Vortex states in nuclear and particle physics, Zhuhai

Nuclear excitation by electron capture with electron vortex beams

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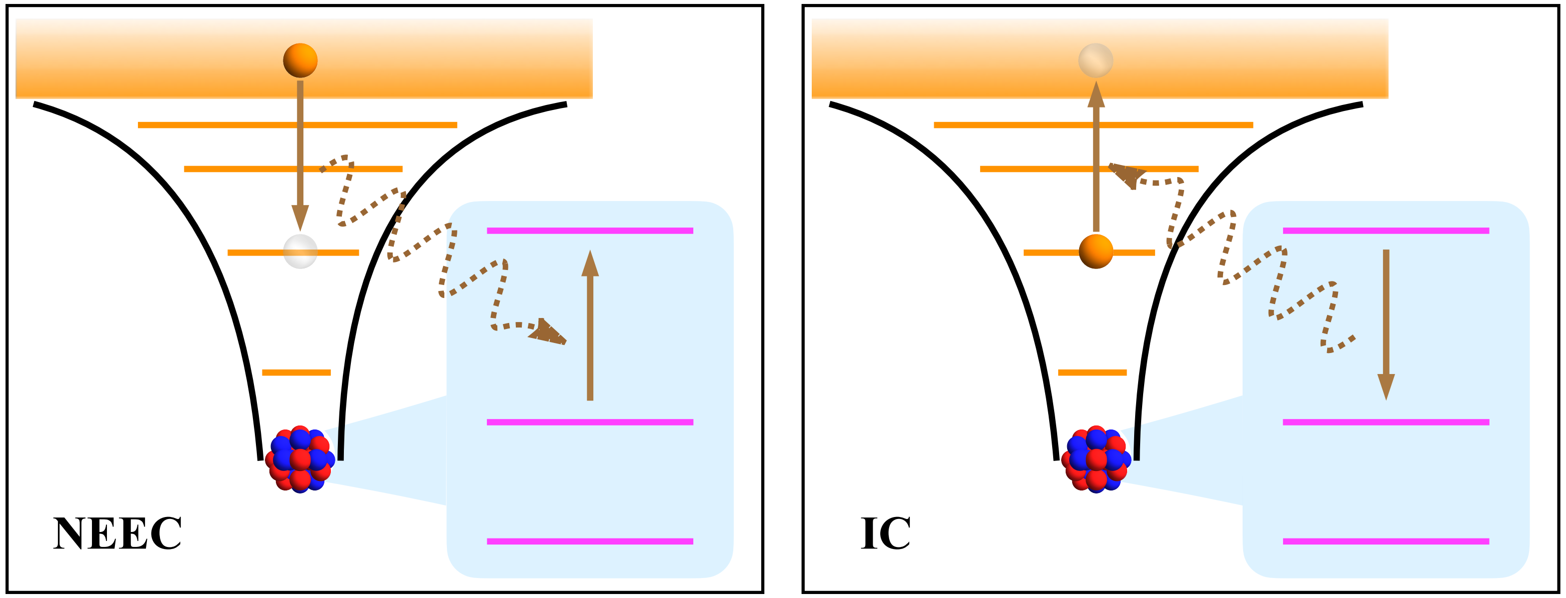
2024.04

NEEC

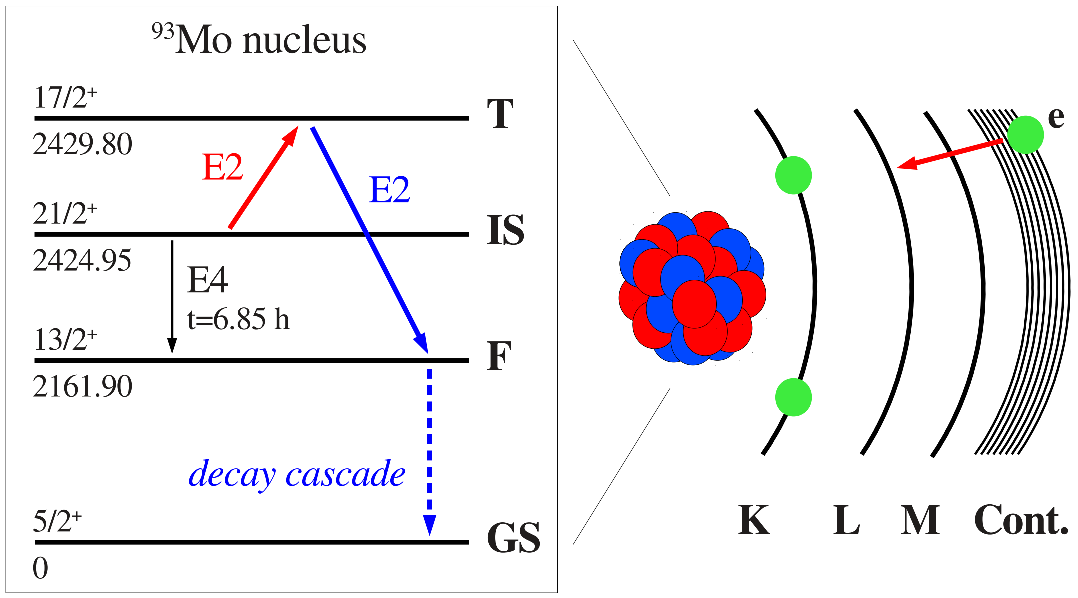
NEEC: Nuclear Excitation by Electron Capture



