Mini-workshop on Quantum effects in atomic and particle physics, Zhuhai

Manipulating isomers via NEEC

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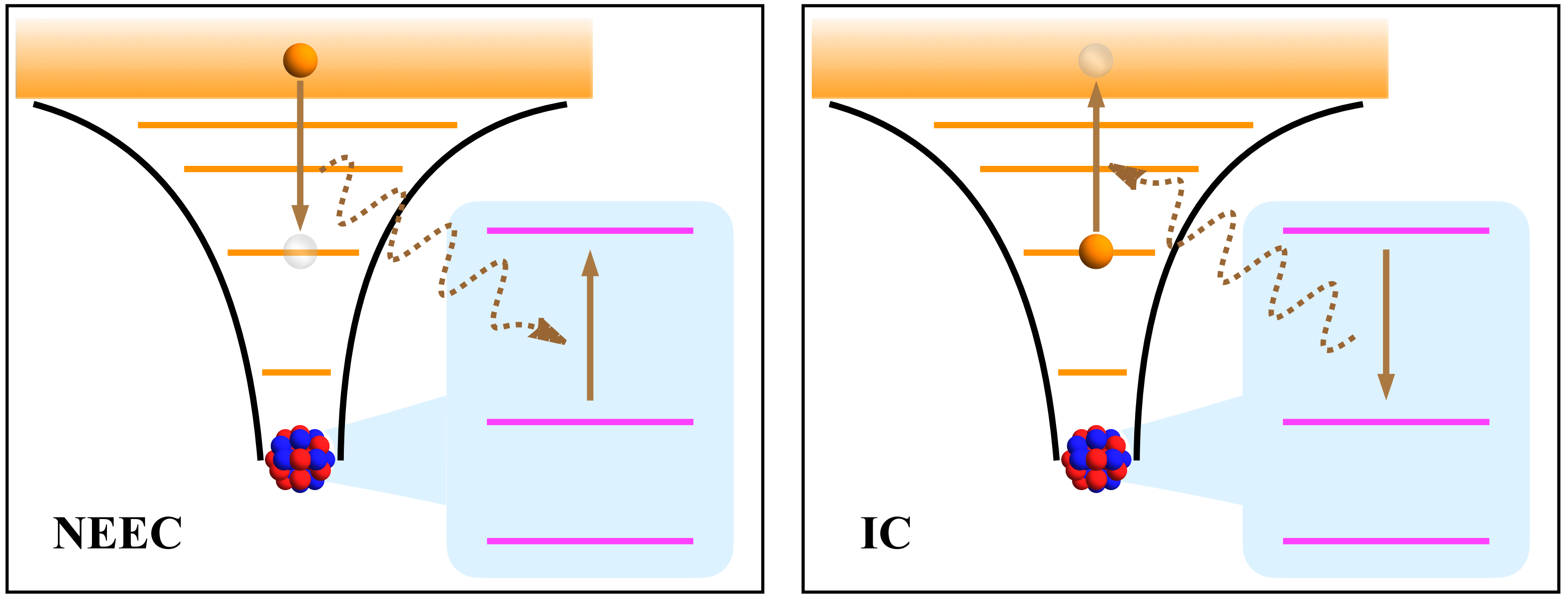
NEEC

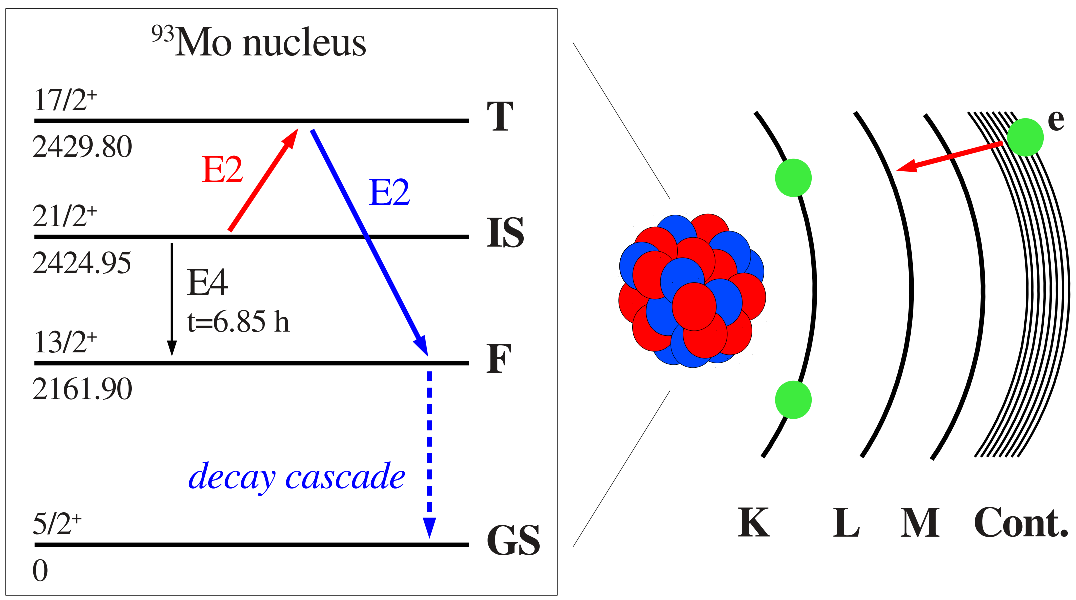
NEEC: Nuclear Excitation by Electron Capture



