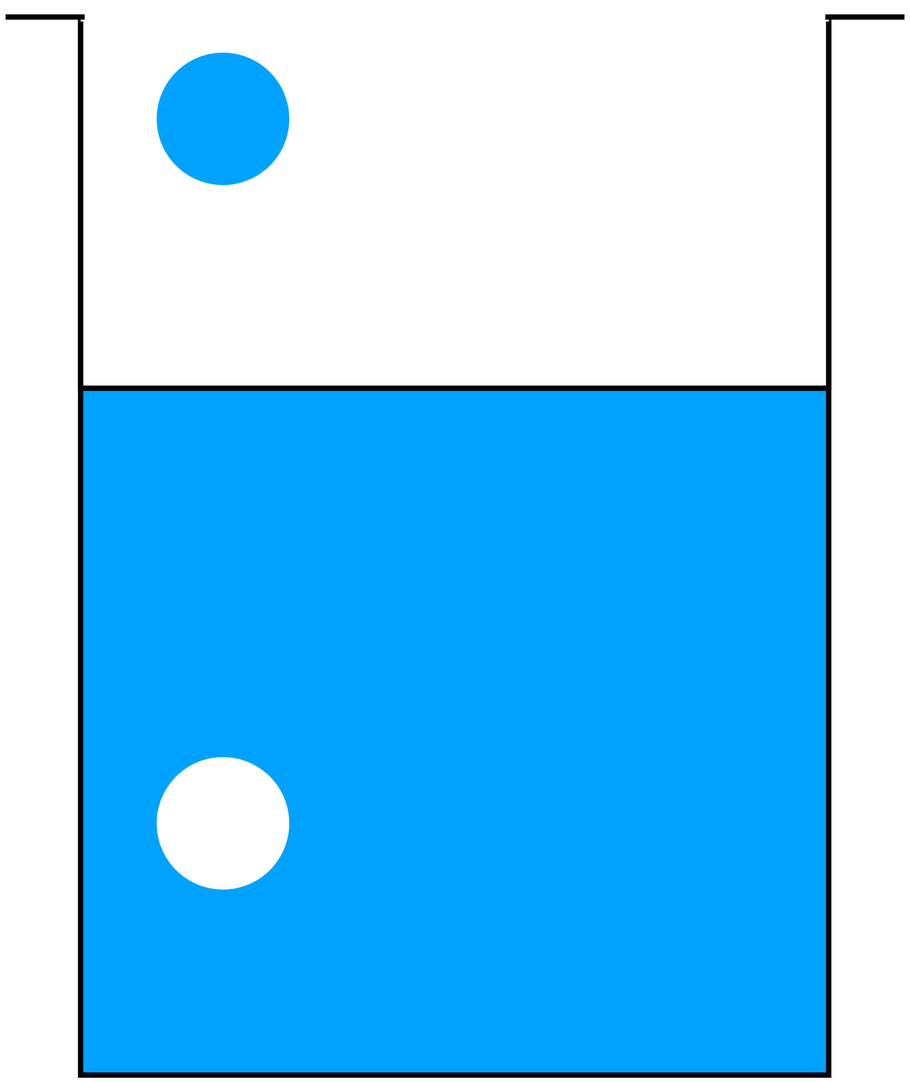

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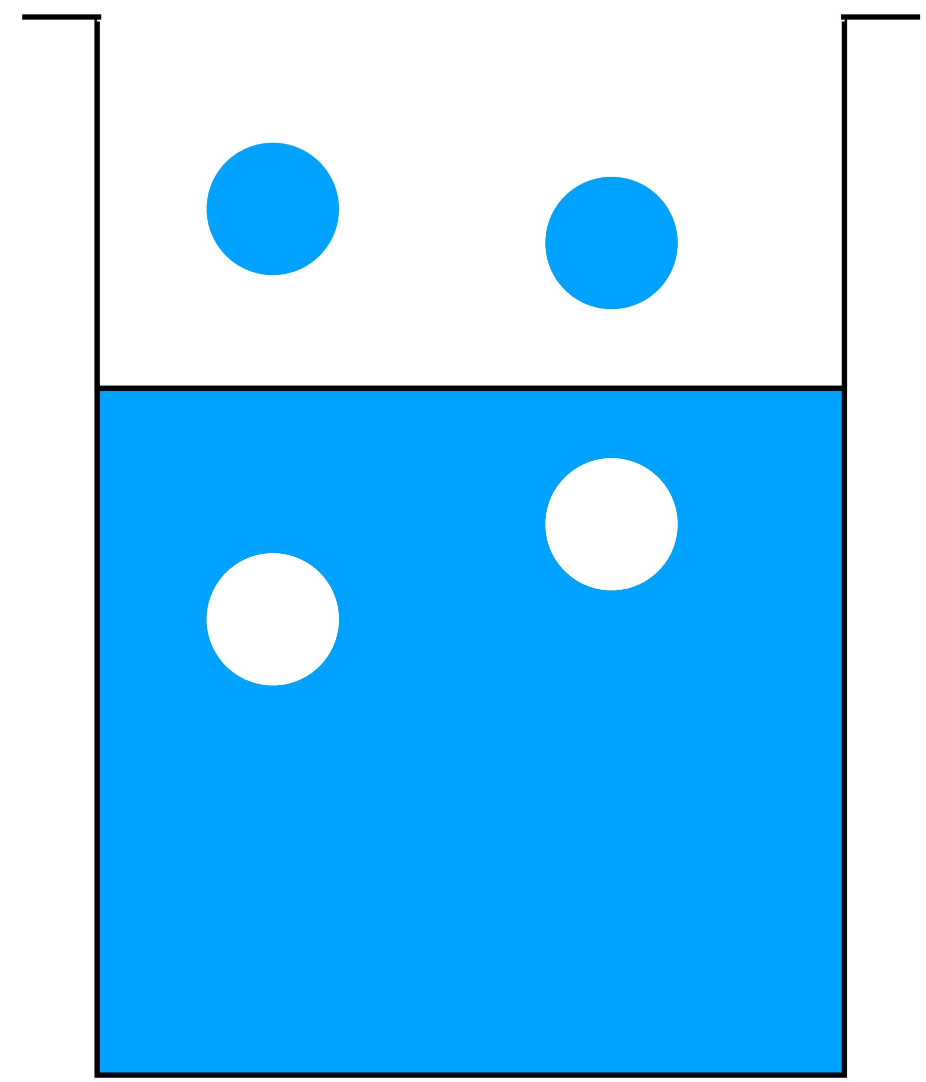

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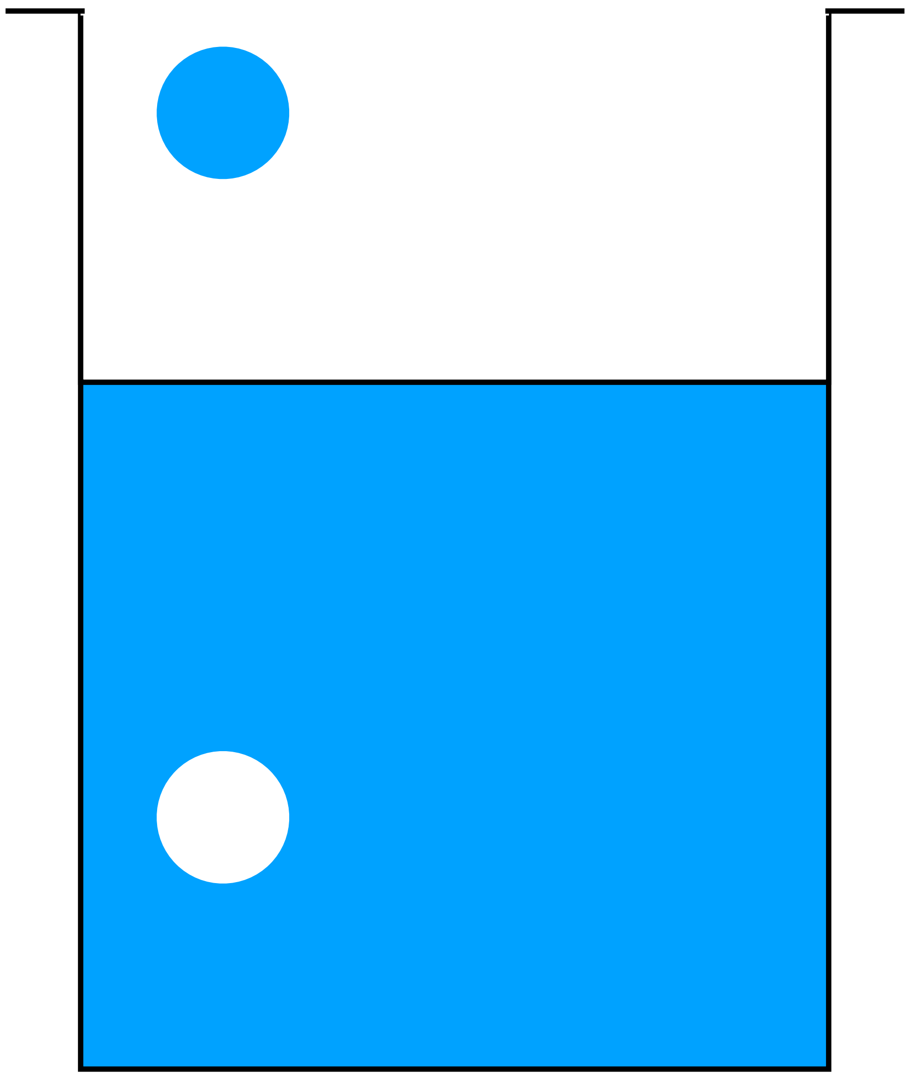
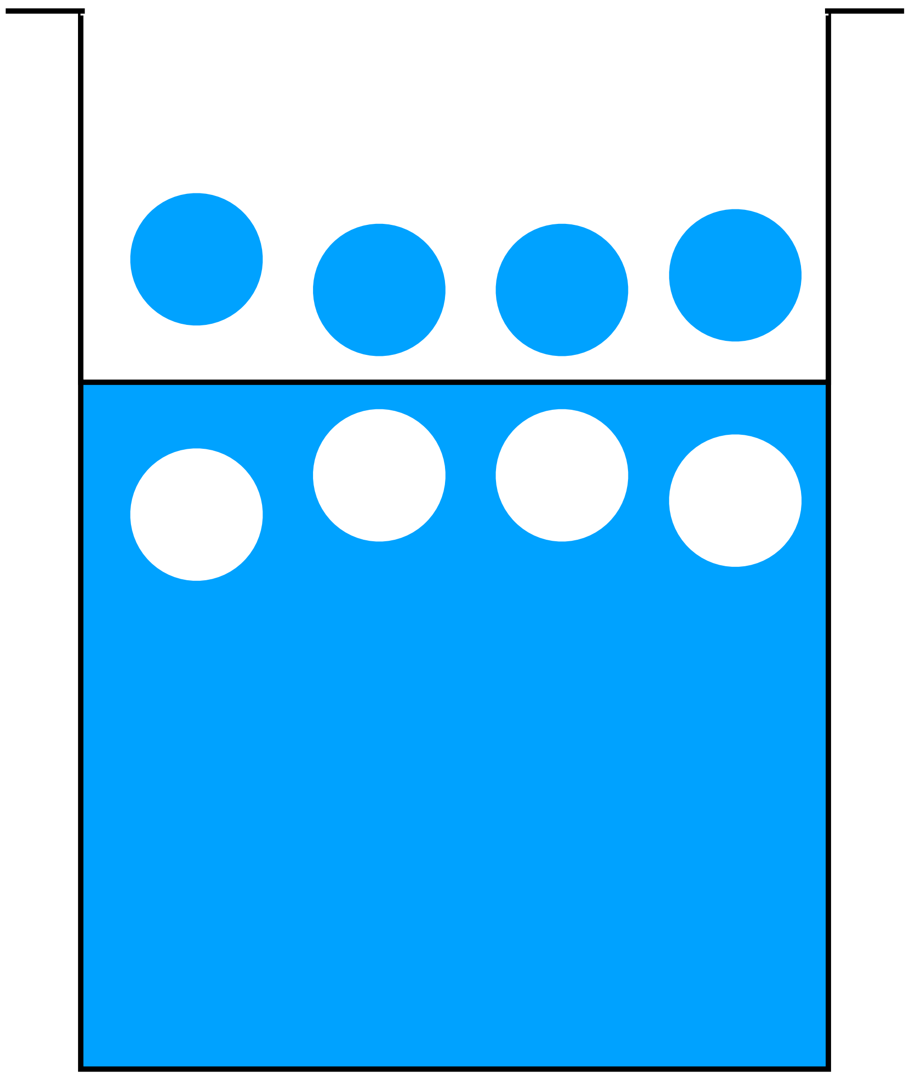
Laser-nucleus interaction and nuclear equilibration