- First proposed theoretically in 1976
- First experimental observation claimed in 2018
- Relevant for studies of Nuclear structure and Nuclear astrophysics
- Manipulating nuclear states by manipulating electrons or ions
- Isomer depletion and Nuclear clock

NEEC

- **NEEC may serve as a trigger for the releasing of stored energy in isomers**



Isomer depletion

Isomer — long-lived excited state of nuclei

Key factors in NEEC

- Vacancies of atomic levels
- Free electrons

Scenarios of studies

- Storage rings
- EBITs
- Nuclear reactions
- Plasmas
  - — Astrophysical plasmas
  - — Laser-generate plasmas
- ……

Outline

- Introduction
- NEEC for isomer depletion
- NEEC with electron vortex beams
- Summary

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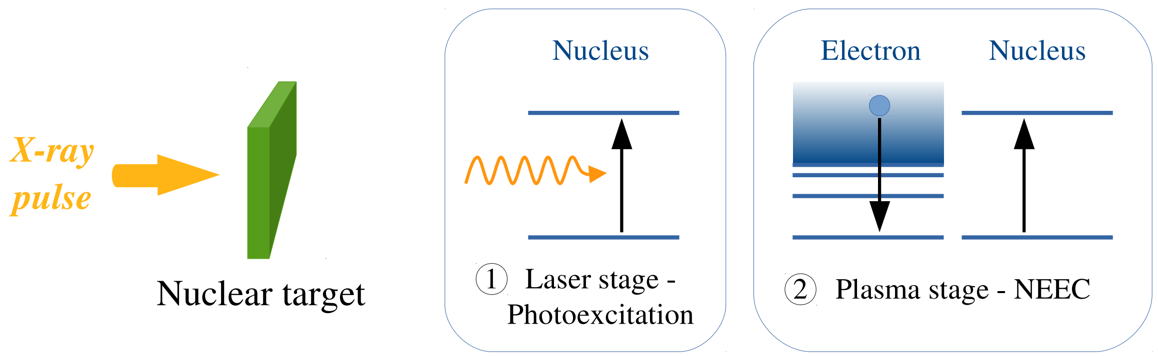
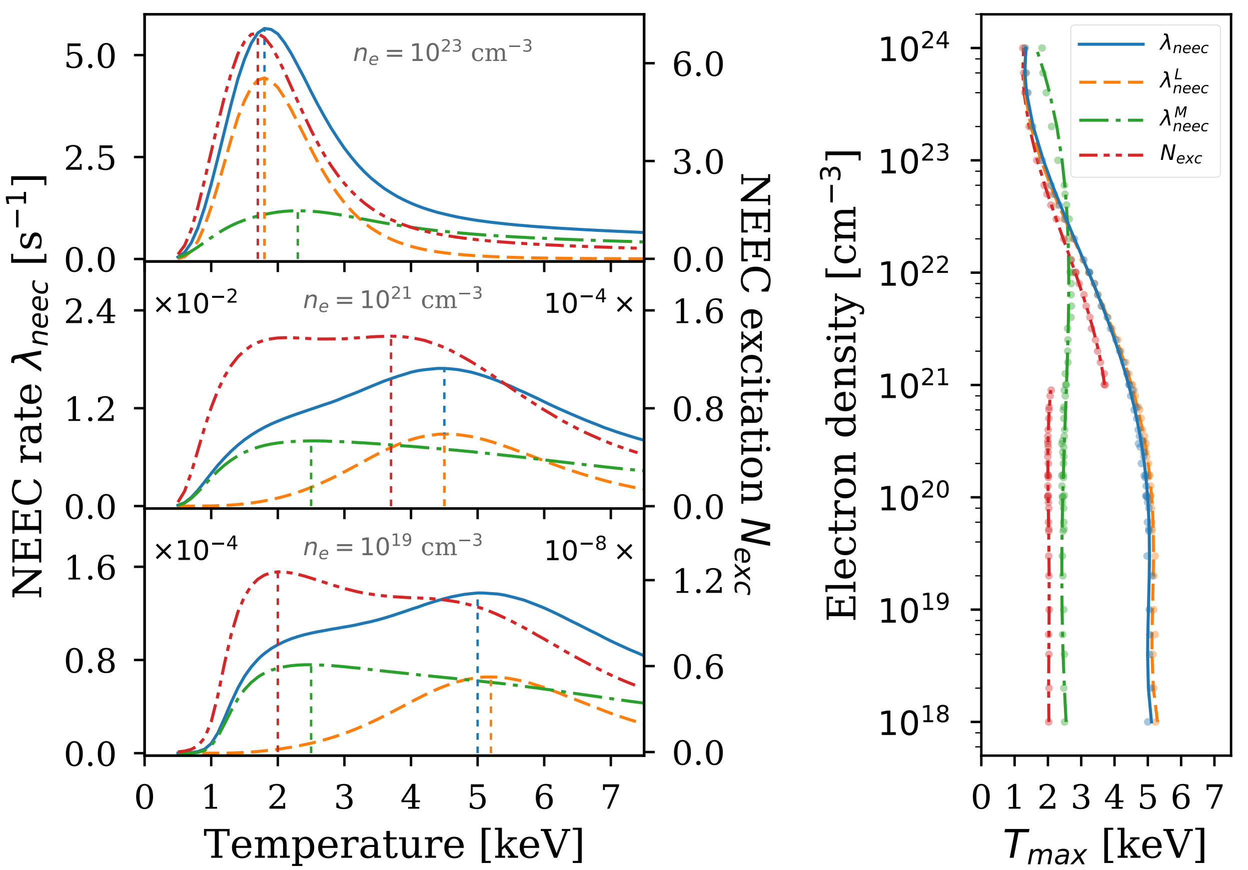
NEEC for isomer depletion