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

NEEC

Isomer depletion



Isomer — long-lived excited state of nuclei

key factors in NEEC

- Vacancies of atomic levels
- Electrons

Scenarios of studies

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

Outline

- ☑ Introduction
- ☑ Isomer depletion
- ☑ Isomer production
- ☑ Summary

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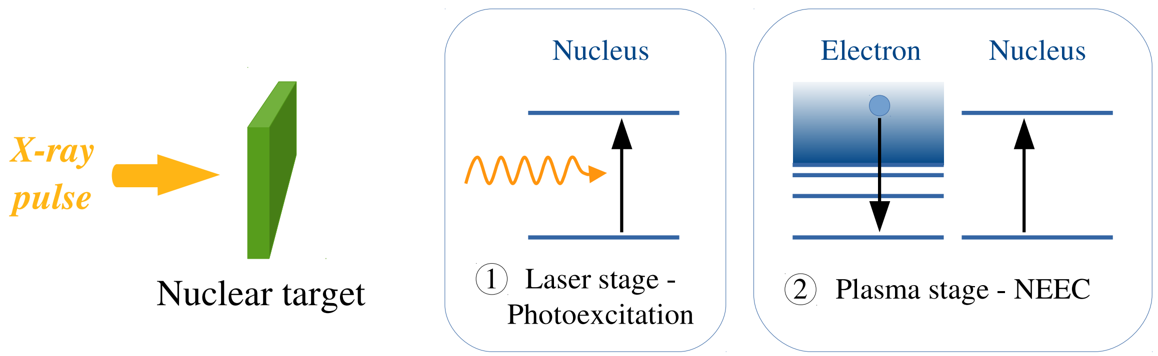
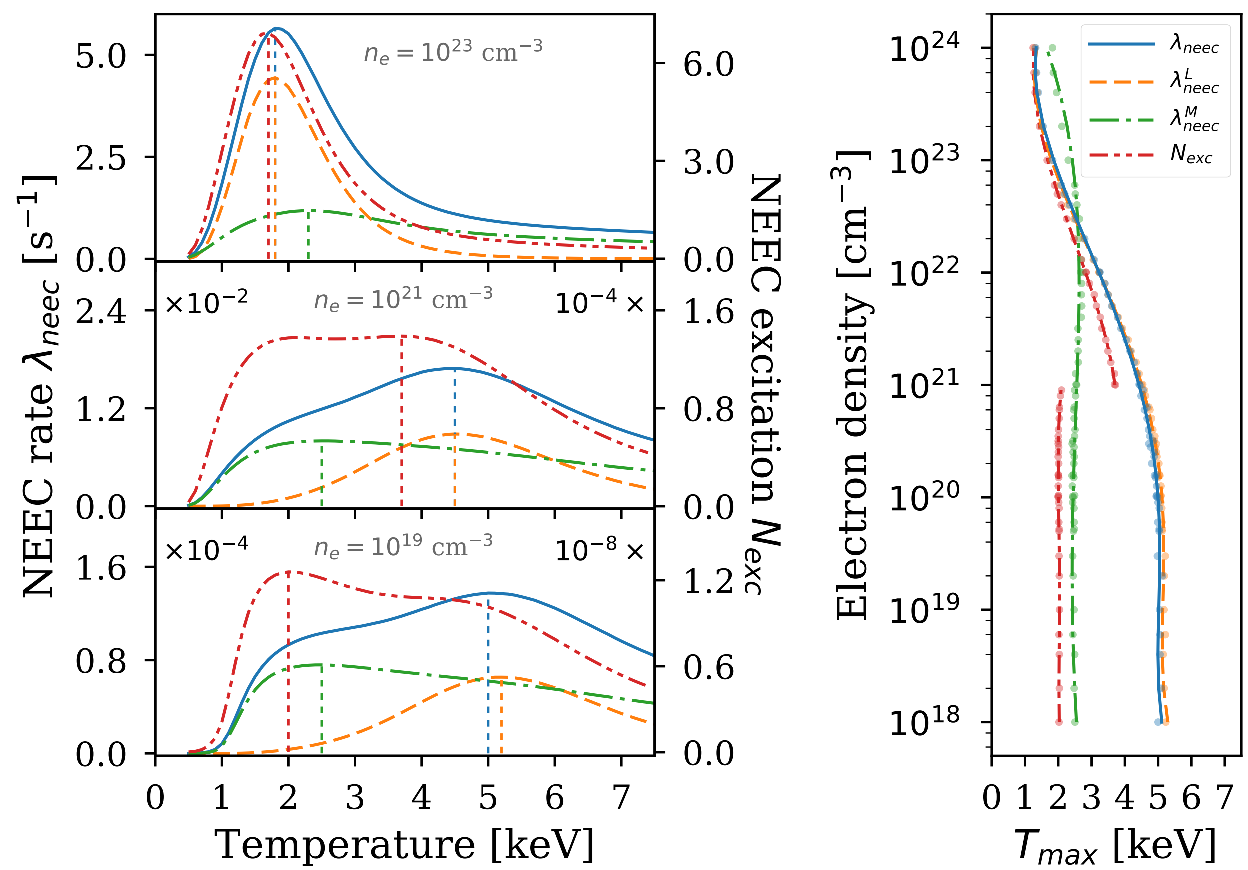
NEEC for isomer depletion





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

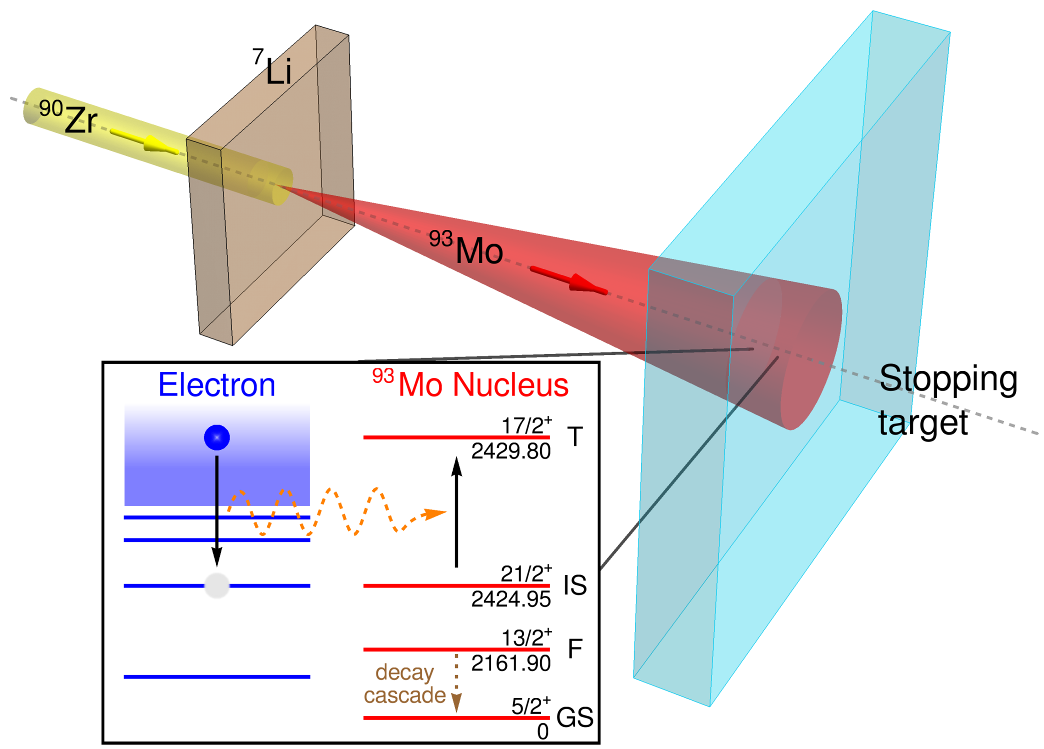
$$N_{\text{exc}} = \int_{V_p} d^3\mathbf{r} \int dt\ n_{\text{iso}}(\mathbf{r},t)\ \lambda_{\text{neec}}(T,n;\mathbf{r},t)$$