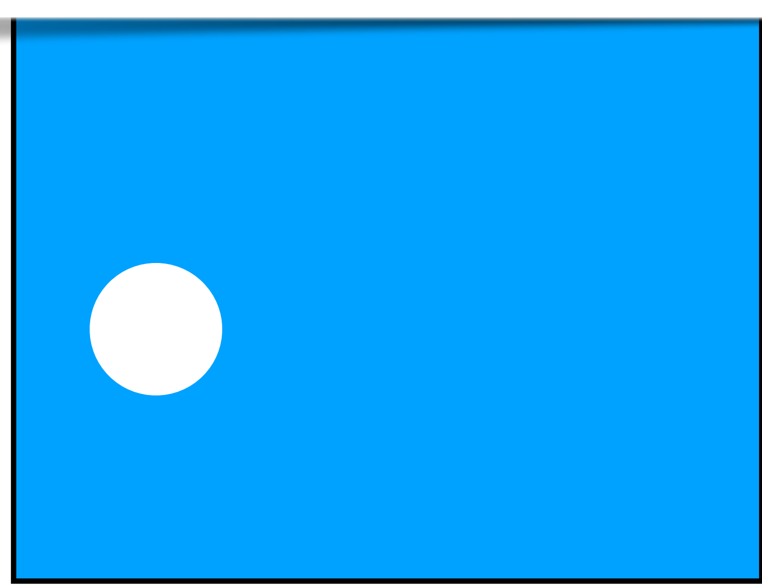
Photon excitation creates p-h pairs



Residual nuclear interaction redistributes energy over p-h pairs

Laser-nucleus interaction and nuclear equilibration

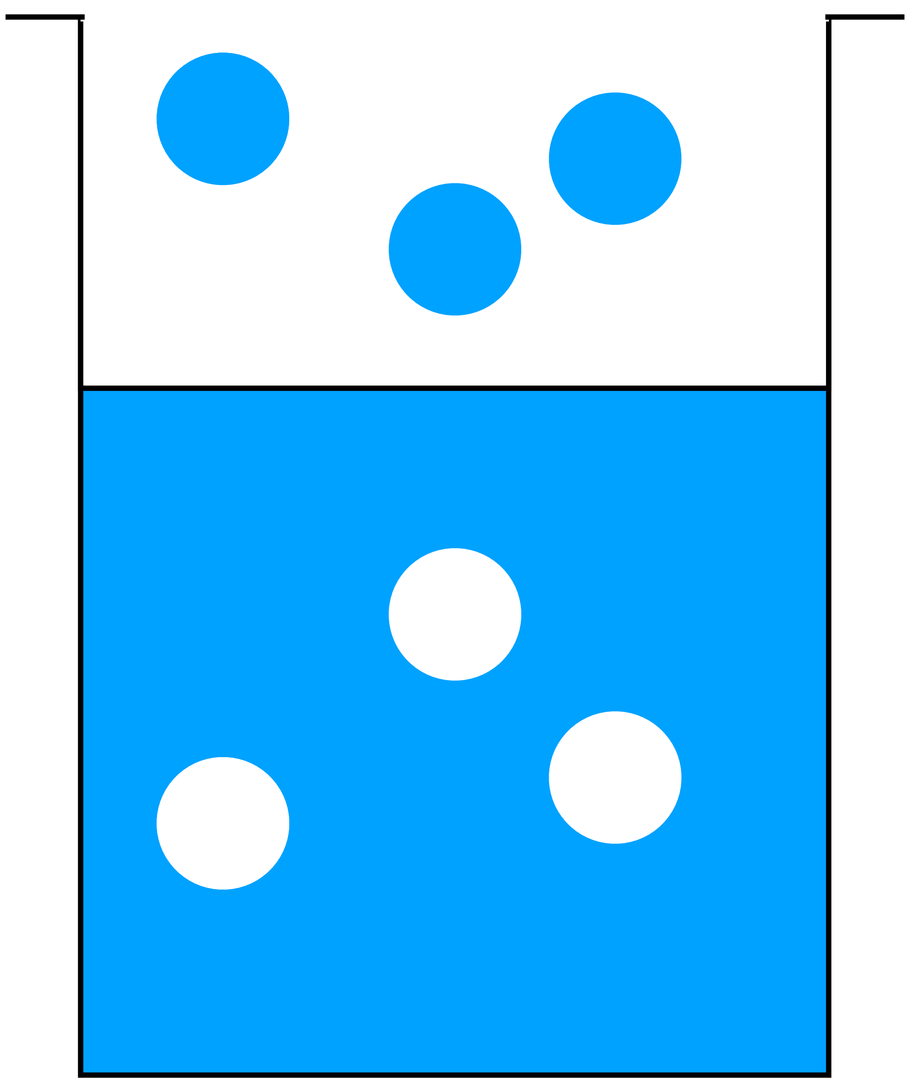
- Theoretical description: mean-field + nucleon-nucleon collisions (“residual” interaction)
- Statistical coupling of all possible states with same energy - “equilibration”
- Equilibration is very fast - “spreading width” 5 MeV corresponds to zeptoseconds (10^{-21} s)



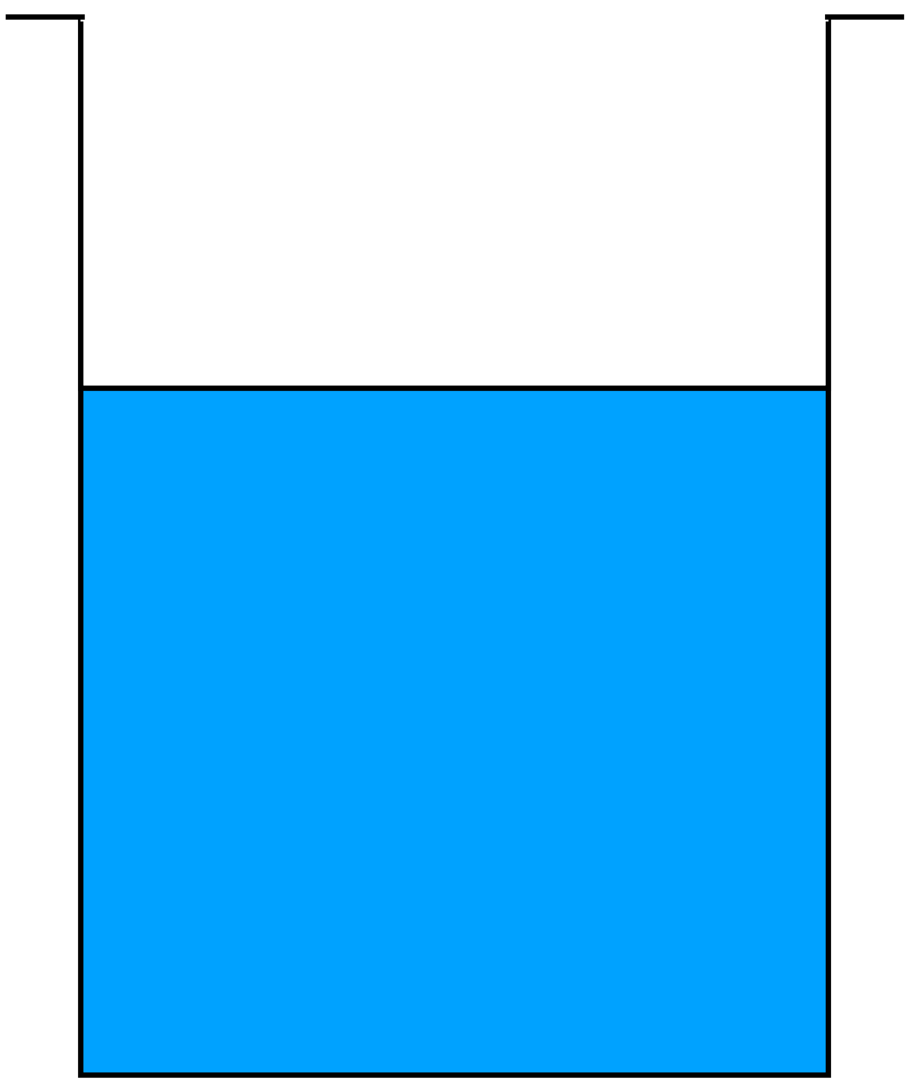
Photon excitation creates p-h pairs

Residual nuclear interaction redistributes energy over p-h pairs

Laser-nucleus interaction and neutron evaporation

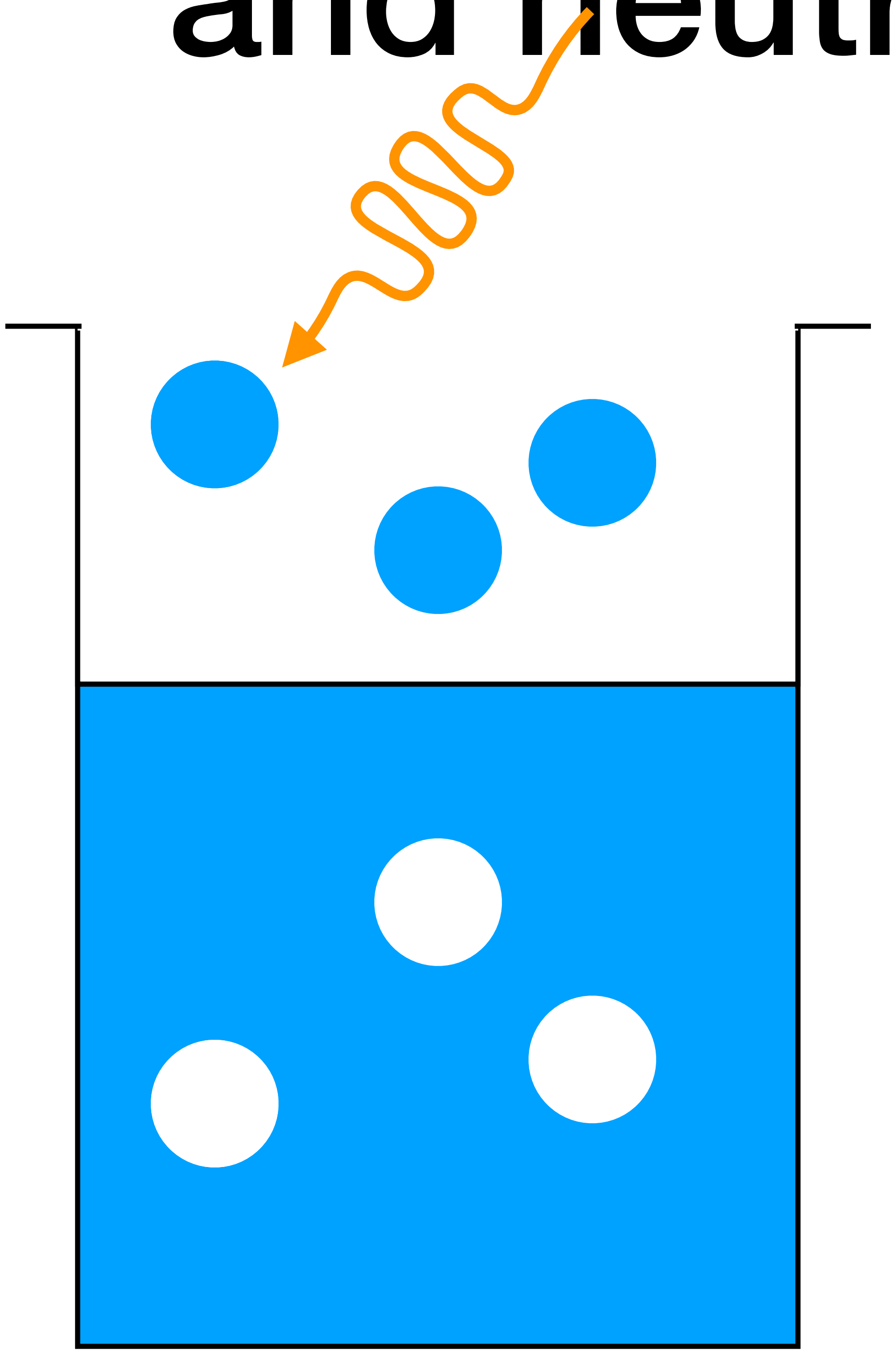


Excitation into continuum



Neutron evaporation
after several absorbed photons

Laser-nucleus interaction and neutron evaporation



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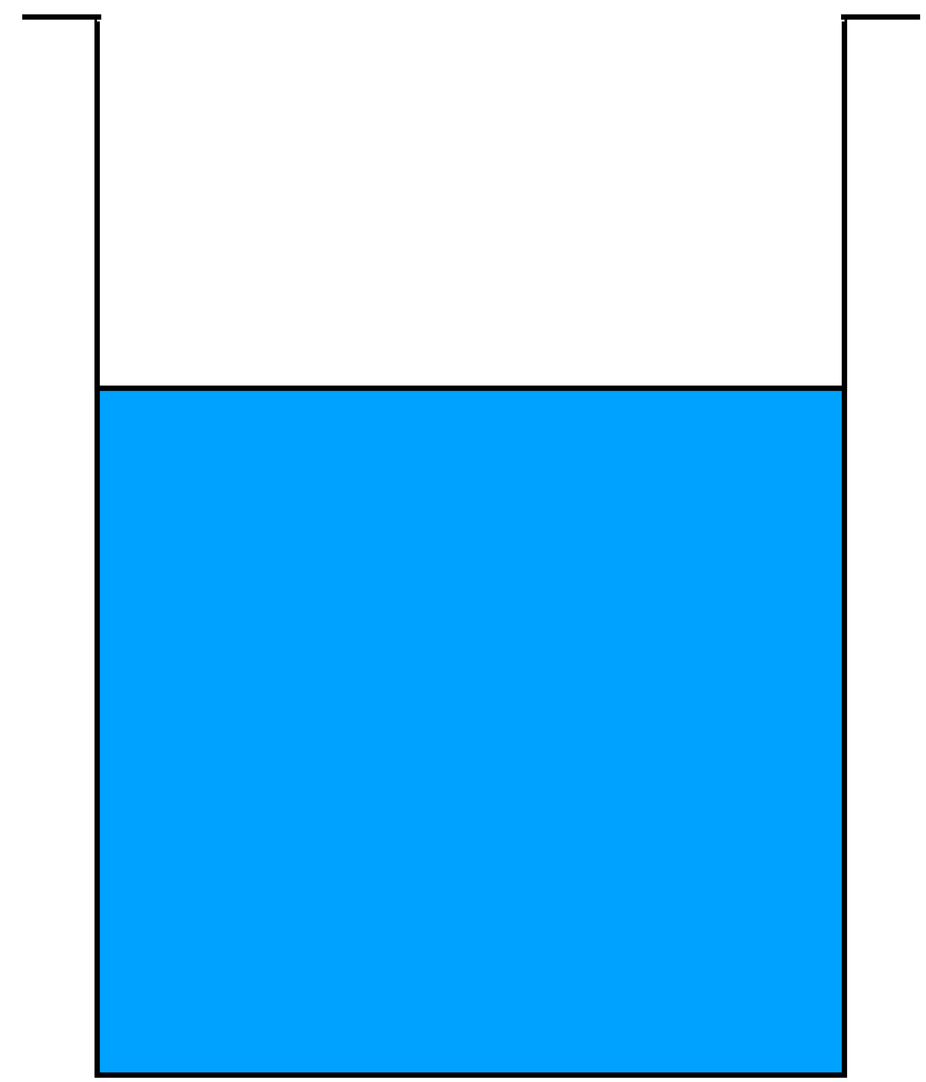

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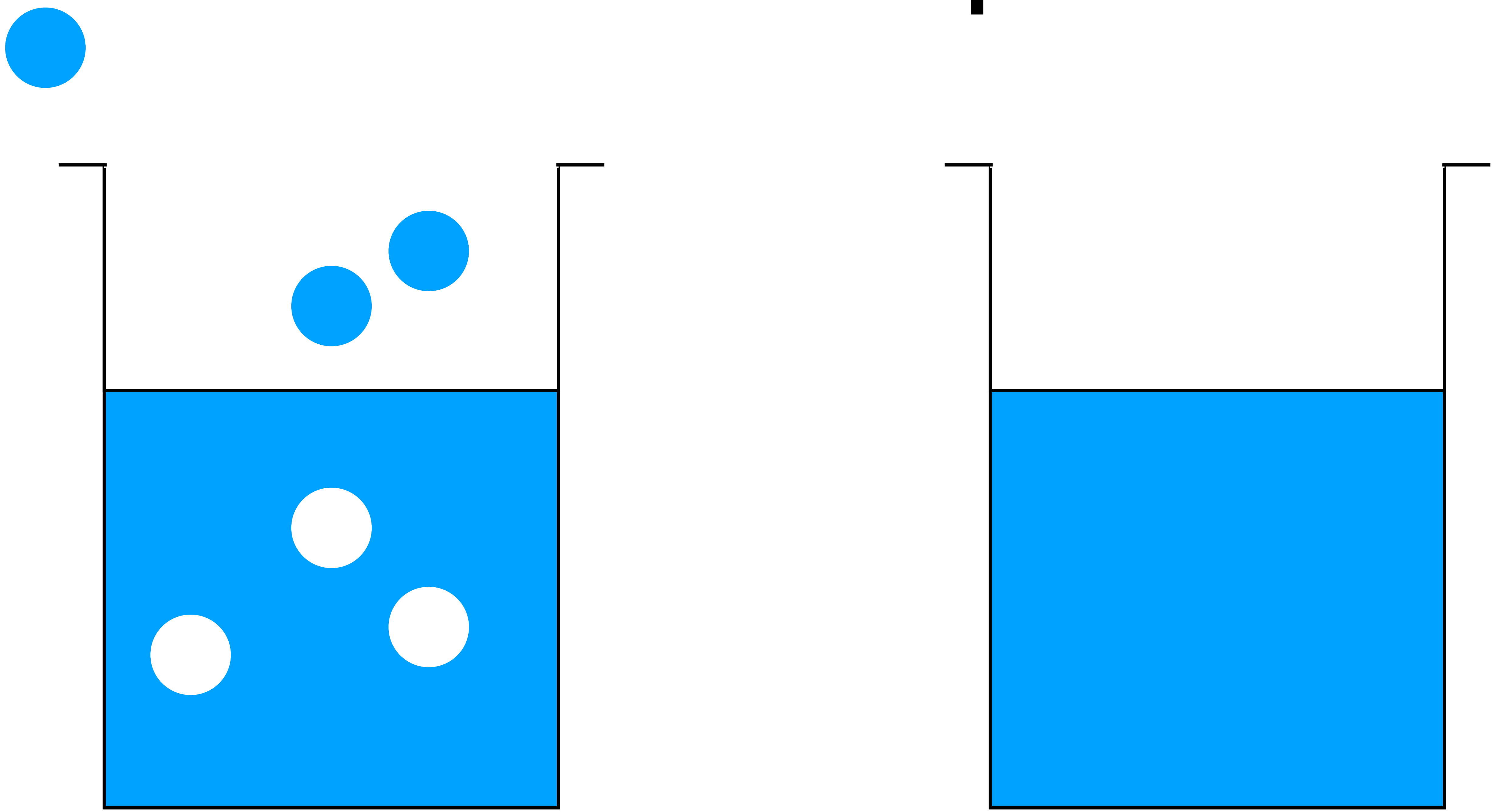