$$\lambda_{\rm neec} = \sum_{q,\alpha} f_q(T,n) \int dE\ \sigma_q^{\alpha}(E)\ \phi(E,T,n)$$

$$N_{\rm exc} = \int_{V_p} d^3\mathbf{r} \int dt\ n_{\rm iso}(\mathbf{r},t)\ \lambda_{\rm neec}(T,n;\mathbf{r},t)$$

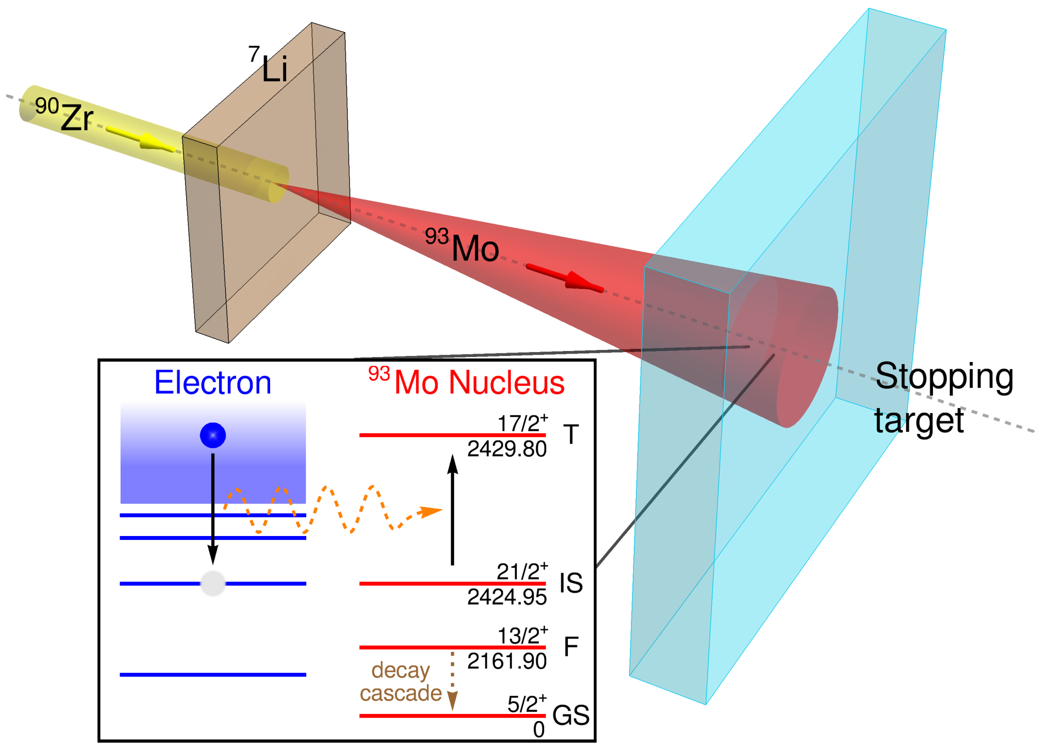


- XFEL NEEC >> XFEL photoexcitation by 10^5
- High power laser NEEC >> XFEL NEEC by 10^6

  $N_{\rm exc} \sim 1/s$

Gunst, Litvinov, Keitel, Pálffy, Phys. Rev. Lett. 112, 082501(2014)
Gunst, Wu, Kumar, Keitel, Pálffy, Phys. Plasmas 22, 112706 (2015)
Wu, Gunst, Keitel, Pálffy, Phys. Rev. Lett. 120, 052504 (2018)
Gunst, Wu, Keitel, Pálffy, Phys. Rev. E 97, 063205 (2018)
Wu, Keitel, Pálffy, Phys. Rev. A 100, 063420 (2019)