- XFEL NEEC >> XFEL photoexcitation by 10^5
- High power laser NEEC >> XFEL NEEC by10^6

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

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 $\ll P_{exc} = 0.01$ by about 8 orders of 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 experimental evidence of NEEC

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

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

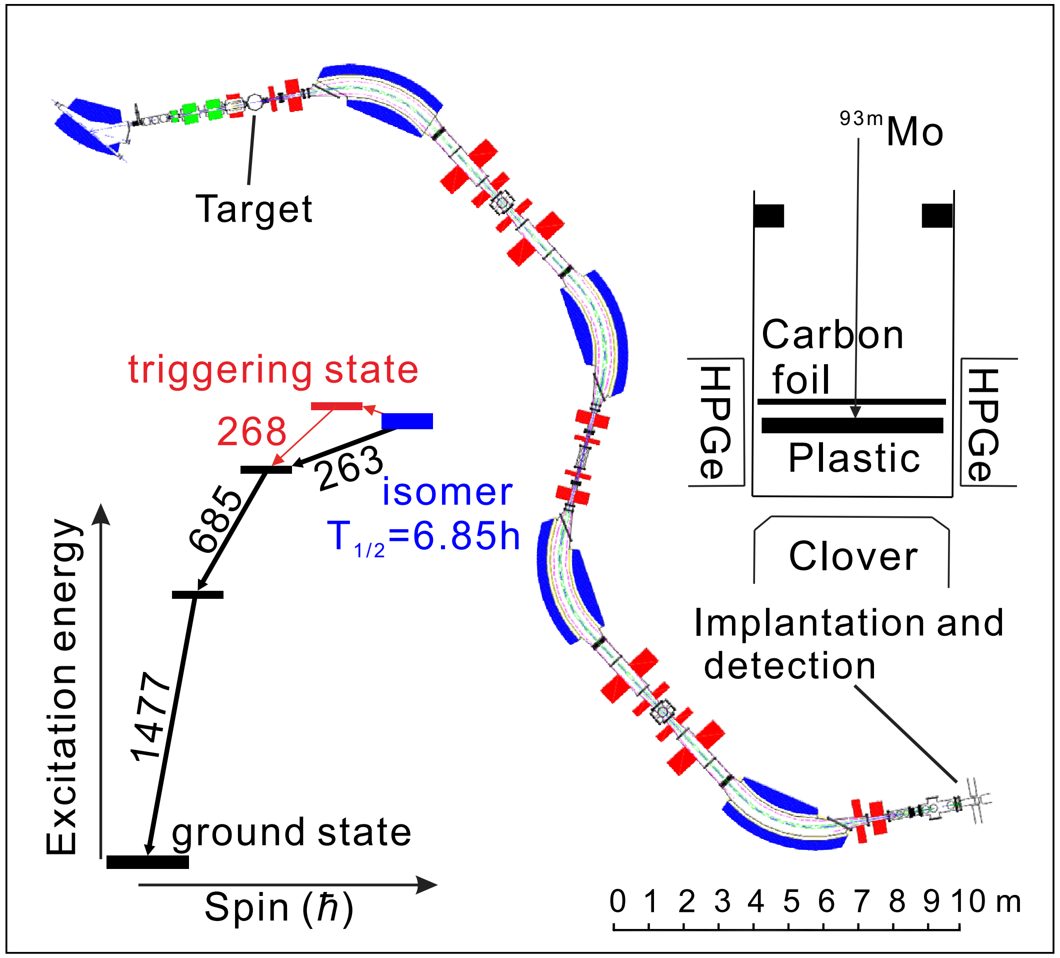
Background analysis

- 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
- $P_{\mathrm{exc}} < 2 \times 10^{-5}$
- Theoretical NEEC probability:
  $P(460\ \mathrm{MeV})/P(840\ \mathrm{MeV}) \sim 8\%$

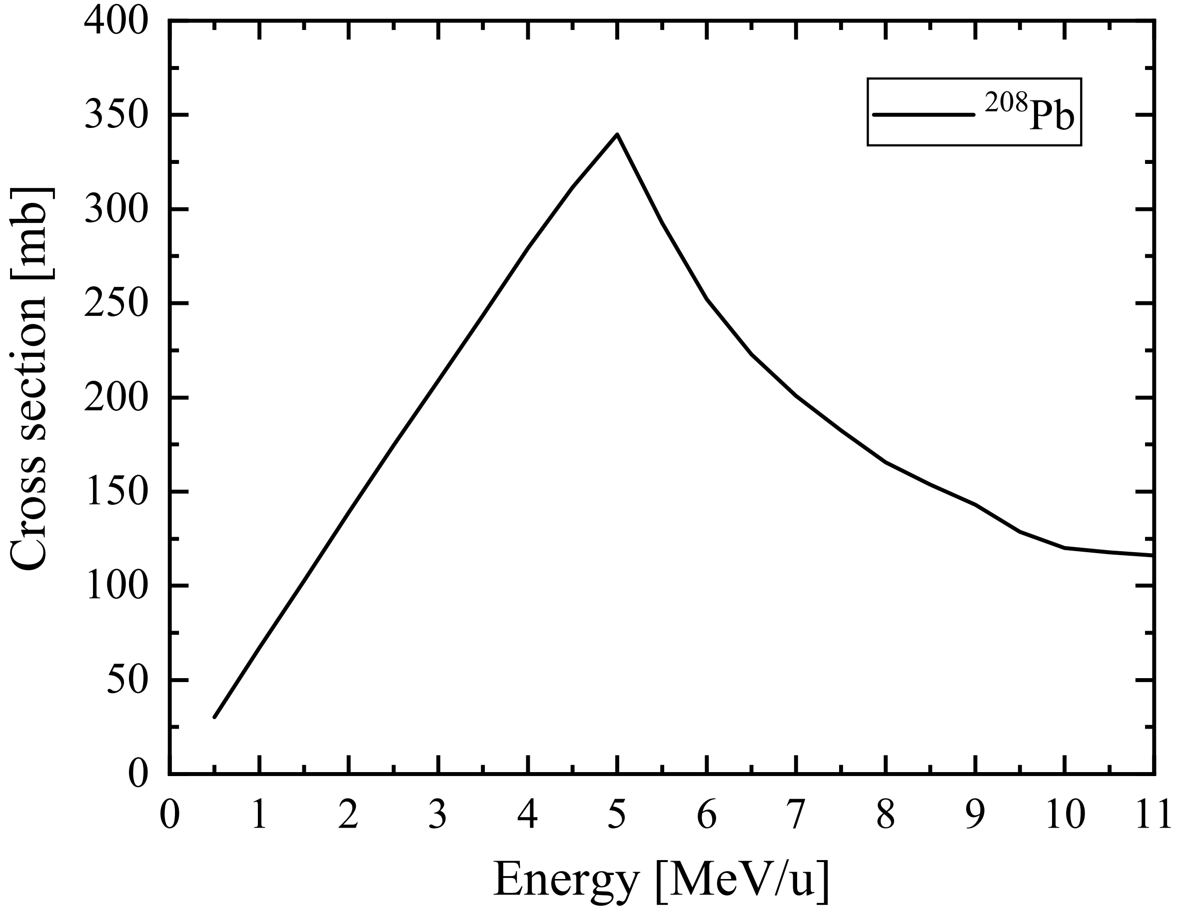
Guo *et al.*, Phys. Rev. Lett. 128, 242502 (2022)