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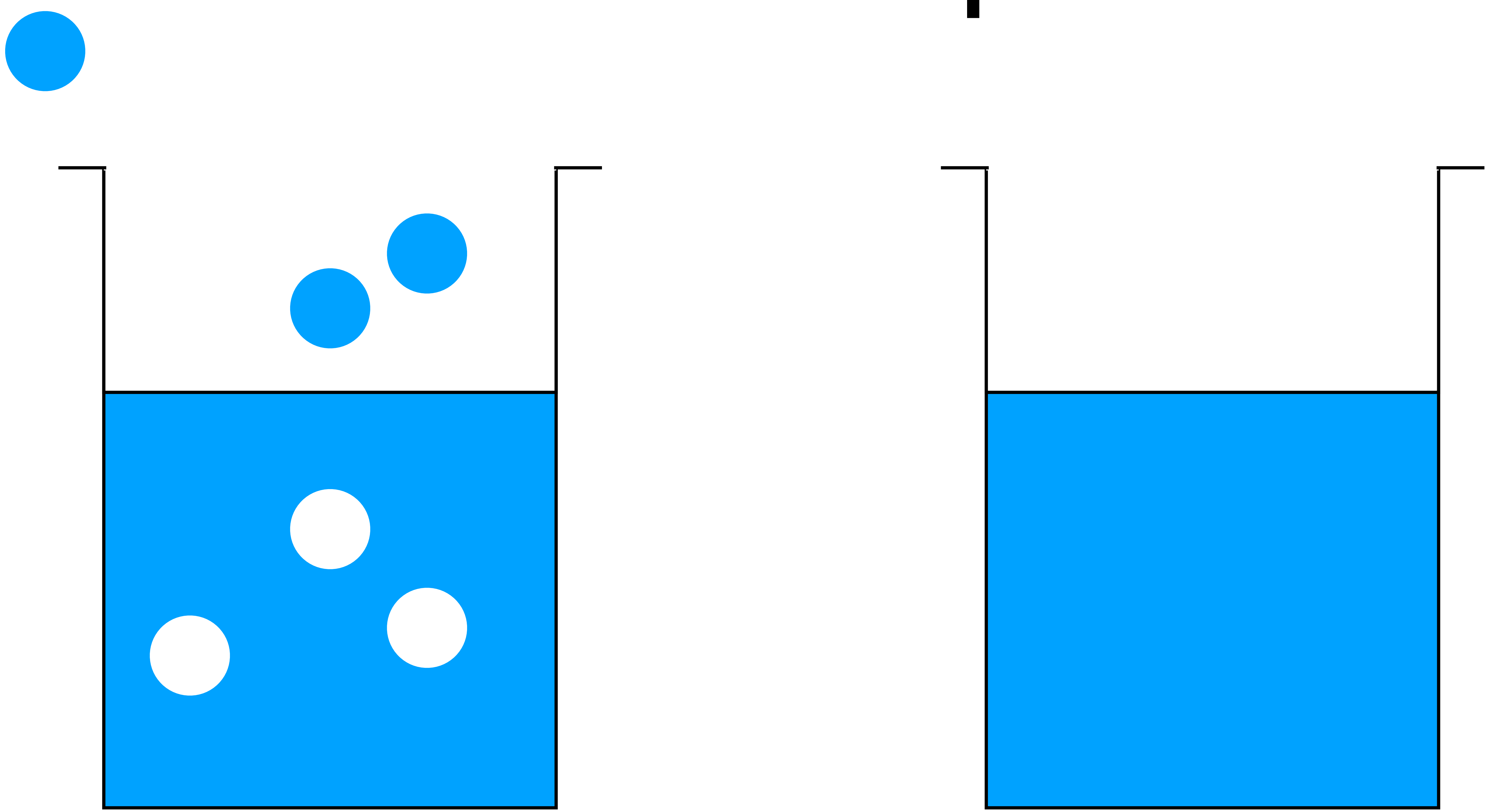

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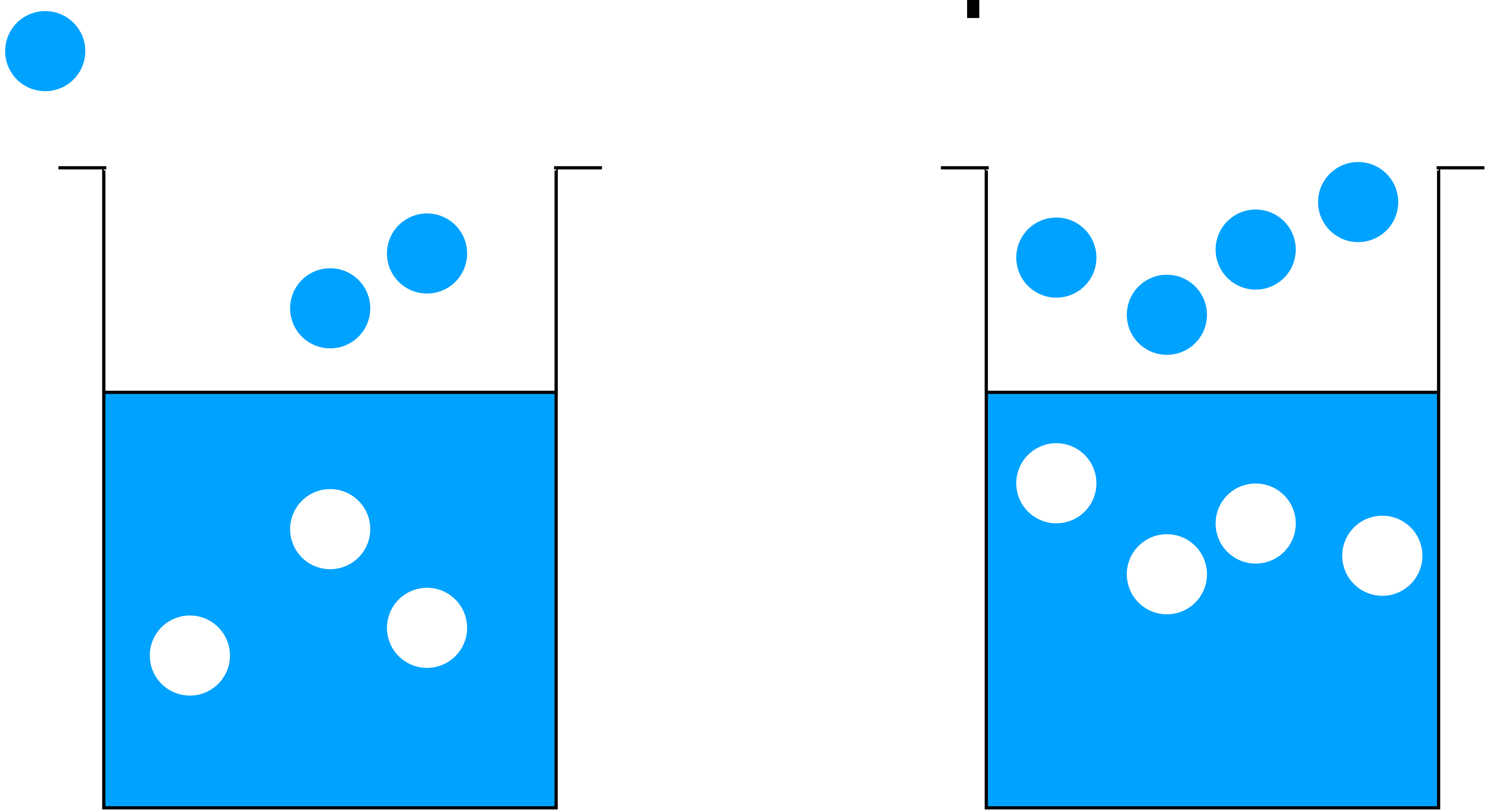

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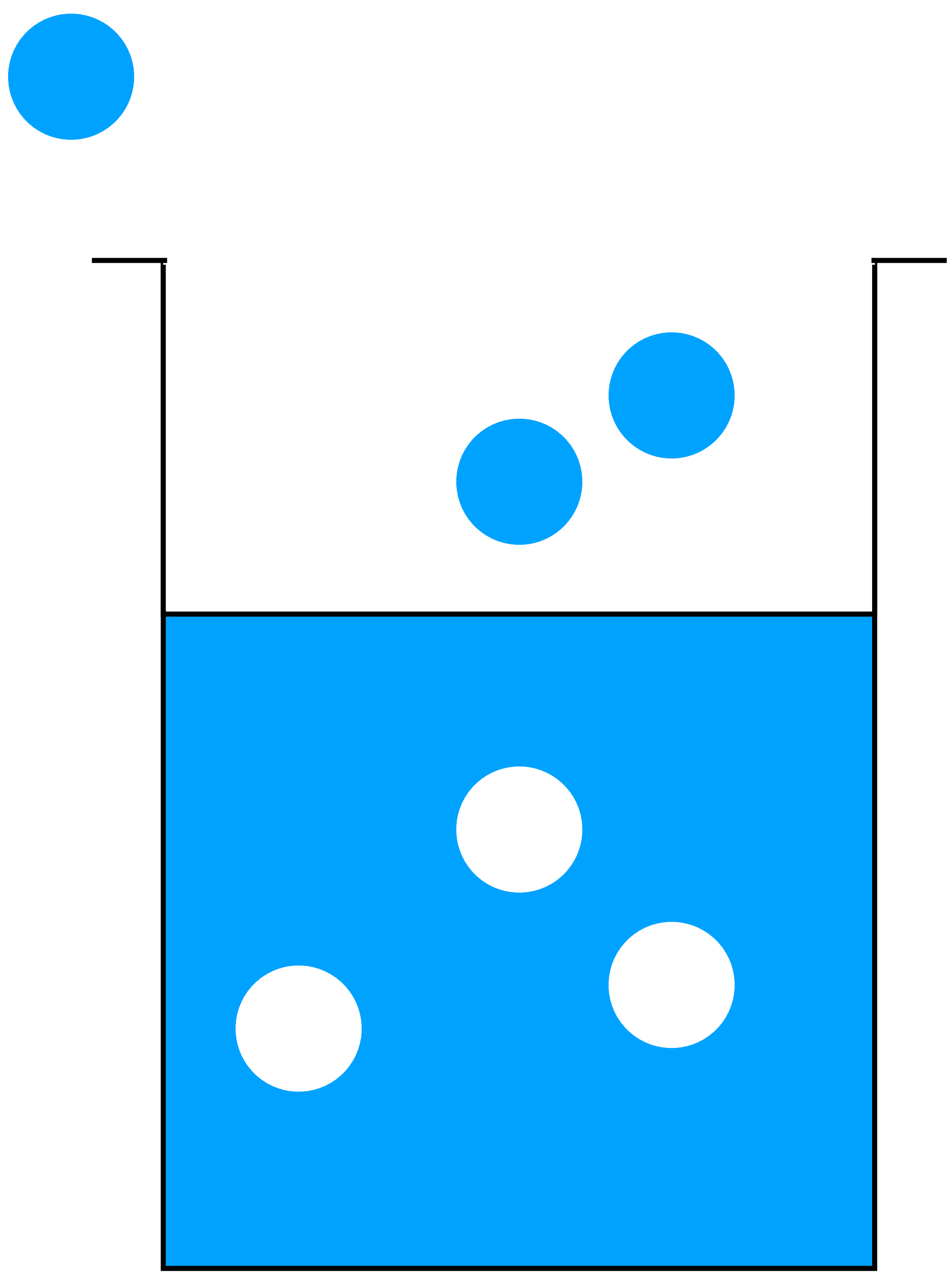