First Claimed NEEC evidence



Theoretical analysis

- NEEC probability << $P_{exc} = 0.01$ by about 8 orders magnitude

Y. Wu *et al.*, Phys. Rev. Lett. 122, 212501 (2019)

J. Rzadkiewicz *et al.*, Phys. Rev. Lett. 127, 042501 (2021)

J. Rzadkiewicz *et al.*, Phys. Rev. C 108, L031302 (2023)

First experiment evidence of NEEC

- **^{93m}Mo isomer depletion**
- $P_{exc} = 0.01$

C. J. Chiara *et al.*, Nature 554, 216 (2018)

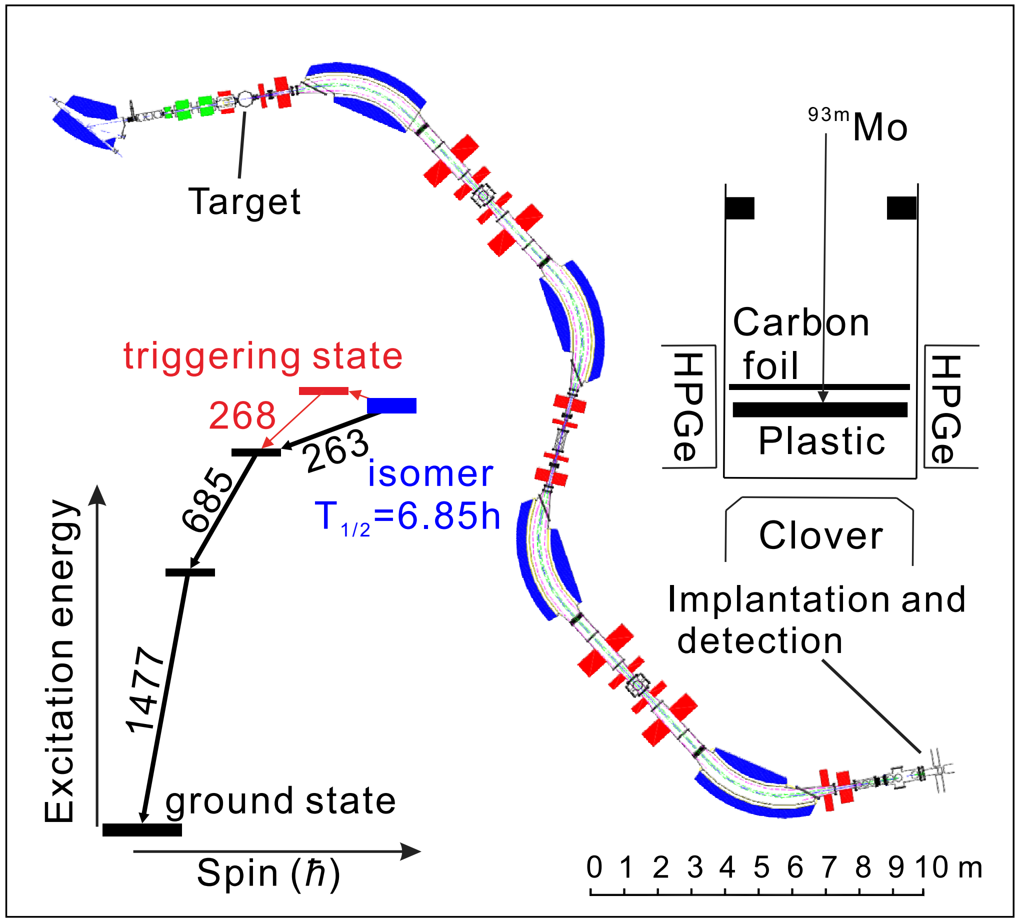
Background analysis

- Overestimated due to complex gamma background?

S. Guo *et al.*, Nature 594, E1 (2021)

C. J. Chiara *et al.*, Nature 594, E3 (2021)