Experiment in 2023

Preliminary

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

Theoretical calculation



Clear observation of 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

Scenarios with control of the occurrence of the NEEC process

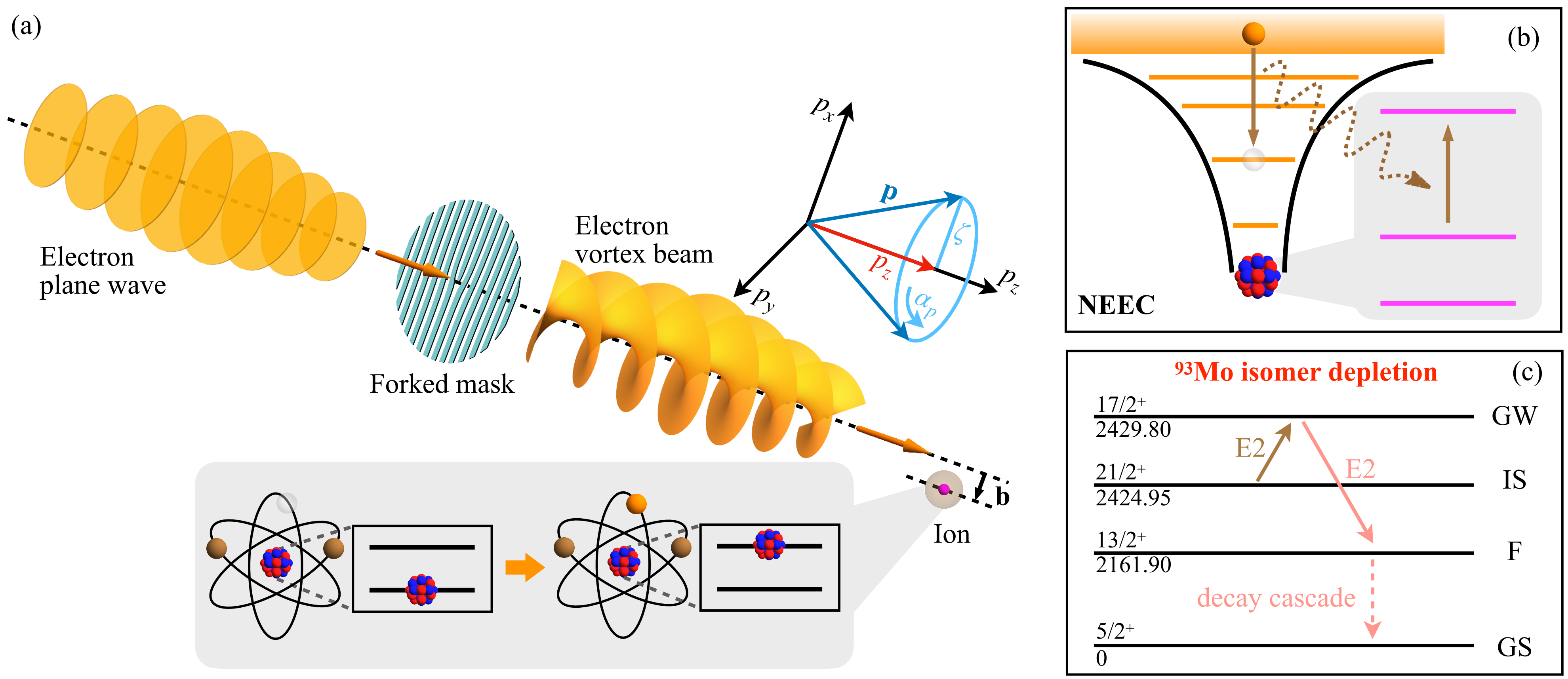
Well-defined initial and final states

Clear signals

Characteristic signals of NEEC

NEEC with electron vortex beams

Shaping electron wave functions to manipulate nuclei?