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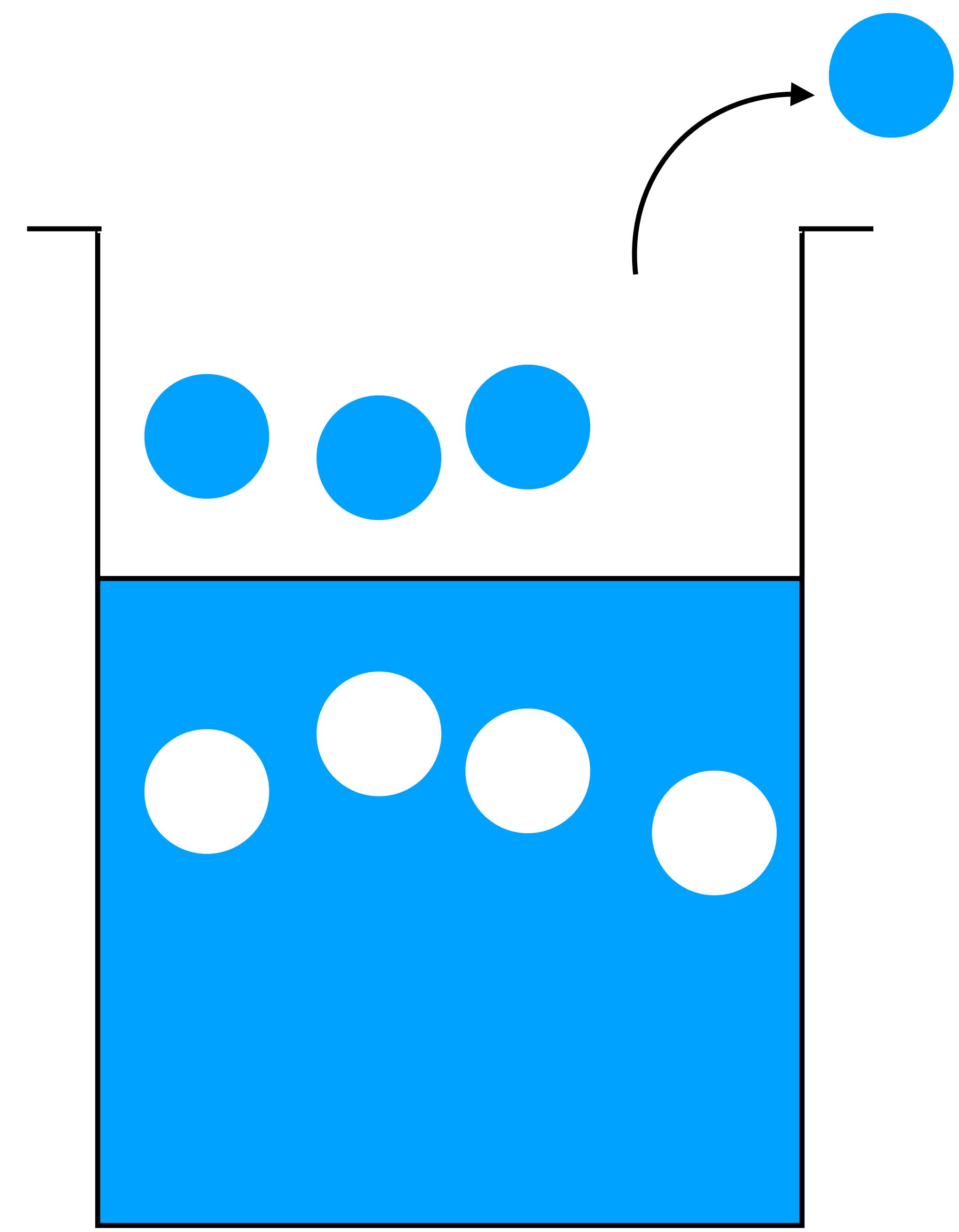
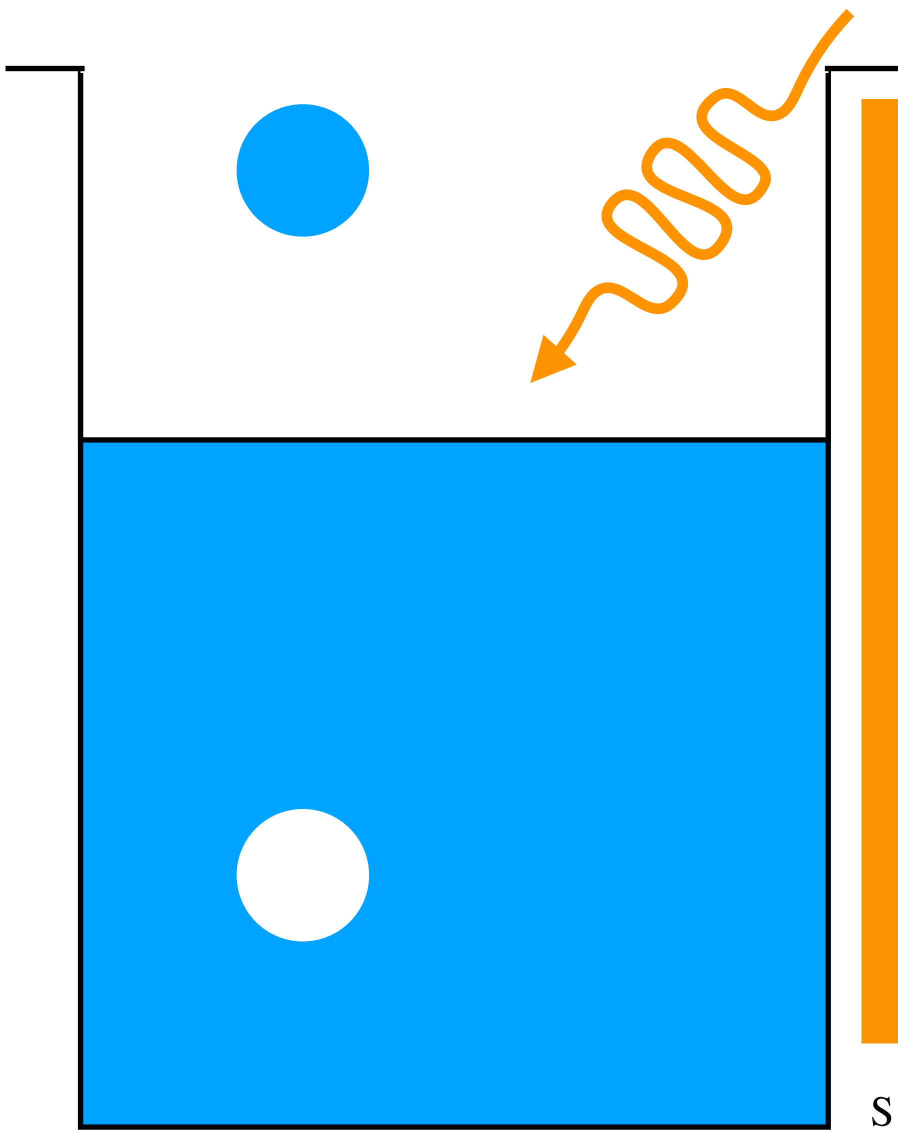


Neutron evaporation after several absorbed photons

Laser-nucleus interaction non-adiabatic regime



Photon excitation

Non-adiabatic Regime

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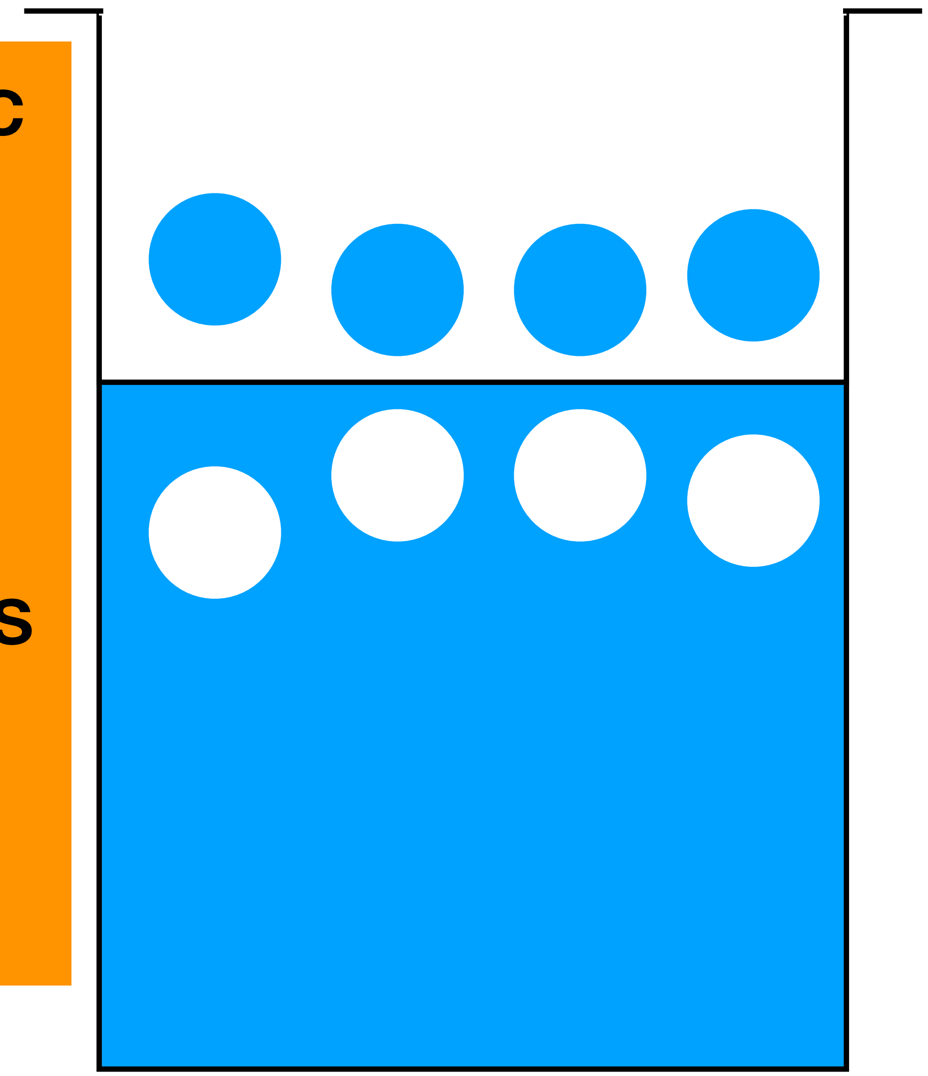
Total equilibration is slower than dipole excitation

S. Kobzak, H. A. Weidenmüller, A. Pálffy
Current work



Nuclear equilibration

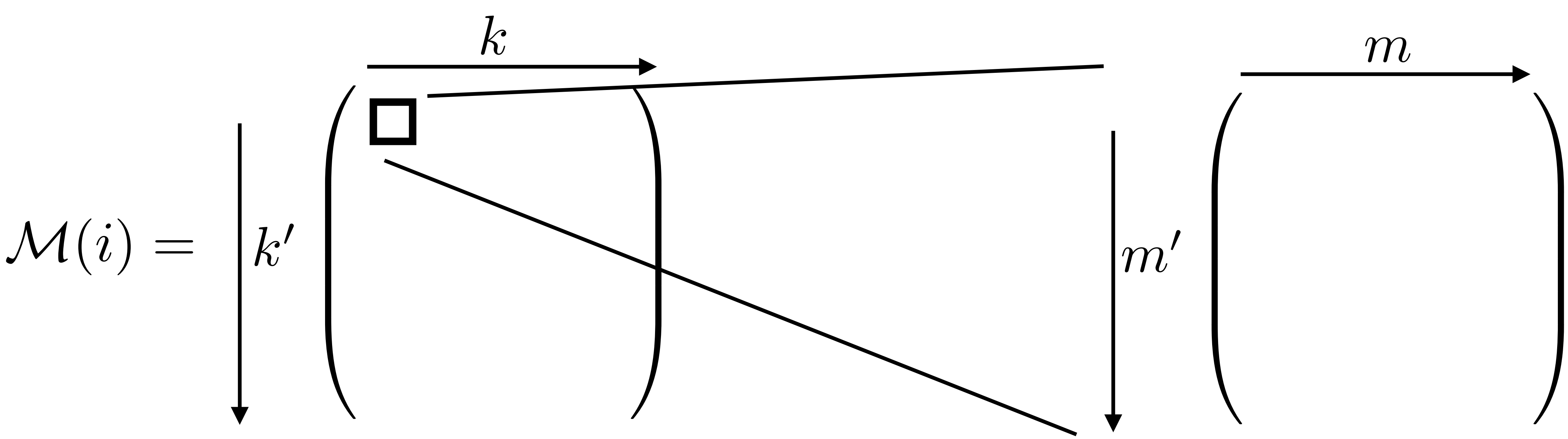
Contents:

1. Laser-nucleus interaction
   - Nucleus as a many-body system
   - Non-adiabatic regime of laser-nucleus interaction
2. **Theory**
   - Master equation
   - Density of states
3. Results
   - Occupation probabilities
   - Neutron evaporation
4. Conclusions

Master equation with p-h states

$P_m(i, k, t)$ is an occupation probability for nuclear species i with k absorbed photons in particle-hole class m at time t.

$$\dot{P}_m(i,k,t) = \mathcal{M}_{k,m;k',m'}(i) P_{m'}(i,k',t)$$



$$\mathcal{M} : W^2_{m,k;m',k'}(i), V^2_{m,m'}(i,k), \Gamma_N(i, k \to k', m); \rho_m(i,k)$$

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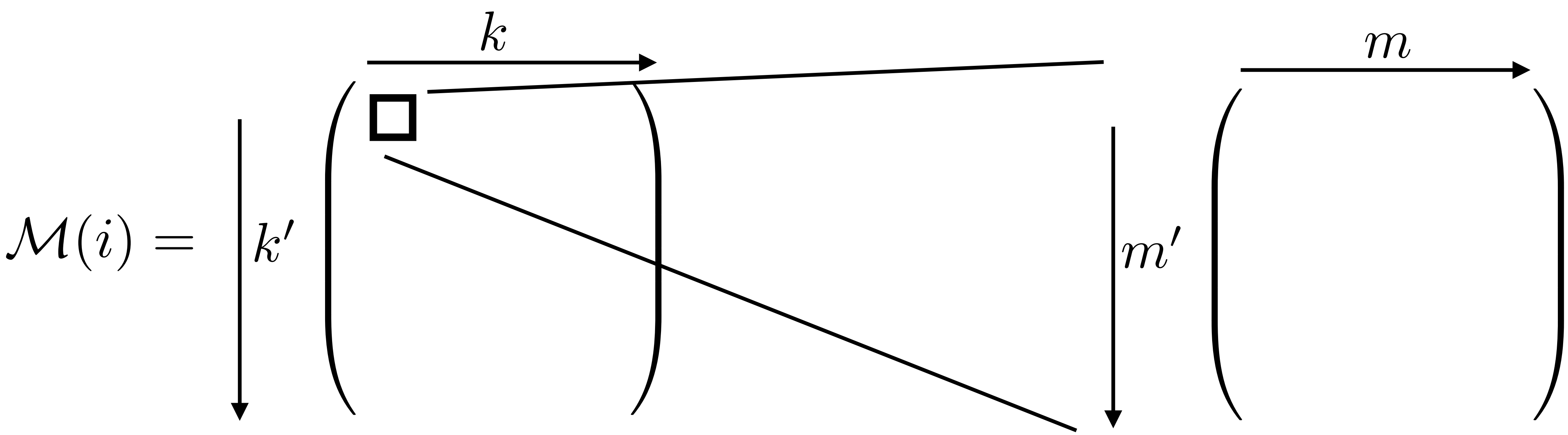


$$\mathcal{M} : W^2_{m,k;m',k'}(i), V^2_{m,m'}(i,k), \Gamma_N(i, k \rightarrow k', m); \rho_m(i,k)$$

