UPC Physics Workshop 2023

Nuclear excitation by electron capture in electron-ion collisions

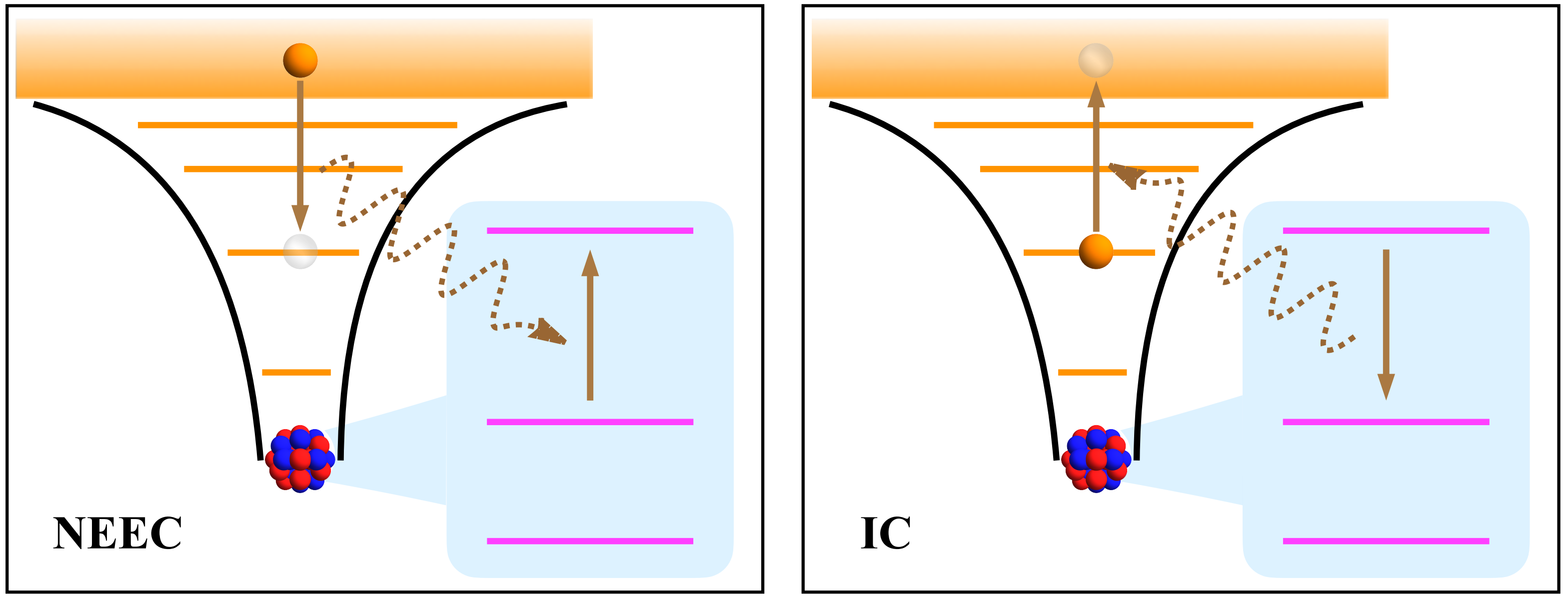
吴远彬

南开大学物理科学学院

2023年05月27日

NEEC

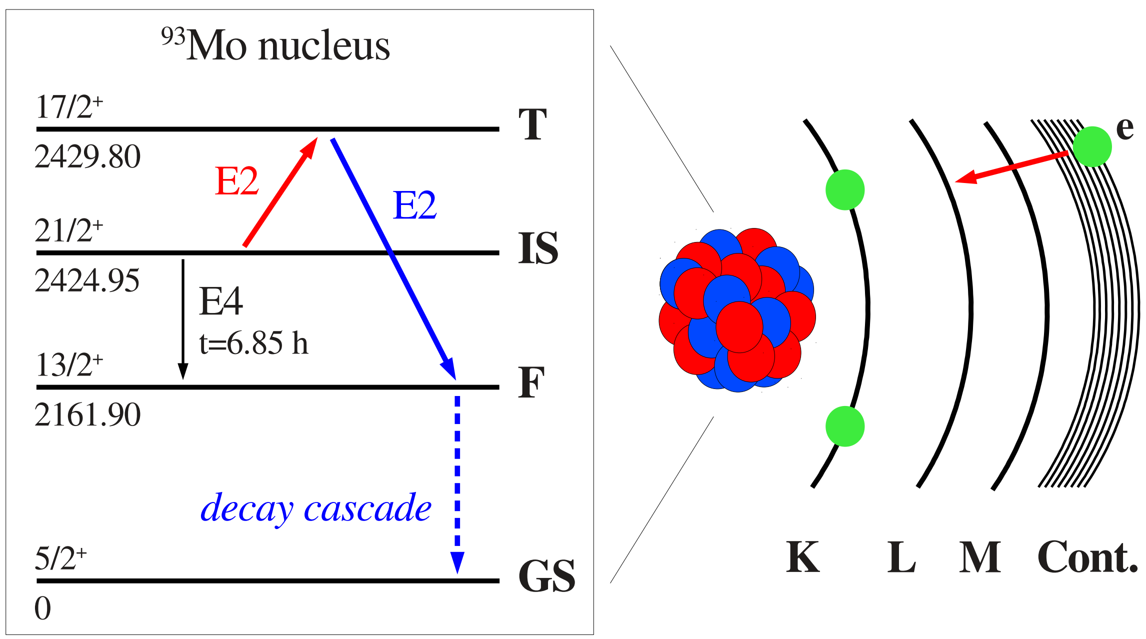
NEEC: Nuclear Excitation by Electron Capture



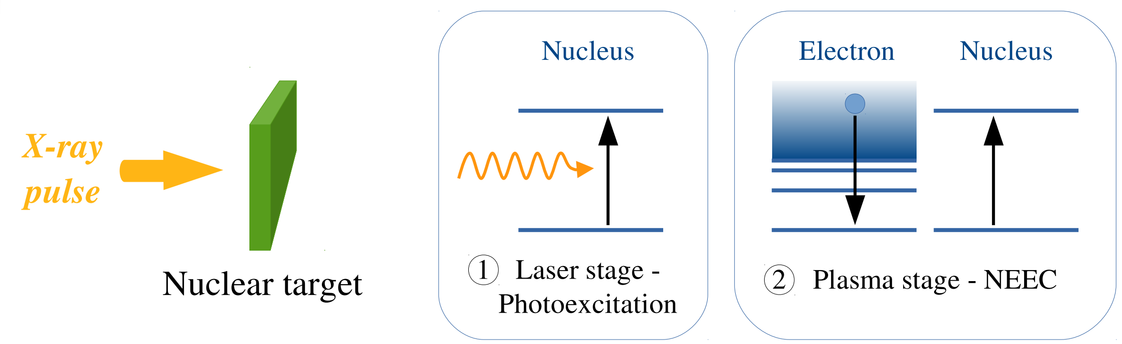
- 1976年在理论上提出，2018年首个实验迹象被报道
- 核结构的研究、核天体物理的研究
- 通过调控电子与原子来调控原子核
- 核能触发 (Isomer triggering)：新型核能
- 核钟 (Nuclear clock) 相关研究

Why NEEC?

- **NEEC有望用于触发同核异能素能量释放：新型核能**



Isomer triggering



激光等离子体

- XFEL NEEC >> XFEL 直接光激发 (10^5)
- 强激光 NEEC >> XFEL NEEC (10^6)

Isomer: **long-lived excited state of nuclei**

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)

Why NEEC?