- Electron vortex beams carry orbital angular momentum

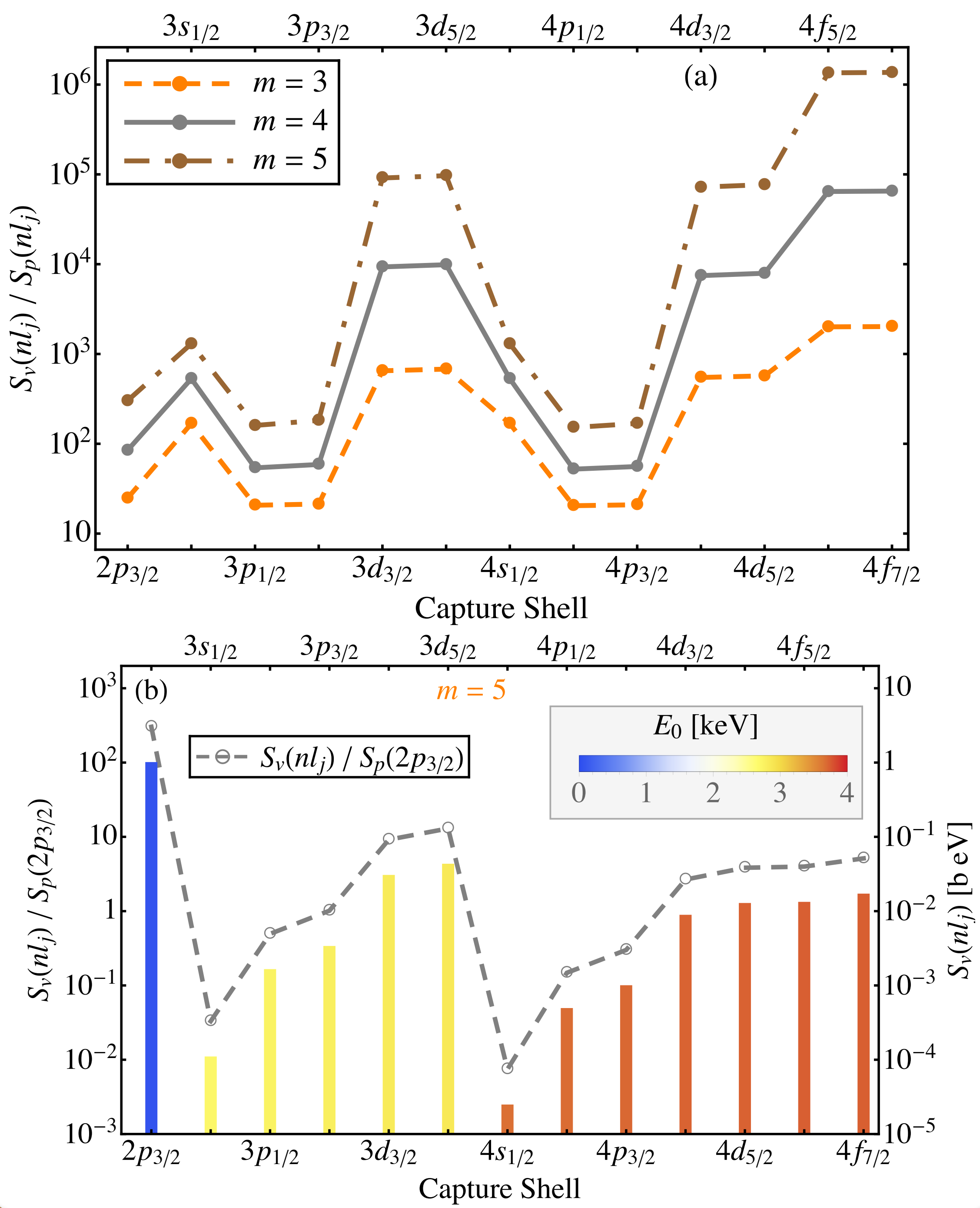
$$\psi(\mathbf{r}) = \int \frac{d^2\mathbf{p}_\perp}{(2\pi)^2} a_{\zeta m}(\mathbf{p}_\perp) u_{\mathbf{p}} e^{i\mathbf{p}\cdot\mathbf{r}} \qquad a_{\zeta m}(\mathbf{p}_\perp) = (-i)^m e^{im\alpha_p} \delta(|\mathbf{p}_\perp| - \zeta)/\zeta$$

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

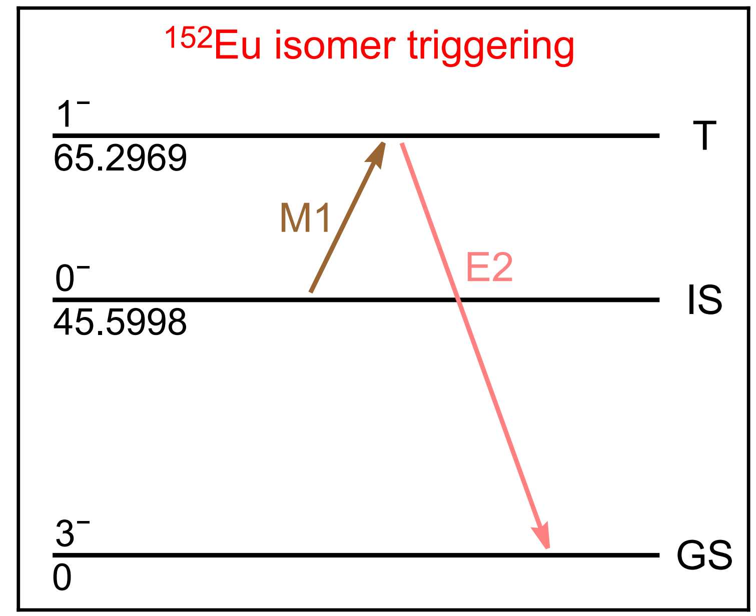
Wu, Gargiulo, Carbone, Keitel, Pálffy, Phys. Rev. Lett. 128, 162501 (2022)