Photon absorption & Stimulated emission

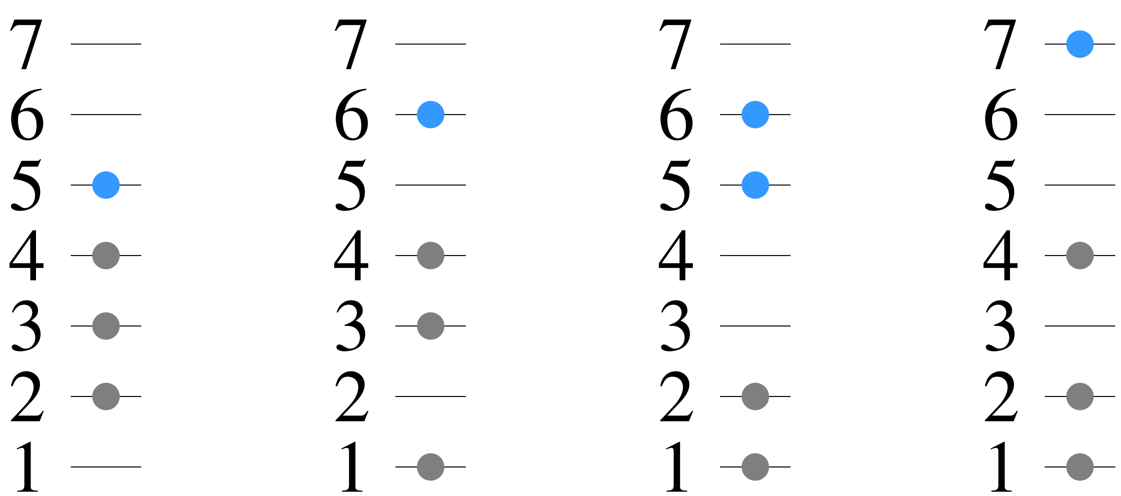
Nuclear equilibration

Neutron evaporation

Density of states

Density of states

Number of possible configurations for a given total energy of the system

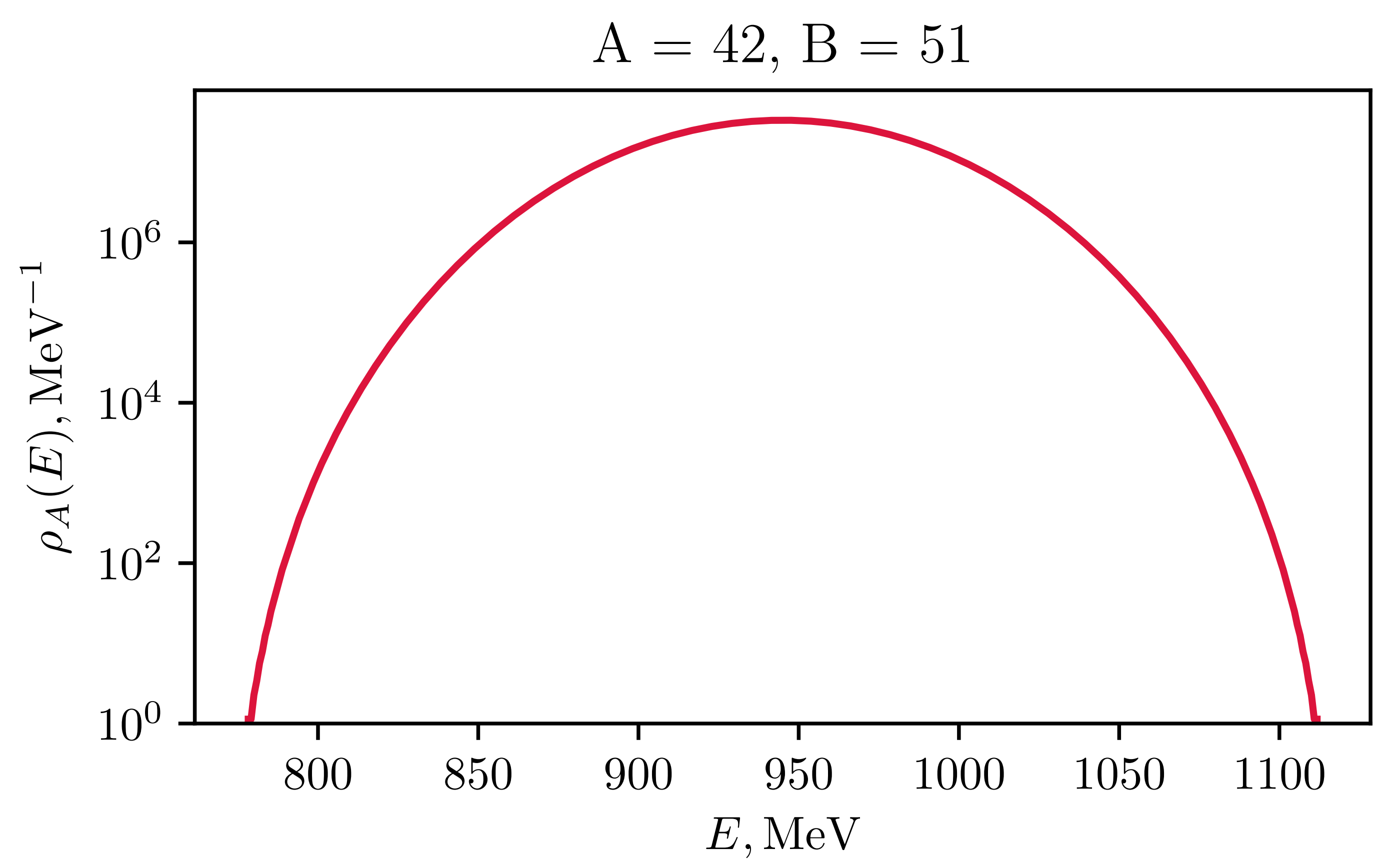


$\rho_1(\varepsilon) = \text{const}$

- $B = 7;\ A = 4$
- $E^* = 14$ (energy units)

$\Rightarrow \rho(E^*) = 4$

- $A \sim 100 \Rightarrow \rho \sim 1..10^{100}$



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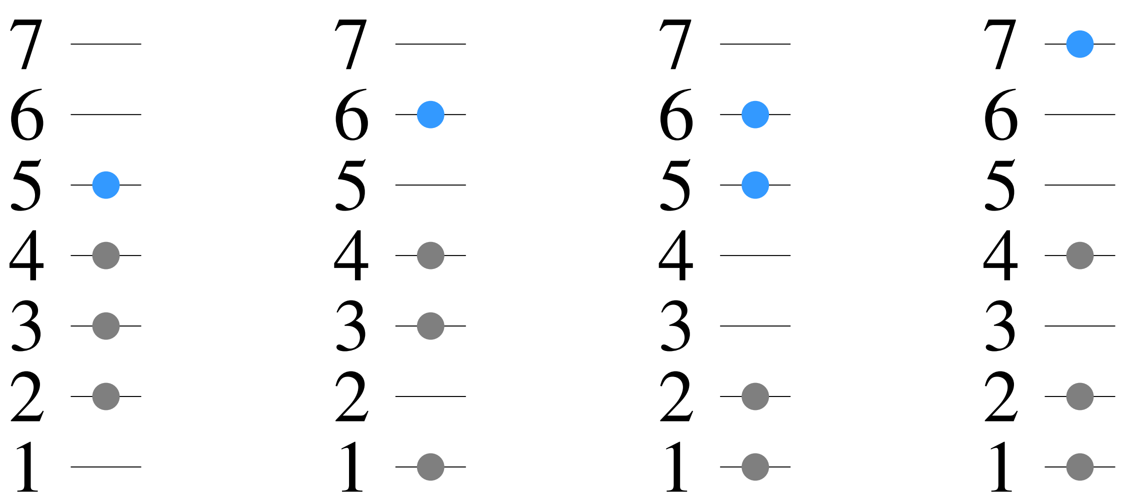

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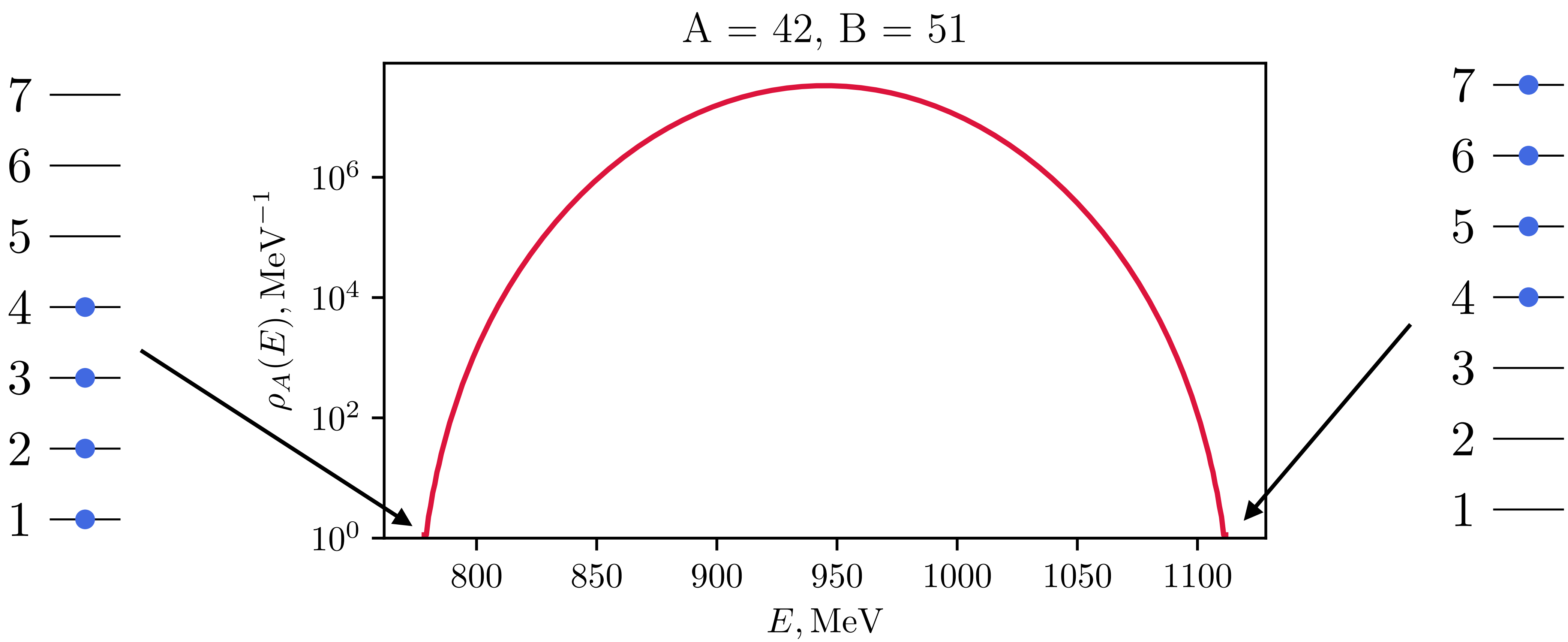
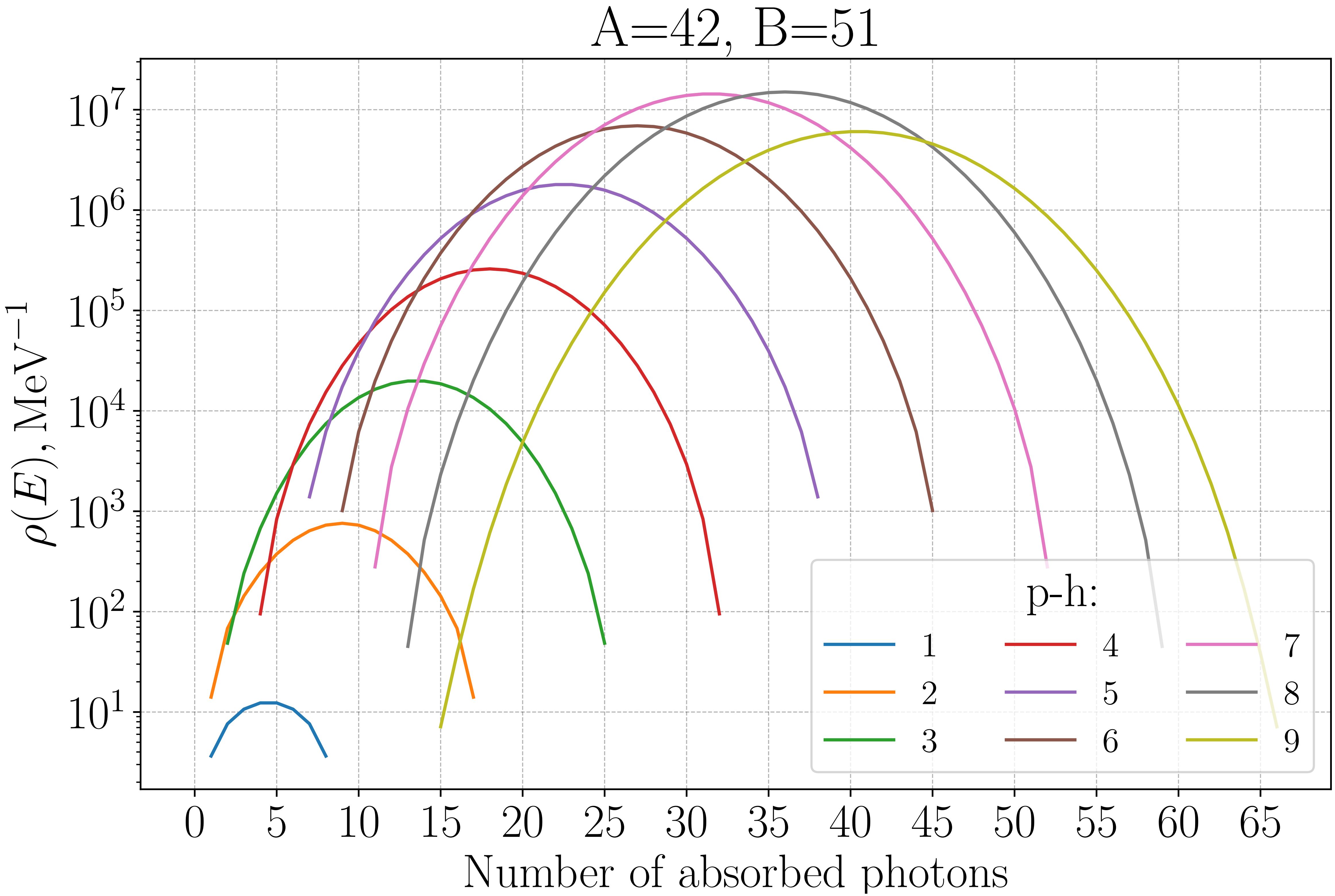


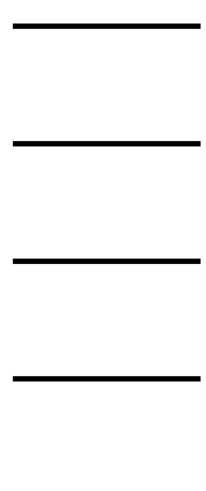
Particle-hole densities



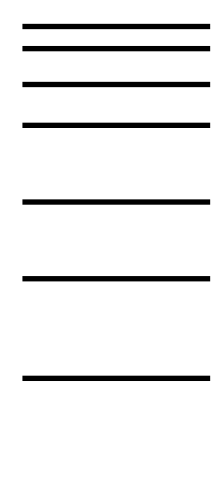
Density of states

Number of possible configurations for a given total energy of the system

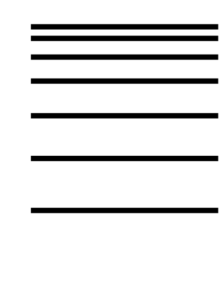
Light nuclei, A~50
Constant spacing



Medium weight, A~100
Linear spacing



Heavy weight, A>100
Quadratic spacing



We need continuous model of density of states

A. Pálffy and H. A. Weidenmüller Nucl. Phys. A 917, 15 (2013)

Master equation with p-h states

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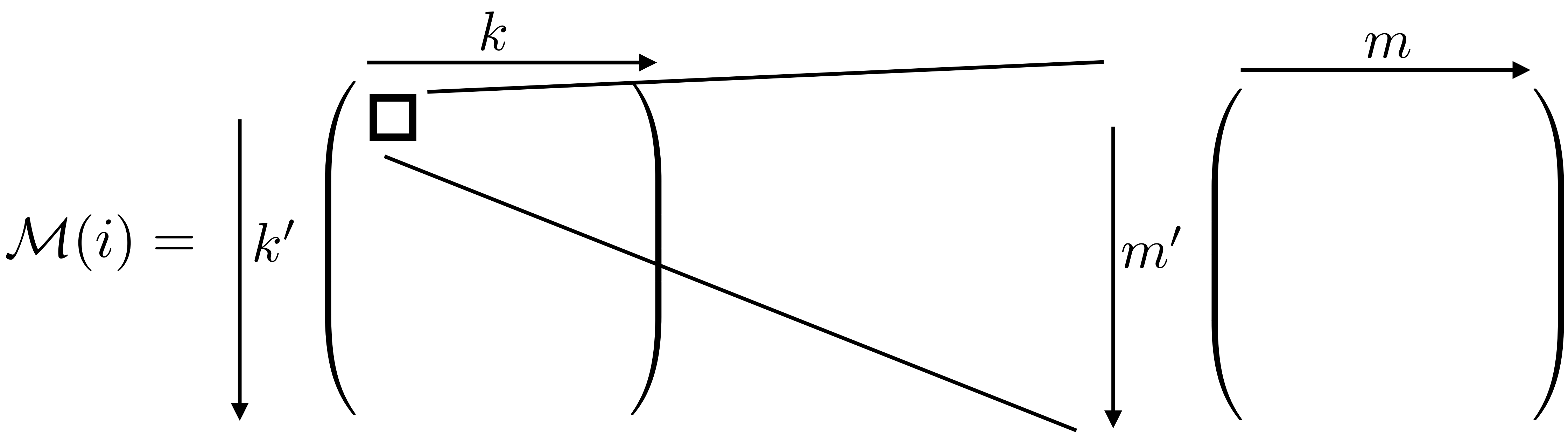

$$\mathcal{M} : W^2_{m,k;m',k'}(i), V^2_{m,m'}(i, k), \Gamma_N(i, k \to k', m); \rho_m(i, k)$$