New experiments with isomer beam



- ^{93m}Mo ion energy： 460 MeV
- Separating ^{93m}Mo production and depletion
- $P_{exc} < 2 \times 10^{-5}$
- Theoretical NEEC probability：

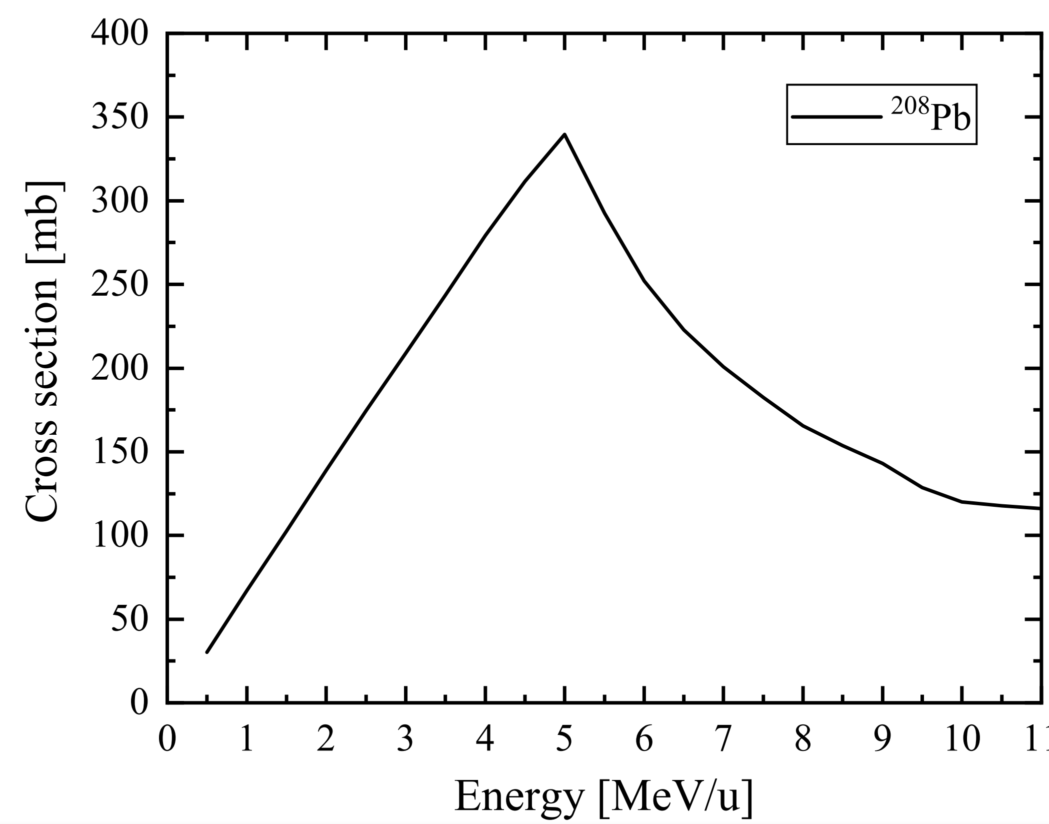
  P(460 MeV)/P(840 MeV) ~ 8%

Guo *et al*., Phys. Rev. Lett. 128, 242502 (2022)

Experiment in 2023 **Preliminary**

- Higher ion energy
- **Pb target 1.6 * 10^{-5} (experiment)**
  1.8* 10^{-5} (inelastic scattering)
- **C target ~2* 10^{-6} (experiment)**
  2 * 10^{-6} (inelastic scattering)

Theoretical calculation



NEEC

Conclusive observations of NEEC

- Clean environments?
- Control of the NEEC process?