NEEC with electron vortex beams

^{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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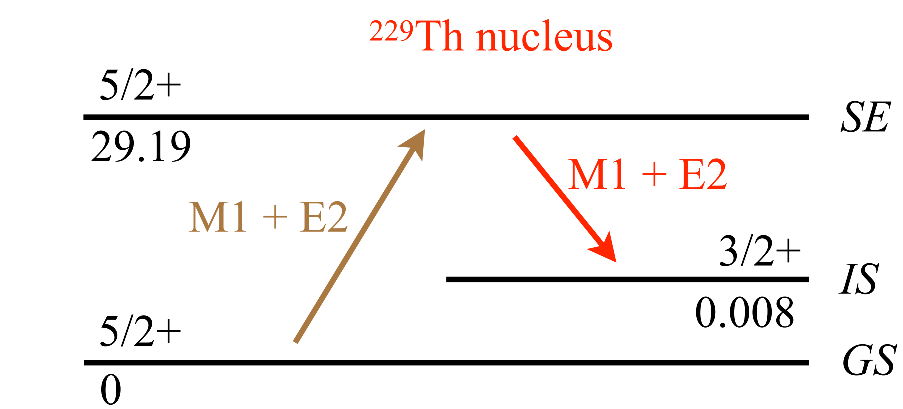
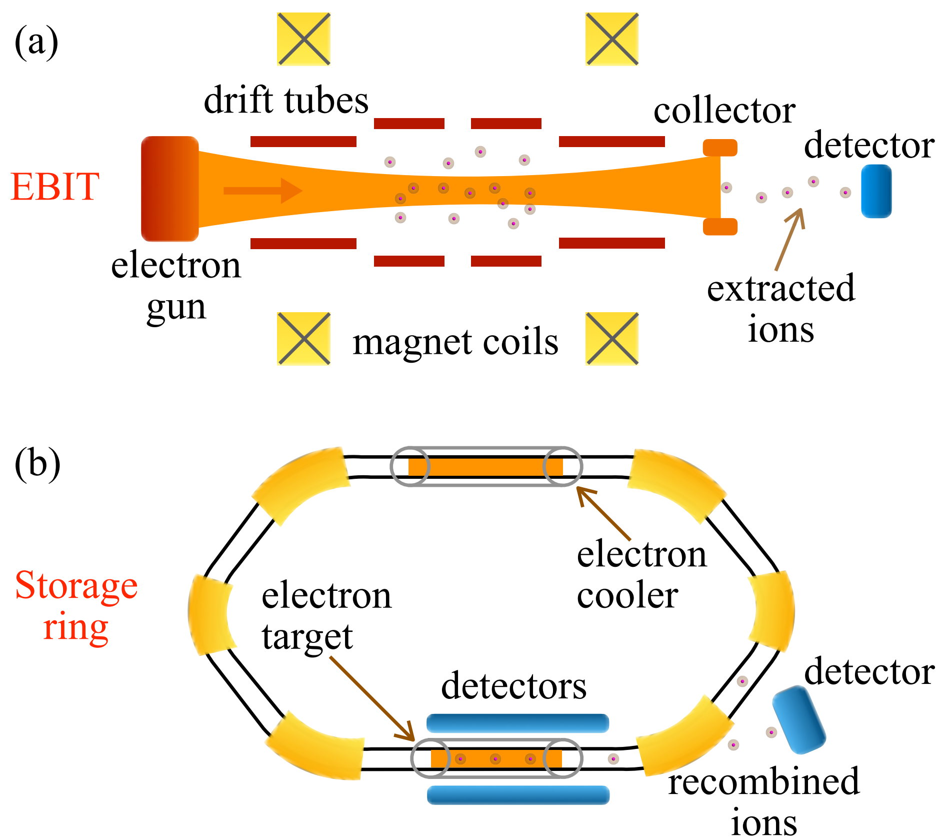
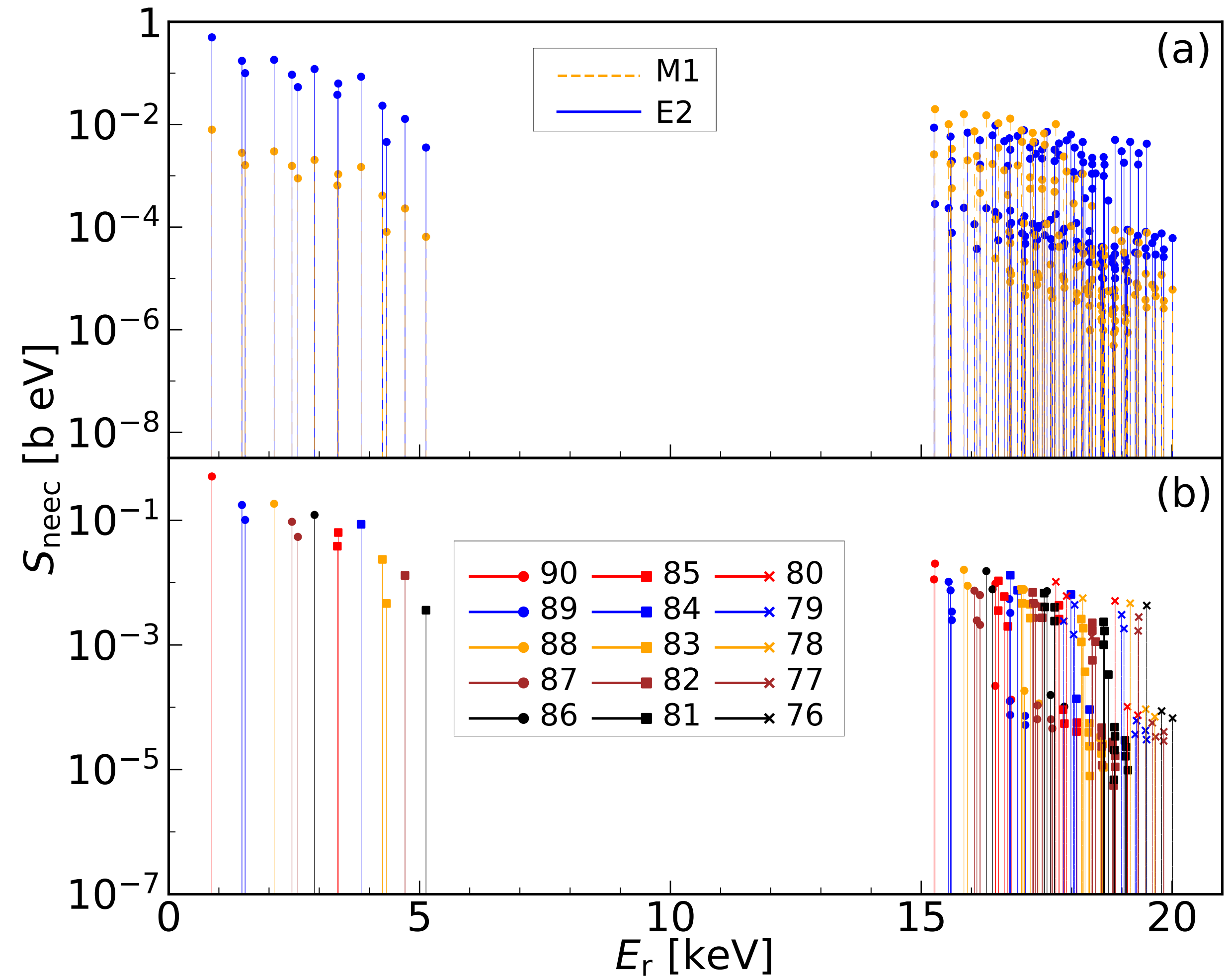
- Introduction
- Isomer depletion
- **Isomer production**
- Summary

^{229m}Th







Zhao, Pálffy, Keitel, Wu, Phys. Rev. C 110, 014330 (2024)