Photon absorption & Stimulated emission

Nuclear equilibration

Neutron evaporation

Density of states

Master equation with p-h states

$\dot{P}_m(i,k,t) =$

Master equation with p-h states

$$\dot{P}_m(i,k,t) = \Theta(\tau_{pulse} - t)\times$$

$$\times \left\{ \sum_{m'} \rho_m(i,k)[W^2_{m'k';mk} P_{m'}(i,k-1,t) + W^2_{m'k';mk} P_{m'}(i,k+1,t)] \right.$$

$$\left. - P_m(i,k,t)[W^2_{mk;m'k'} \rho_{m'}(i,k+1) + W^2_{mk;m'k'} \rho_{m'}(i,k-1)] \right\}$$

Photon absorption and Stimulated emission

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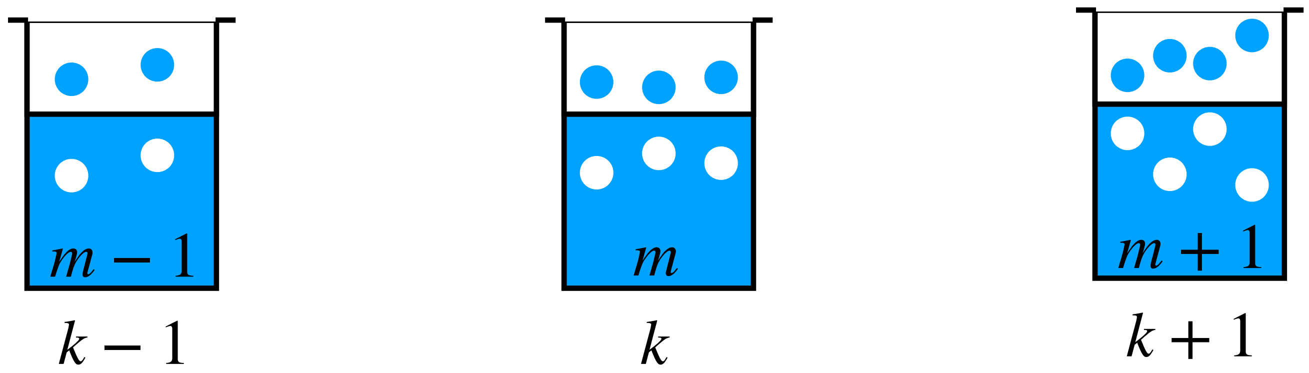
Photon absorption and Stimulated emission



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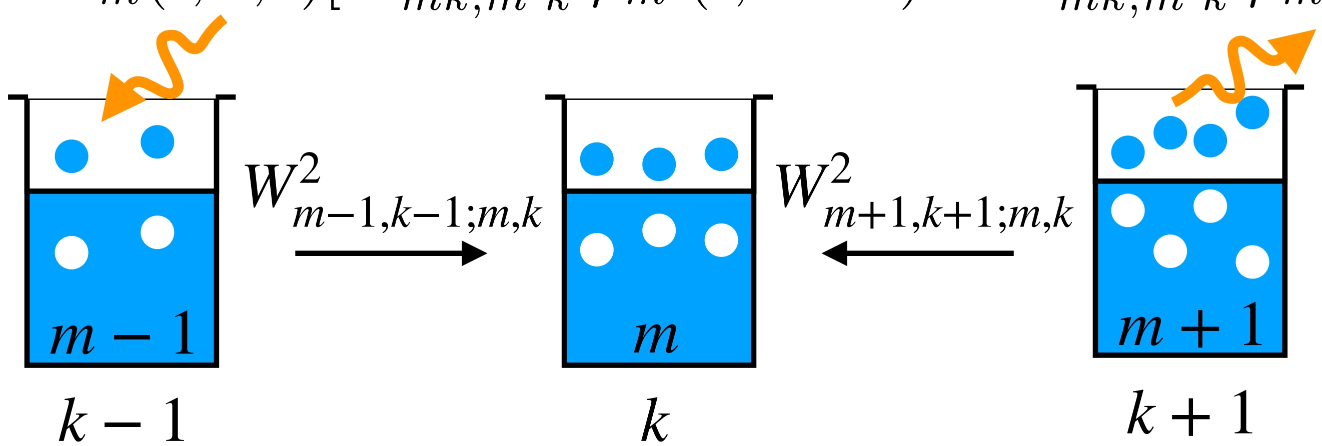
Photon absorption and Stimulated emission

Gain



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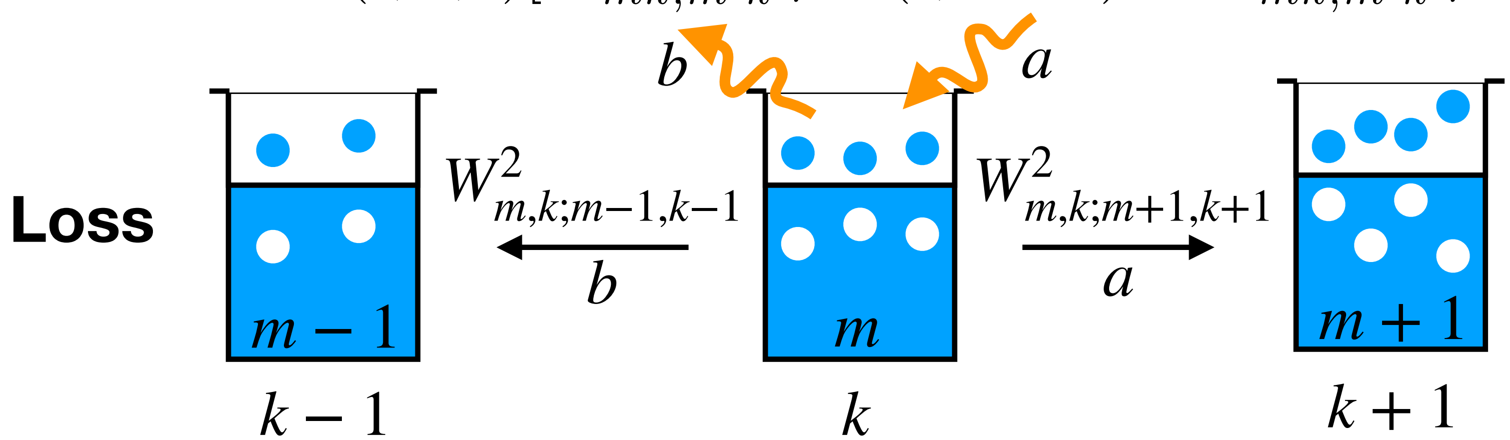
Photon absorption and Stimulated emission



Master equation with p-h states

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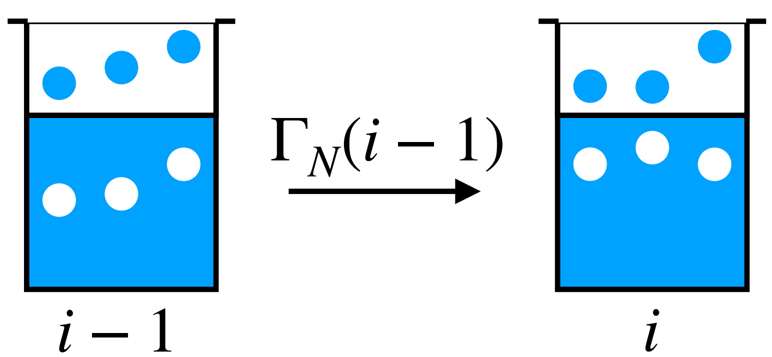
$$\times\left\{\sum_{m'} \rho_m(i,k)[W^2_{m'k';mk} P_{m'}(i,k-1,t) + W^2_{m'k';mk} P_{m'}(i,k+1,t)]\right.$$
$$\left. - P_m(i,k,t)[W^2_{mk;m'k'}\rho_{m'}(i,k+1) + W^2_{mk;m'k'}\rho_{m'}(i,k-1)]\right\}$$
$$+ \sum_{k'm'} \Gamma_N(i-1,k' \to k,m')P_{m'}(i-1,k')$$
$$- \sum_{k'm'} \Gamma_N(i,k \to k',m)P_m(i,k)$$

Photon absorption and Stimulated emission

Neutron evaporation

Gain



Master equation with p-h states

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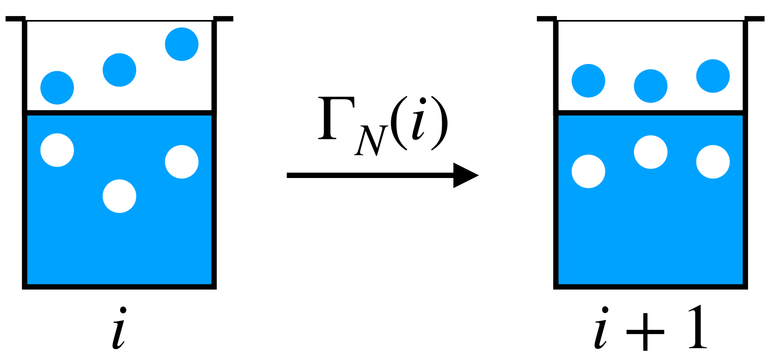
Photon absorption and Stimulated emission

Neutron evaporation

Loss



Master equation with p-h states

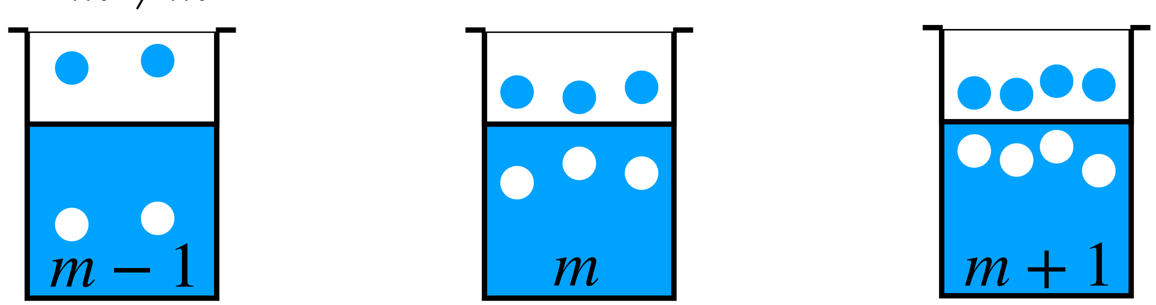
$$\dot{P}_m(i,k,t) = \Theta(\tau_{pulse}-t)\times$$
$$\times\left\{\sum_{m'}\rho_m(i,k)[W^2_{m'k';mk}P_{m'}(i,k-1,t)+W^2_{m'k';mk}P_{m'}(i,k+1,t)]\right.$$
$$\left.-P_m(i,k,t)[W^2_{mk;m'k'}\rho_{m'}(i,k+1)+W^2_{mk;m'k'}\rho_{m'}(i,k-1)]\right\}$$

Photon absorption and Stimulated emission

$$+\sum_{k'm'}\Gamma_N(i-1,k'\to k,m')P_{m'}(i-1,k')$$
$$-\sum_{k'm'}\Gamma_N(i,k\to k',m)P_m(i,k)$$

Neutron evaporation

$$+\sum_{m'\neq m}V^2_{m'm}(i,k)\rho_m(i,k)P_{m'}(i,k,t)$$
$$-\sum_{m'\neq m}V^2_{mm'}(i,k)\rho_{m'}(i,k)P_m(i,k,t)$$



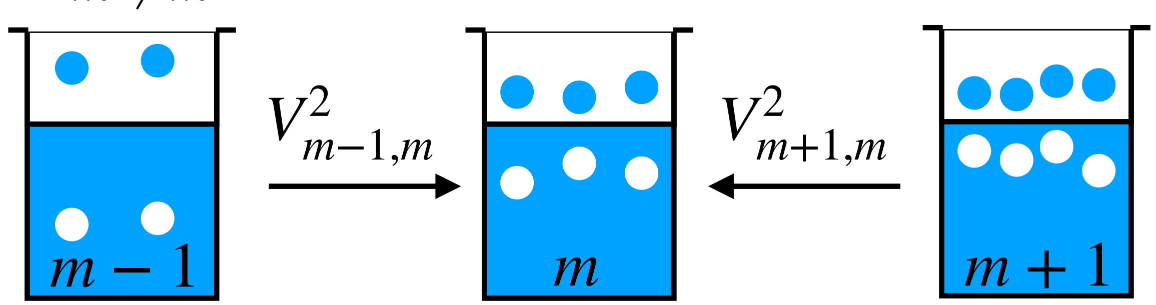
Master equation with p-h states

$$
\begin{aligned}
\dot{P}_m(i,k,t) = {} & \Theta(\tau_{pulse} - t)\times \\
& \times \Big\{ \sum_{m'} \rho_m(i,k)[W^2_{m'k';mk} P_{m'}(i,k-1,t) + W^2_{m'k';mk} P_{m'}(i,k+1,t)] \\
& \quad - P_m(i,k,t)[W^2_{mk;m'k'} \rho_{m'}(i,k+1) + W^2_{mk;m'k'} \rho_{m'}(i,k-1)] \Big\} \\
& + \sum_{k'm'} \Gamma_N(i-1,k' \to k,m') P_{m'}(i-1,k') \\
& - \sum_{k'm'} \Gamma_N(i,k \to k',m) P_m(i,k) \\
& + \sum_{m' \neq m} V^2_{m'm}(i,k) \rho_m(i,k) P_{m'}(i,k,t) \\
& - \sum_{m' \neq m} V^2_{mm'}(i,k) \rho_{m'}(i,k) P_m(i,k,t)
\end{aligned}
$$