首个NEEC实验迹象在2018年被报道

- 离子束-固体靶相互作用
- ^{93m}Mo同核异能素衰变

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

- 首个NEEC实验迹象的理论分析?
- 通过电子波函数的改变来影响NEEC?
  — 涡旋电子束

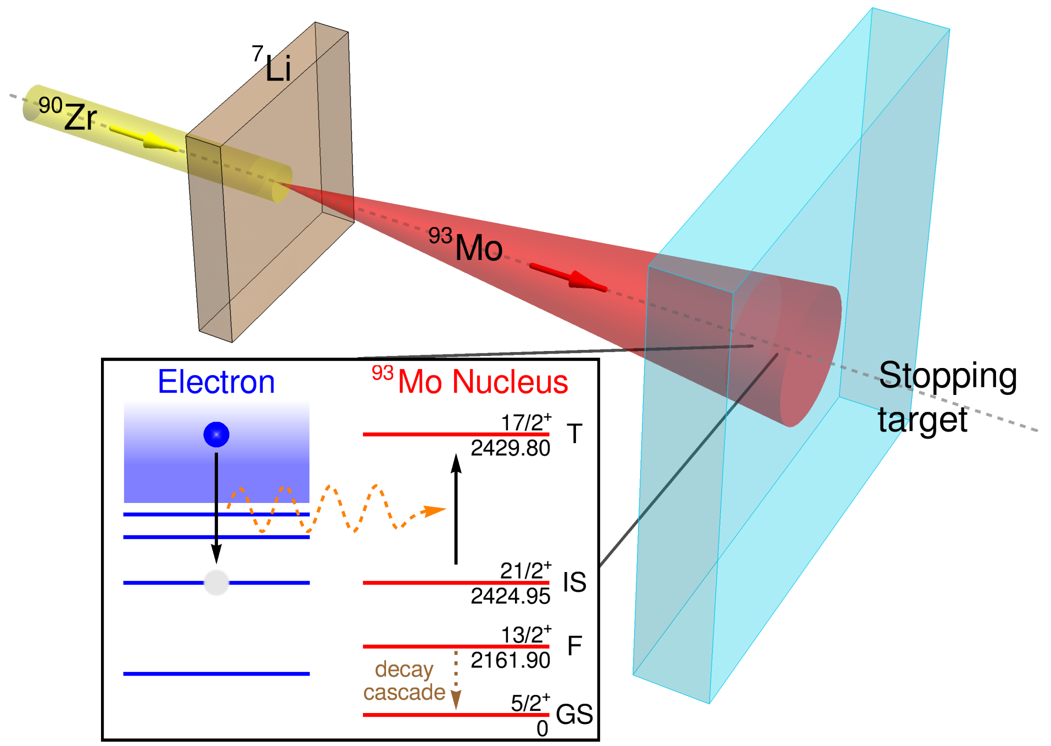
报告提纲

- ☑研究背景
- ☑首个NEEC实验迹象的讨论
- ☑涡旋电子束
- ☑总结

报告提纲

- 研究背景
- 首个NEEC实验迹象的讨论
- 涡旋电子束
- 总结

First Claimed NEEC evidence



Wu, Keitel, Pálffy, Phys. Rev. Lett. 122, 212501 (2019)

首次实验观测NEEC

- ^{93m}Mo 衰变
- $P_{\rm exc} = 0.01$
- 没有相关的NEEC理论计算

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

NEEC 截面

NEEC 截面

$$\sigma_q^\alpha(E) = S_q^\alpha \frac{\Gamma_{q,\alpha}/(2\pi)}{(E - E_{q,\alpha})^2 + \frac{1}{4}\Gamma_{q,\alpha}^2}$$

S_q^α : resonance strength

$$S_q^\alpha \propto \left| \langle \Psi_g^N | \langle \Psi_g^e | H_N | \Psi_i^e, \psi_s \rangle | \Psi_i^N \rangle \right|^2$$

- Coulomb interaction (E transitions)

$$H_{en} = \int d^3 r_n \frac{\rho_n(\vec{r}_n)}{|\vec{r}_e - \vec{r}_n|}$$

- Magnetic Hamiltonian (M transitions)

$$H_{magn} = -\frac{1}{c}\overrightarrow{\alpha} \int d^3 r_n \frac{\vec{j}_n(\vec{r}_n)}{|\vec{r} - \vec{r}_n|}$$

Matrix elements

- Nuclear via reduced transition probability $B(E/ML)$
- Electronic wavefunctions
  Bound electrons: GRASP92

First Claimed NEEC evidence

NEEC几率

$$P = \sum_{q,\alpha} \int f_q \phi \sigma_q^\alpha dt$$

NEEC截面

$$\sigma_q^\alpha(E) = S_q^\alpha(E) \frac{\Gamma_{q,\alpha}/(2\pi)}{(E - E_{q,\alpha})^2 + \frac{1}{4}\Gamma_{q,\alpha}^2}$$