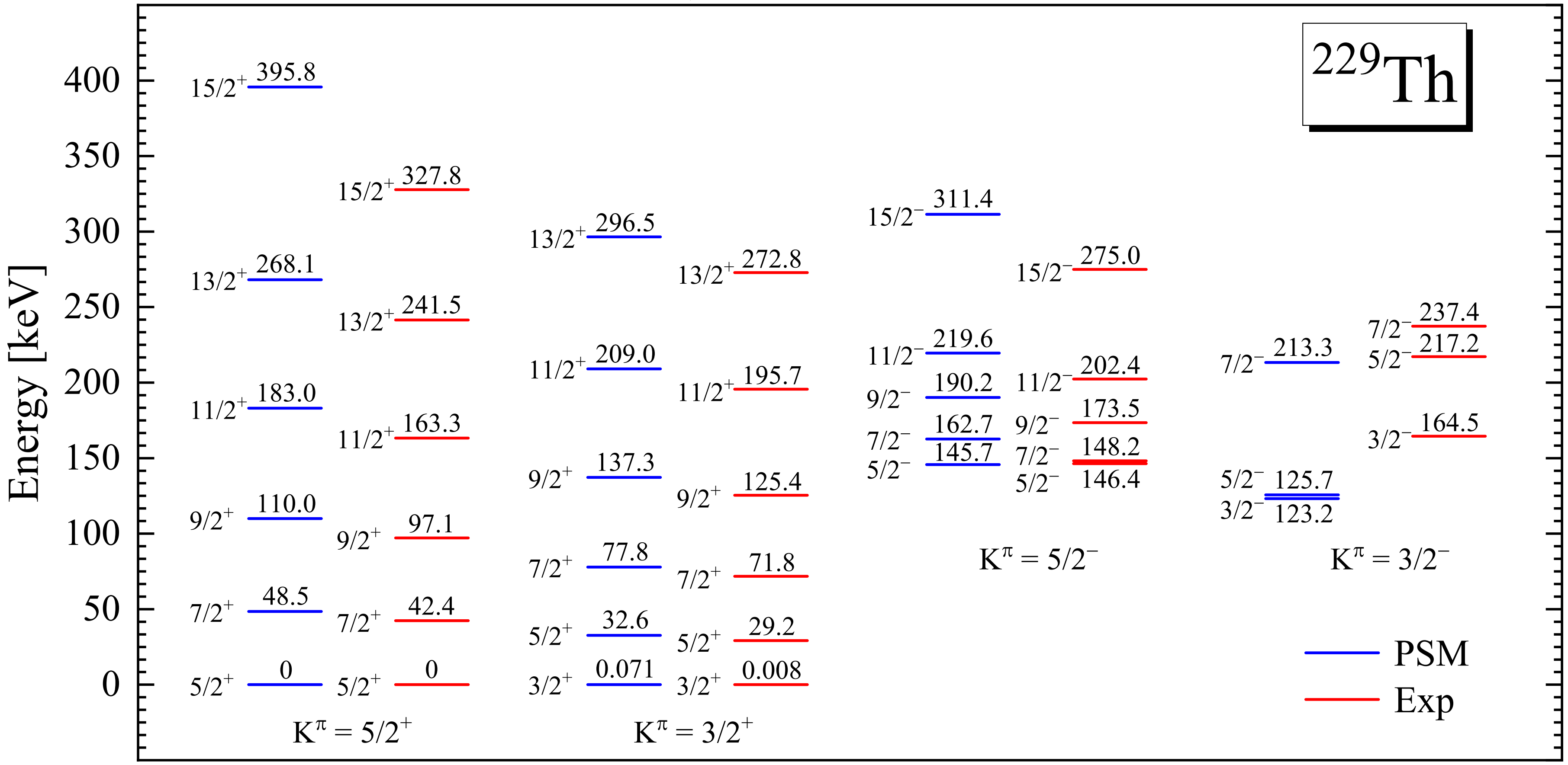
- ^{229m}Th production
- NEEC characteristic signal

  recombined ion

  x-ray photon (atomic transition)

  gamma photon (30 ns delay)