Photon absorption and Stimulated emission

Neutron evaporation

Gain



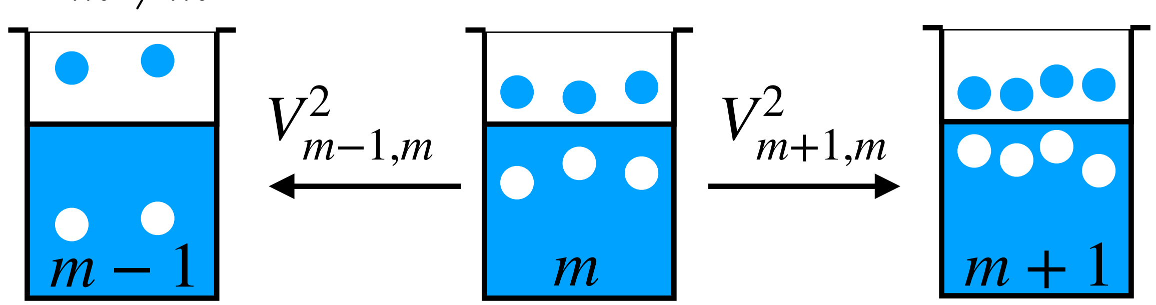
Master equation with p-h states

$$
\begin{aligned}
\dot{P}_m(i,k,t) = \; & \Theta(\tau_{pulse} - t) \times \\
& \times \left\{ \sum_{m'} \rho_m(i,k)[W^2_{m'k';mk} P_{m'}(i,k-1,t) + W^2_{m'k';mk} P_{m'}(i,k+1,t)] \right. \\
& \left. \quad - P_m(i,k,t)[W^2_{mk;m'k'} \rho_{m'}(i,k+1) + W^2_{mk;m'k'} \rho_{m'}(i,k-1)] \right\} \\
& + \sum_{k'm'} \Gamma_N(i-1,k' \to k,m') P_{m'}(i-1,k') \\
& - \sum_{k'm'} \Gamma_N(i,k \to k',m) P_m(i,k) \\
& + \sum_{m' \neq m} V^2_{m'm}(i,k) \rho_m(i,k) P_{m'}(i,k,t) \\
& - \sum_{m' \neq m} V^2_{mm'}(i,k) \rho_{m'}(i,k) P_m(i,k,t)
\end{aligned}
$$

Photon absorption and Stimulated emission

Neutron evaporation

Loss



Master equation with p-h states

$$\dot{P}_m(i,k,t) = \Theta(\tau_{pulse} - t)\times$$
$$\times\left\{\sum_{m'} \rho_m(i,k)[W^2_{m'k';mk}P_{m'}(i,k-1,t) + W^2_{m'k';mk}P_{m'}(i,k+1,t)]\right.$$
$$\left. - P_m(i,k,t)[W^2_{mk;m'k'}\rho_{m'}(i,k+1) + W^2_{mk;m'k'}\rho_{m'}(i,k-1)]\right\}$$

Photon absorption and Stimulated emission

$$+ \sum_{k'm'} \Gamma_N(i-1,k' \to k,m')P_{m'}(i-1,k')$$
$$- \sum_{k'm'} \Gamma_N(i,k \to k',m)P_m(i,k)$$

Neutron evaporation

$$+ \sum_{m' \neq m} V^2_{m'm}(i,k)\rho_m(i,k)P_{m'}(i,k,t)$$
$$- \sum_{m' \neq m} V^2_{mm'}(i,k)\rho_{m'}(i,k)P_m(i,k,t)$$

Nuclear equilibration

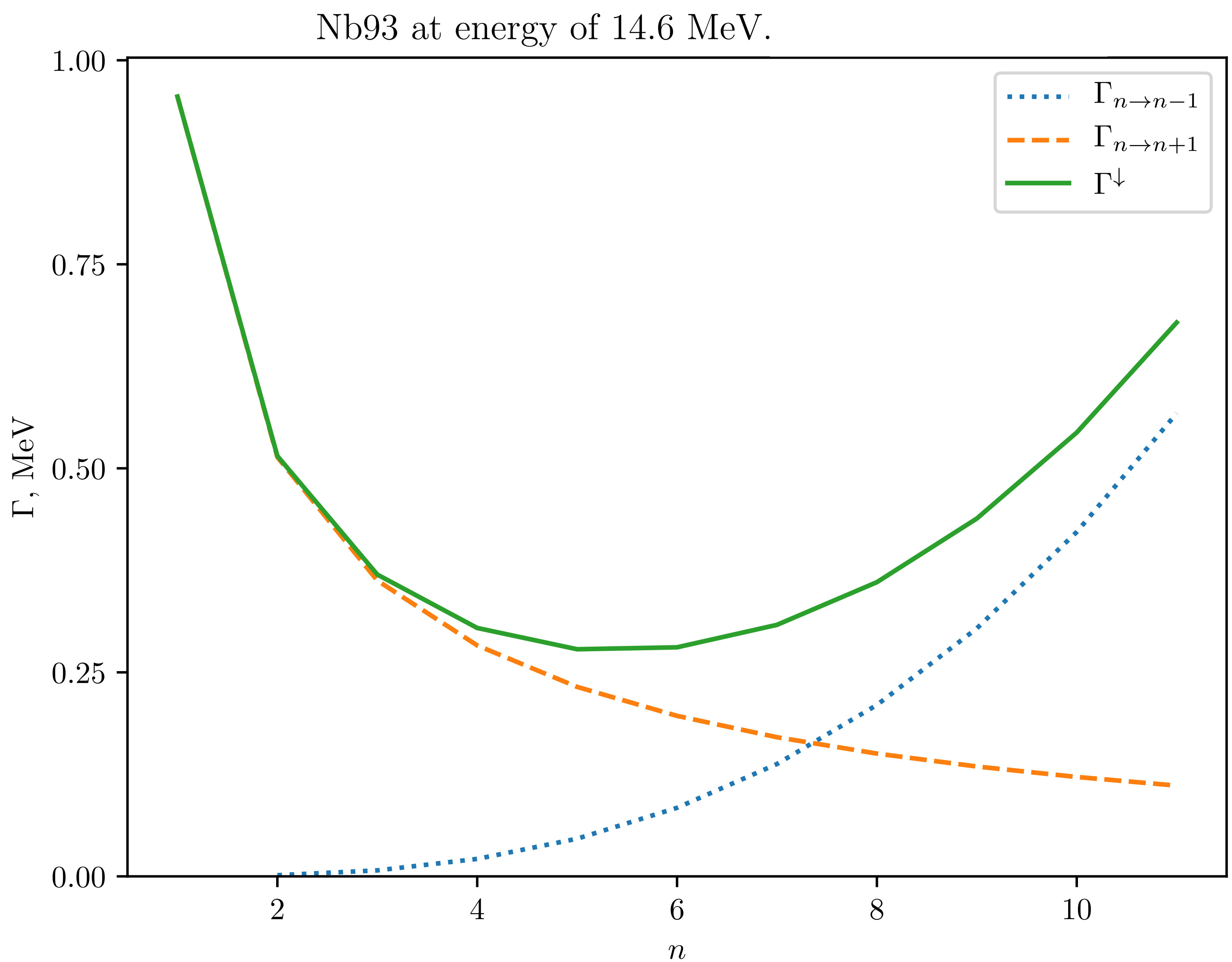
Nuclear equilibration

$$\Gamma^{\downarrow}_{m} = \Gamma^{\downarrow}_{m,m+1} + \Gamma^{\downarrow}_{m-1,m} = 2\pi\hbar \sum_{m,m'} V^2_{mm'}\rho_{m'}$$

$$2\pi\hbar V^2_{m,m+1}\rho_{m+1} = \Gamma^{\downarrow}_{m,m+1}$$

- M. Herman, G. Reffo, and H. A. Weidenmüller, Nucl. Phys. A 536 (1992) 124.

Spreading width



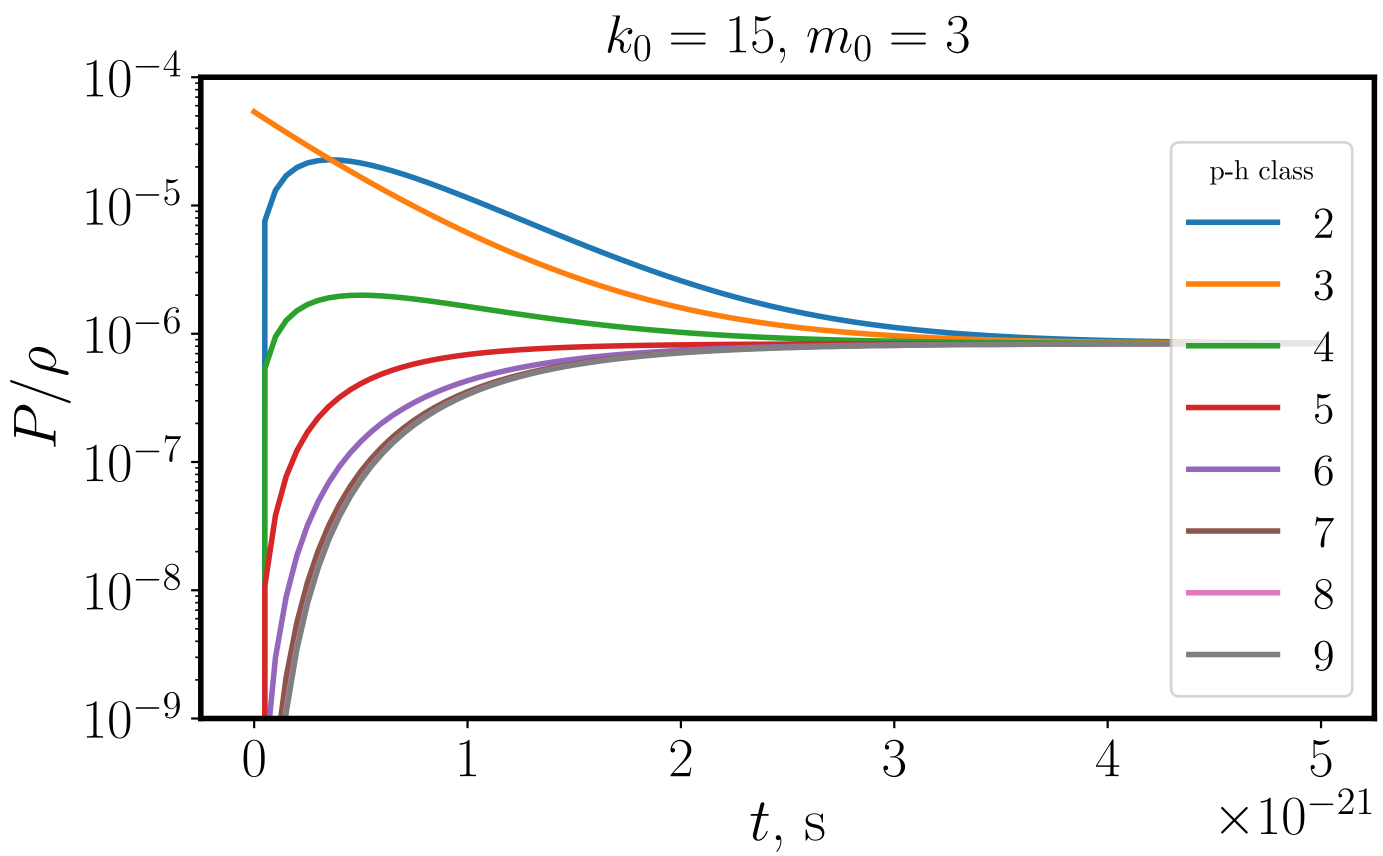
- M. Herman, G. Reffo, and H. A. Weidenmüller, Nucl. Phys. A 536 (1992) 124.

Contents:

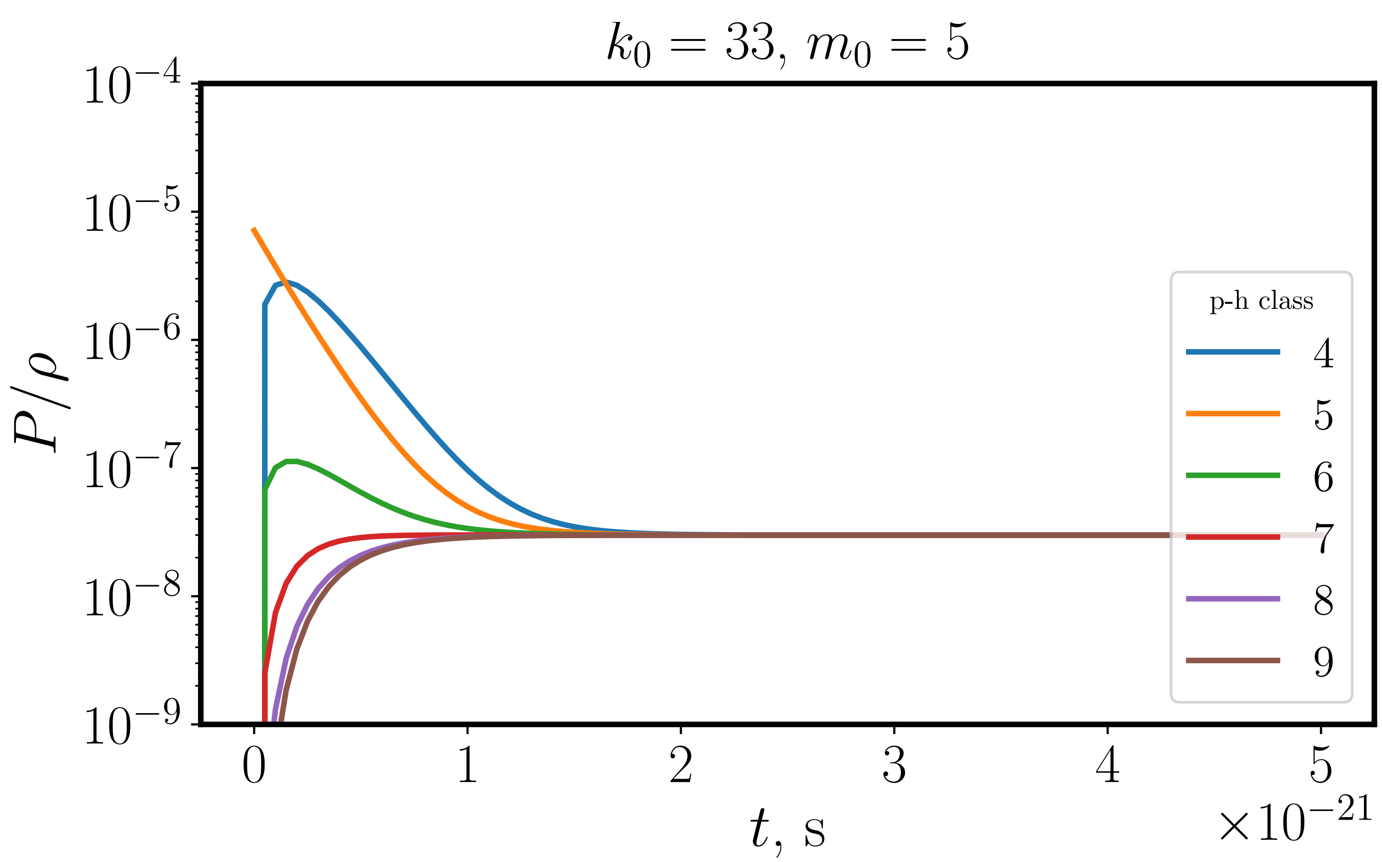
1. Laser-nucleus interaction
   - Nucleus as a many-body system
   - Non-adiabatic regime of laser-nucleus interaction
2. Theory
   - Master equation
   - Density of states
3. **Results**
   - Occupation probabilities
   - Neutron evaporation
4. Conclusions