Electron is one of the key factors in NEEC

- Shaping electron wave functions to manipulate the NEEC process?

— Electron vortex beams

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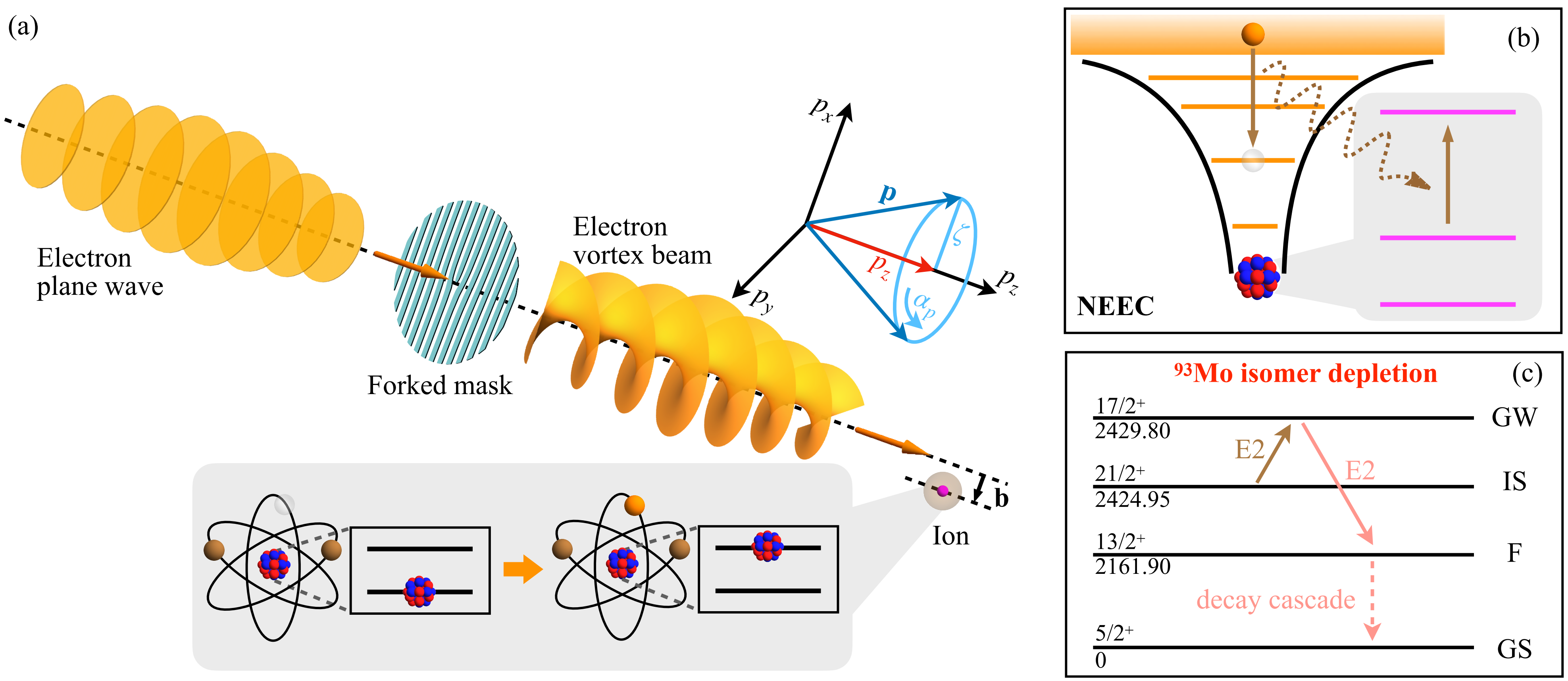
NEEC with electron vortex beams

Electron is one of the key factors in NEEC:
Shaping electron wave functions to manipulate nuclei?



$$\psi(\mathbf{r}) = \int \frac{d^2\mathbf{p}_\perp}{(2\pi)^2} a_{\zeta m}(\mathbf{p}_\perp) u_{\mathbf{p}} e^{i\mathbf{p}\cdot\mathbf{r}} \qquad a_{\zeta m}(\mathbf{p}_\perp) = (-i)^m e^{im\alpha_p} \delta(|\mathbf{p}_\perp| - \zeta)/\zeta$$

m: vortex quantum number $\qquad \mathbf{p} = (\mathbf{p}_\perp, p_z) = (\zeta \cos\alpha_p, \zeta \sin\alpha_p, p_z)$