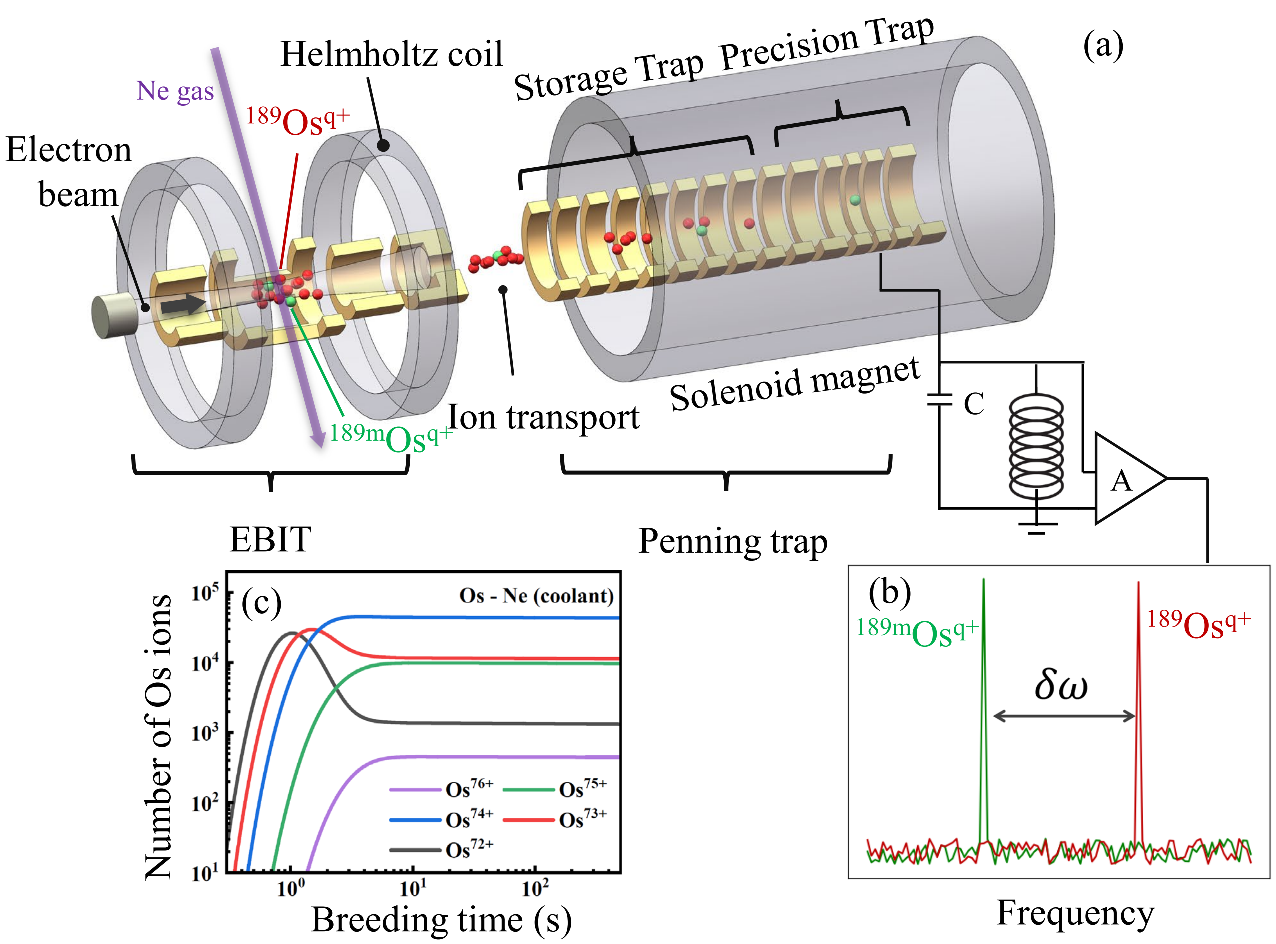
^{229m}Th — Projected shell model



Type	J_i (K_i^π)	J_f (K_f^π)	Exp	Refs. [35, 63, 64]	PSM
	9/2 $(5/2^+)$	7/2 $(5/2^+)$	170 ± 30	213 (224)	217
	9/2 $(5/2^+)$	5/2 $(5/2^+)$	65 ± 7	82 (85)	75
	9/2 $(5/2^+)$	5/2 $(3/2^+)$	6.2 ± 0.8	19.98 (17.37)	15.7
$E2$	7/2 $(5/2^+)$	5/2 $(5/2^+)$	300 ± 160	252 (267)	274
	5/2 $(3/2^+)$	5/2 $(5/2^+)$	...	27.11 - 39.49 [35]	9.99
	5/2 $(3/2^+)$	3/2 $(3/2^+)$	...	234.86 - 239.18 [35]	267.37
	3/2 $(3/2^+)$	5/2 $(5/2^+)$	...	27.04 (23.05)	10.47
	9/2 $(5/2^+)$	7/2 $(5/2^+)$	0.0076 ± 0.0012	0.0178 (0.0157) 0.0038 - 0.0185 [64]	0.0057
	9/2 $(5/2^+)$	7/2 $(3/2^+)$	0.0117 ± 0.0014	0.0151 (0.0130) 0.0144 - 0.0151 [64]	0.0157
$M1$	7/2 $(5/2^+)$	5/2 $(5/2^+)$	0.011 ± 0.004	0.0093 (0.0085) 0.0011 - 0.0096 [64]	0.003
	5/2 $(3/2^+)$	5/2 $(5/2^+)$	0.00326 ± 0.00076 [35]	0.0012 - 0.0050 [35]	0.0026
	5/2 $(3/2^+)$	3/2 $(3/2^+)$	$0.0318^{+0.0102}_{-0.0091}$ [35]	0.0332 - 0.0648 [35]	0.0282
	3/2 $(3/2^+)$	5/2 $(5/2^+)$	$0.0172^{+0.0031}_{-0.0023}$ [26] $0.0219^{+0.0006}_{-0.0006}$ [29] $0.0272^{+0.0074}_{-0.0082}$ [25] $0.0295^{+0.0013}_{-0.0012}$ [30] $0.0213^{+0.0013}_{-0.0012}$ [28] $0.0214^{+0.0002}_{-0.0001}$ [31]	0.0076 (0.0061) 0.0056 - 0.0081 [64]	0.0297

Chen, Wang, Wu, submitted

EBIT + Penning trap



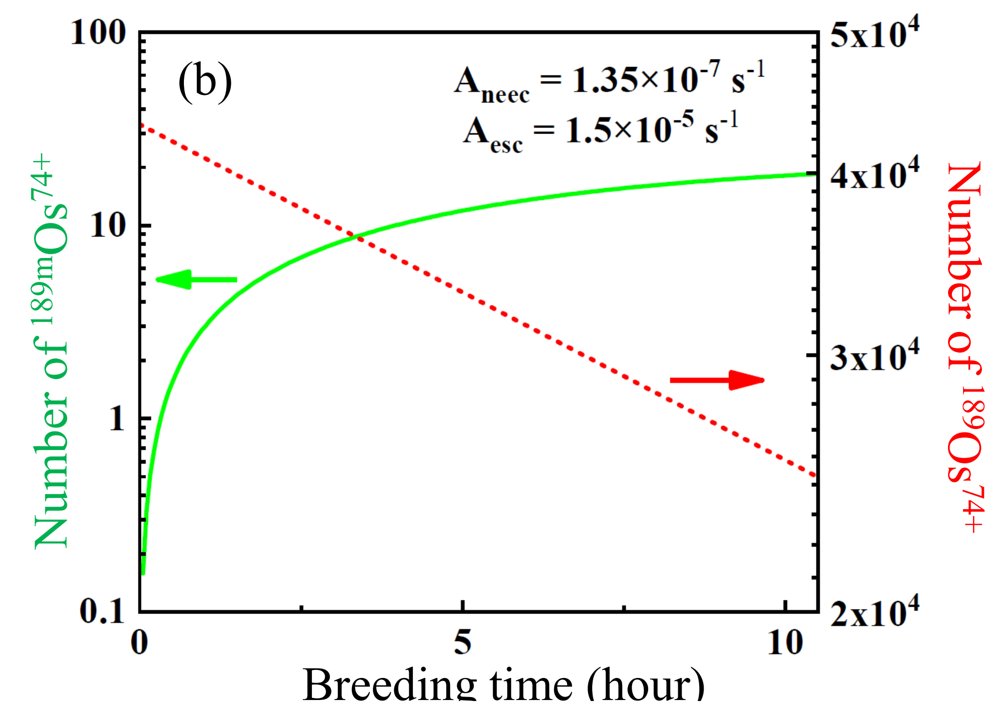
EBIT — Electron beam ion trap

B. Tu *et al.*, submitted

3/2- (GS)

7/2- (216.7 keV or 219.4 keV)

9/2- (30.8 keV, IS)



- Isomer production in an EBIT
- Detection of isomer in a Penning trap

Background clean

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总结

- NEEC can play important roles in isomer depletion and isomer production
- Conclusive observations of NEEC are highly demanded
- Electron vortex beams can strongly affect the NEEC process
- Storage rings and EBITs may provide clean environments for NEEC observations
- Characteristic signal of NEEC which can distinguish NEEC from other nuclear excitation mechanisms should be helpful

谢谢大家！