Investigation of equilibration in p-h

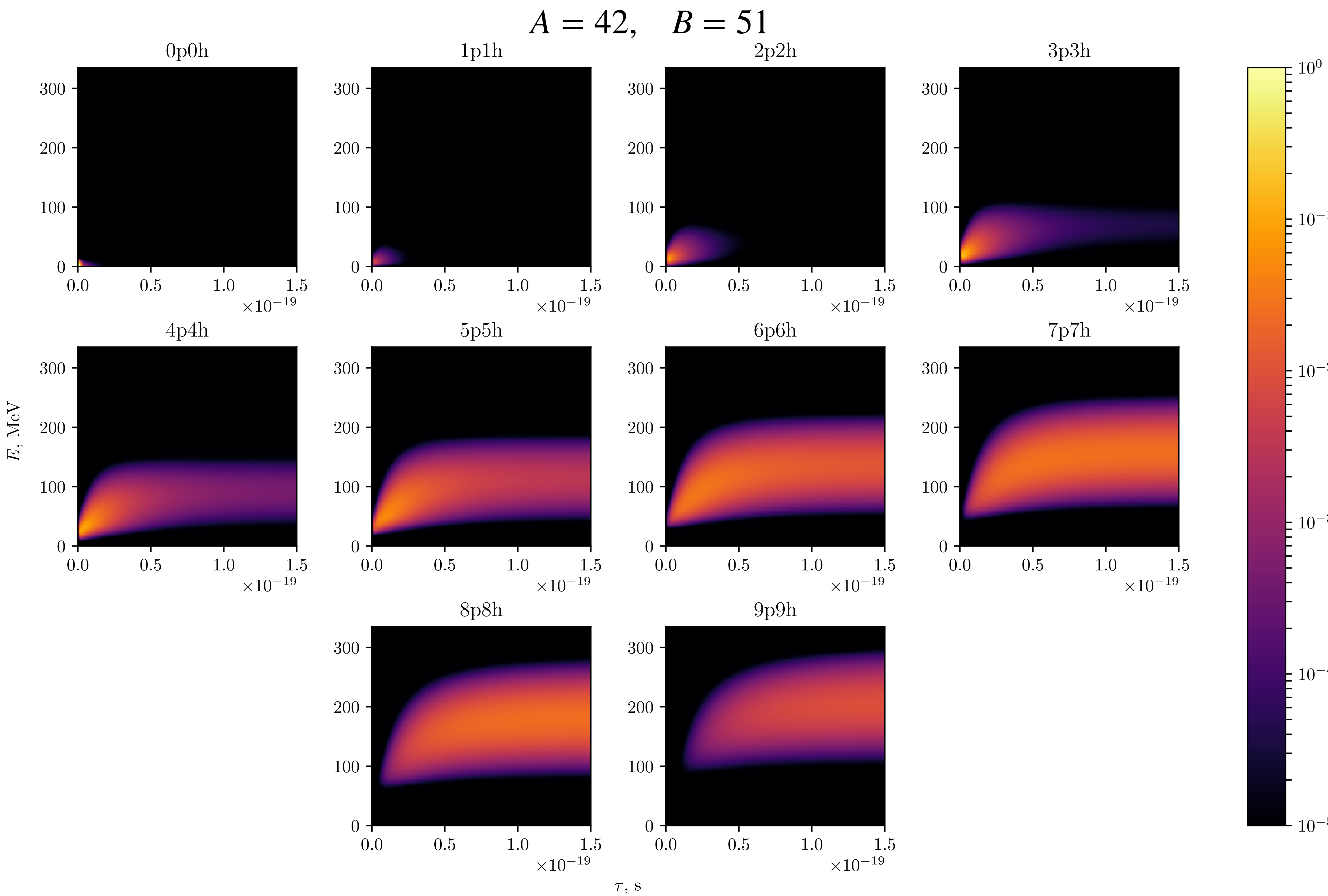
$A = 42, \quad B = 51$



$A = 42, \quad B = 51$

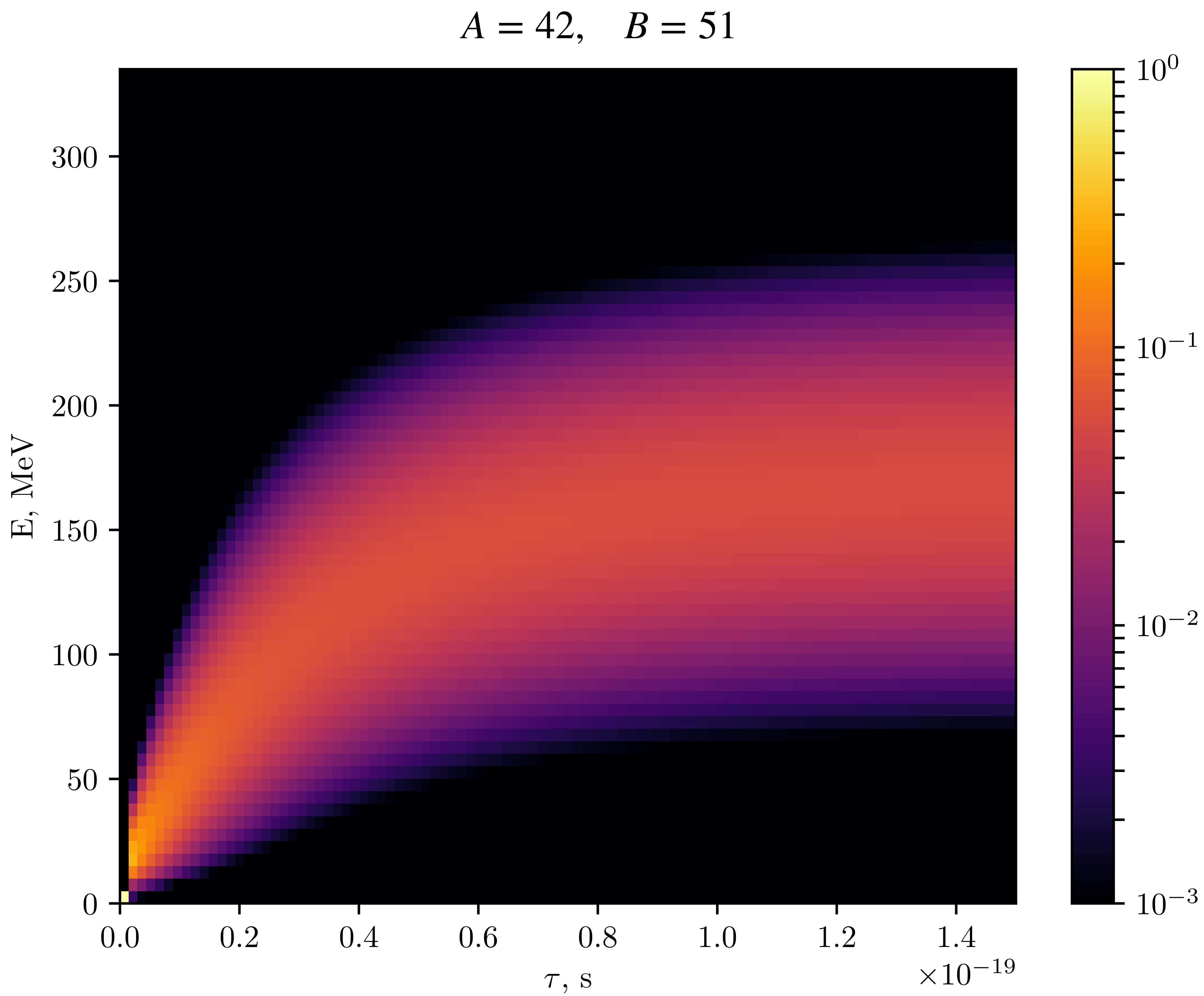


Results

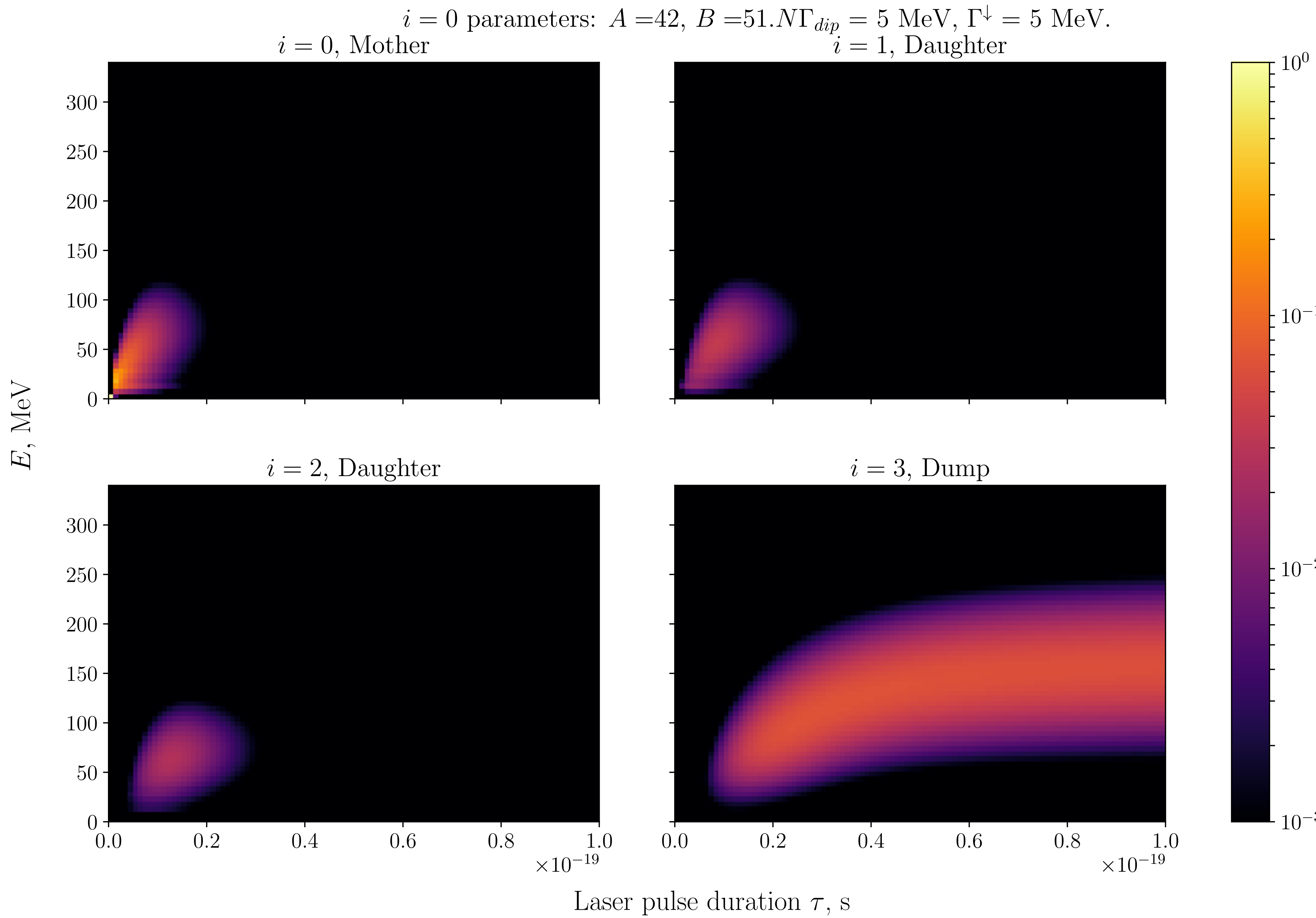


$A = 42, \quad B = 51$
0p0h
1p1h
2p2h
3p3h
4p4h
5p5h
6p6h
7p7h
8p8h
9p9h
E, MeV
τ, s
0
100
200
300
0.0
0.5
1.0
1.5
$\times 10^{-19}$
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}

Results


$A = 42, \quad B = 51$
E, MeV
300
250
200
150
100
50
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
$\times 10^{-19}$
τ, s
10^{0}
10^{-1}
10^{-2}
10^{-3}

Neutron evaporation

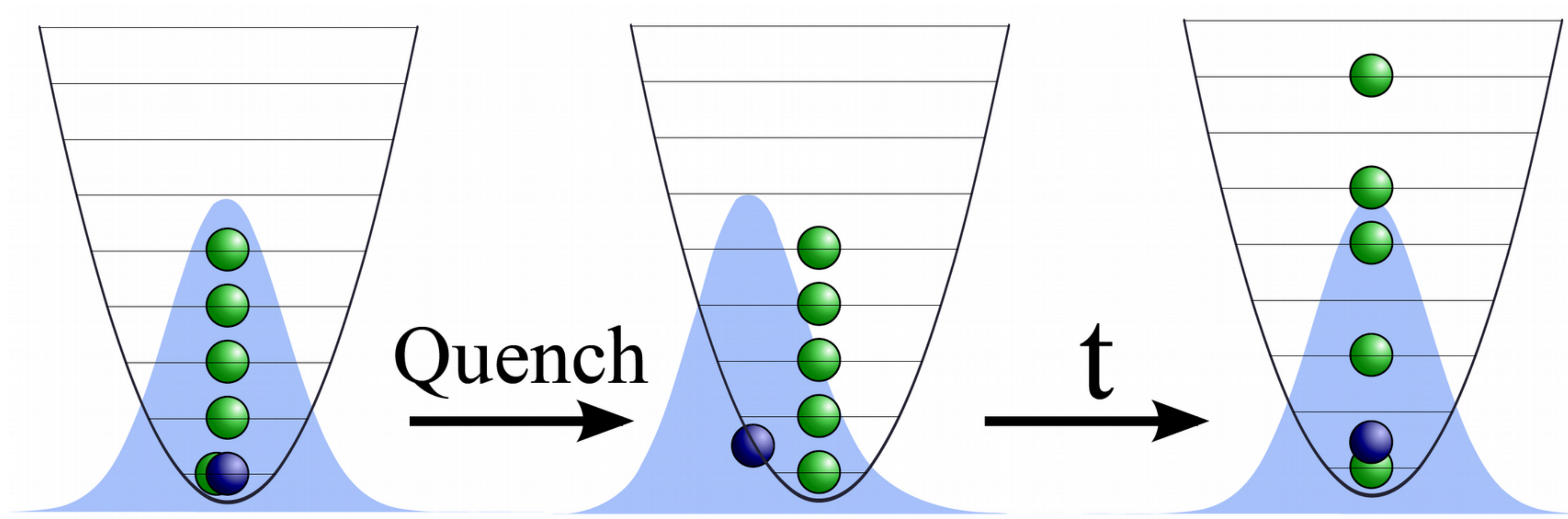


Proton-rich nuclei far from the valley of stability!

Summary

- Nuclear excitation with MeV coherent pulse leads to new energy domain in laser-induced nuclear reactions.
- For the first time investigated equilibration in p-h classes
- Production of proton rich nuclei far from the valley of stability is possible
- Experiments & theory: shed more light on unexplored domain
- Current experiments on ultra-cold atoms can help to simulate nucleus as a system of strongly interacting particles

Outlook: Parallel to cold atoms?



- **A possibility to simulate nuclear excitation and emission of single nucleons**
- **A powerful tool for investigation of different regimes via tuning of quench and atom-atom interaction strength.**
- **More freedom of parameters than in nucleus**

Non-adiabatic laser-nucleus interaction with nucleon emission

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Thanks for your attention!

Summary

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