Wu, Gargiulo, Carbone, Keitel, Pálffy, Phys. Rev. Lett. 128, 162501 (2022)

NEEC with electron vortex beams

NEEC - Plane wave electron

$$\sigma_{neec} = \frac{2\pi^2}{p^2} Y_{neec} L_d(E - E_d)$$

$$Y_{neec} = Y_a \sum_{\kappa} Y_b$$

NEEC - Vortex electron

$$\sigma_{neec} = \frac{2\pi^2}{p^2} \frac{2p}{J_z} Y_{neec} L_d(E - E_d)$$

$$Y_{neec} = \frac{b^2}{4\pi} \int_0^{2\pi} \int_0^{2\pi} \frac{d\alpha_p}{2\pi} \frac{d\alpha_k}{2\pi} e^{im(\alpha_p - \alpha_k)} Y_{neec}^{p,k} \, {}_0F_1(2; u)$$

$$Y_{neec}^{p,k} = 4\pi Y_a \sum_{\kappa, m_l} \frac{Y_b}{2l+1} Y^*_{lm_l}(\theta_k, \varphi_k) Y_{lm_l}(\theta_p, \varphi_p)$$

$$u = -b^2 \zeta^2 [1 - \cos(\alpha_k - \alpha_p)]/2$$

Transitions of electric multipolarity L

$$Y_a = \frac{4\pi^2(2J_d + 1)}{(2J_i + 1)(2L + 1)^2} \frac{B\rho_i}{R_0^{2(L+2)}}; \quad Y_b = \left[C(j_d \; L \; j; \frac{1}{2} \; 0 \; \frac{1}{2}) \right]^2 |R_{L,\kappa_d,\kappa}|^2$$

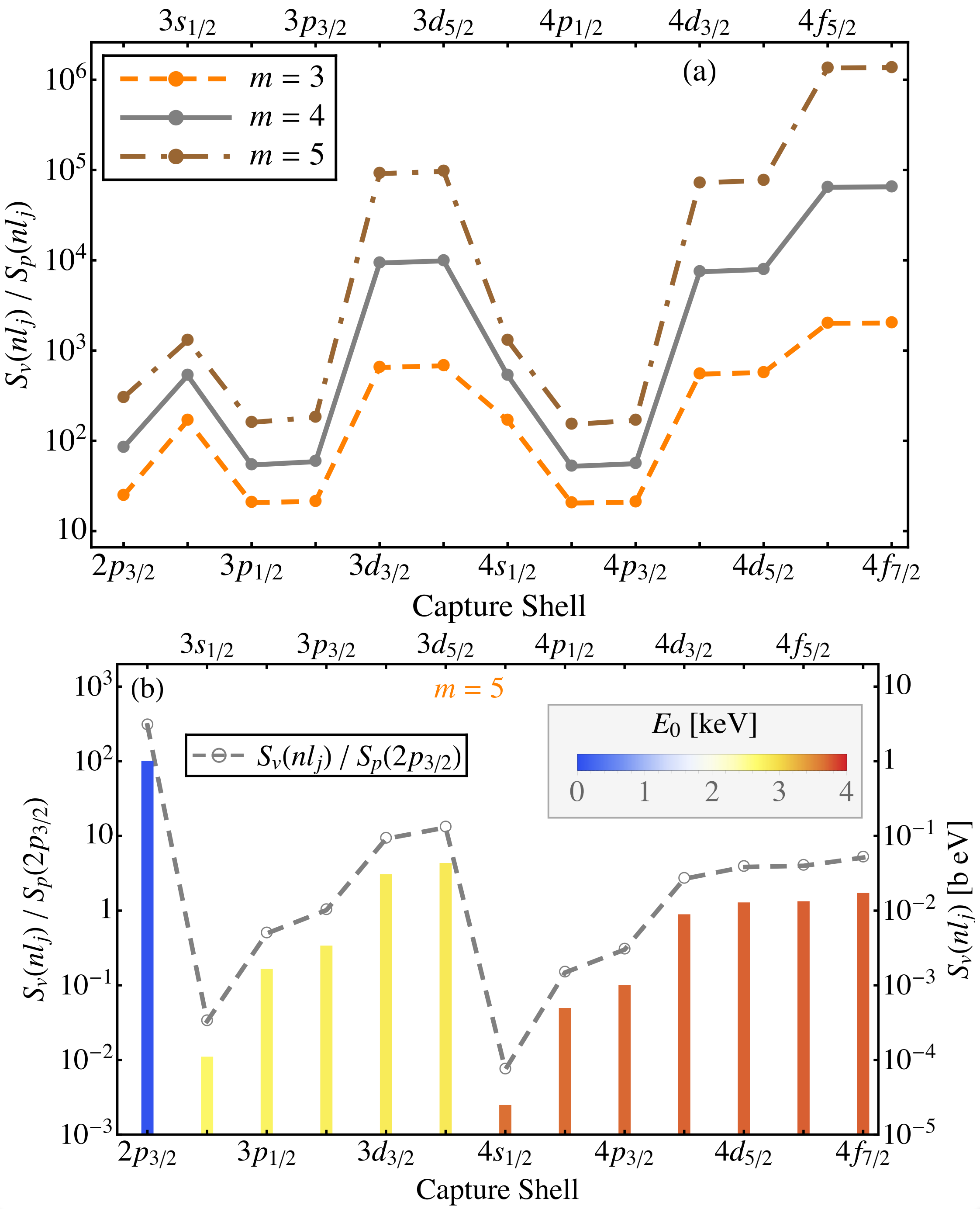
Transitions of magnetic multipolarity L

$$Y_a = \frac{4\pi^2(2J_d + 1)}{(2J_i + 1)L^2(2L + 1)^2} B\rho_i; \quad Y_b = (2j + 1)(\kappa_d + \kappa)^2 \begin{pmatrix} j_d & j & L \\ \frac{1}{2} & -\frac{1}{2} & 0 \end{pmatrix}^2 \left| R_{L,\kappa_d,\kappa} \right|^2$$

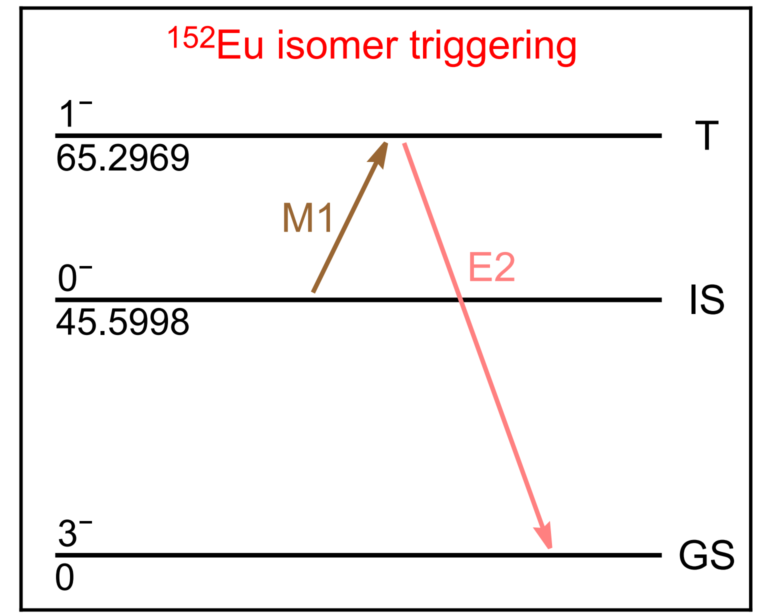
Wu, Gargiulo, Carbone, Keitel, Pálffy, Phys. Rev. Lett. 128, 162501 (2022)

NEEC with electron vortex beams

^{93m}Mo E2 transition



^{152m}Eu M1 transition



nl_j	S_p(b eV)	S_v(b eV) $m = 3$	S_v(b eV) $m = 5$
$2s_{1/2}$	$8.05*10^{-4}$	$1.14*10^{-3}$	$1.14*10^{-3}$
$2p_{1/2}$	$7.85*10^{-5}$	$1.35*10^{-3}$	$3.34*10^{-3}$
$2p_{3/2}$	$1.25*10^{-5}$	$4.21*10^{-4}$	$7.61*10^{-3}$

$$\zeta = p_z;\ \ \zeta b = 1$$

Wu, Gargiulo, Carbone, Keitel, Pálffy, Phys. Rev. Lett. 128, 162501 (2022)

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Summary

- NEEC can play important roles in isomer depletion
- Conclusive observations of NEEC are highly demanded
- Electron vortex beams can strongly affect the NEEC process
- Control nuclear excitations by shaping electron wave functions

Thank you for your attention!