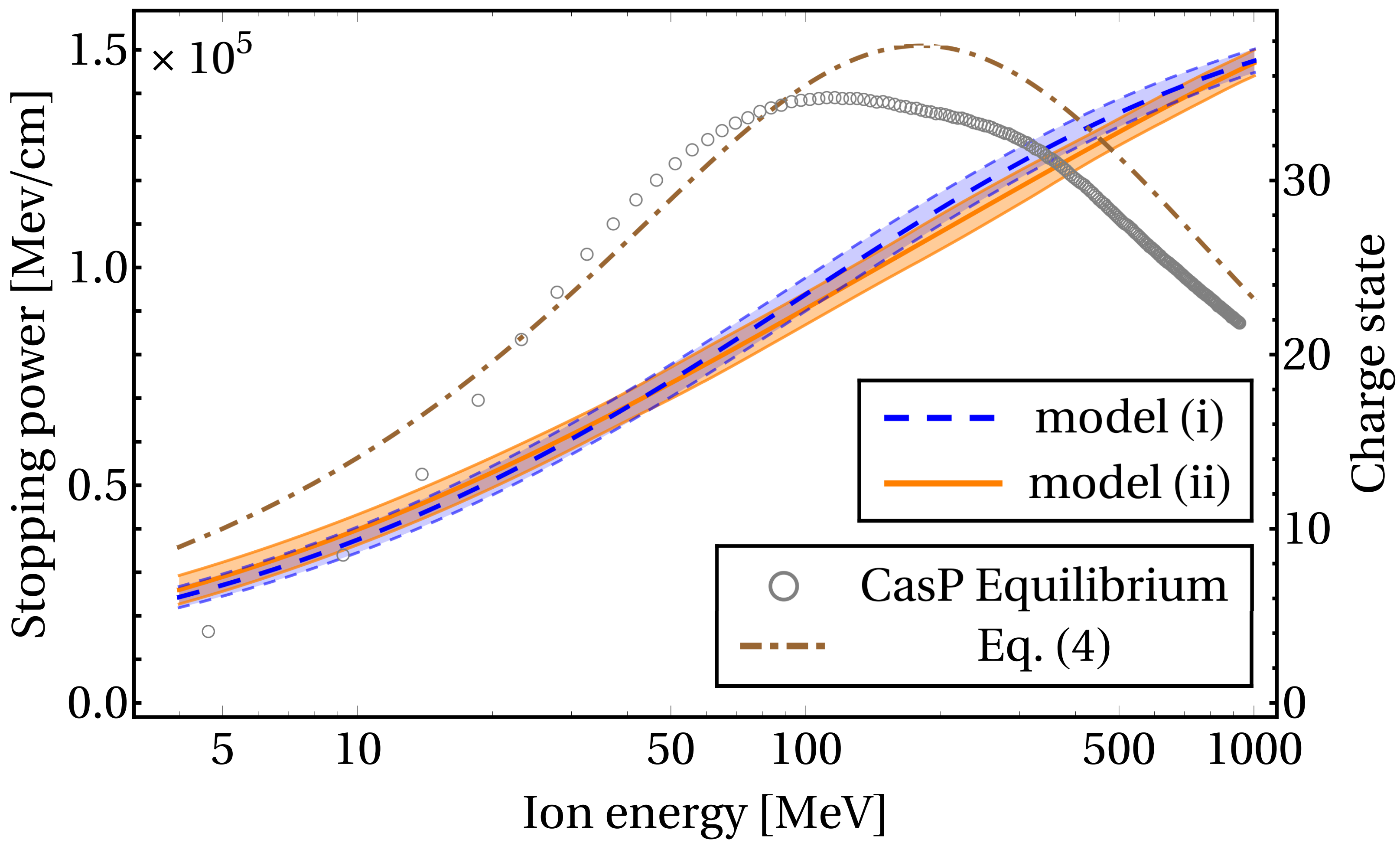
Γ很小

$$P = \sum_{q,\alpha} f_q(E_{q,\alpha}^{\text{ion}}) P_q^\alpha(E_{q,\alpha}^{\text{ion}})$$

$$P_q^\alpha = n_e S_q^\alpha(E_{q,\alpha}) \frac{m_i}{m_e} \frac{1}{-\left(\frac{E^{\text{ion}}}{dx}\right)\Big|_{E_{q,\alpha}^{\text{ion}}}}$$

Wu, Keitel, Pálffy, Phys. Rev. Lett. 122, 212501 (2019)

First Claimed NEEC evidence



- **Convolution approximation for swift Particle (CasP) code**

  Schiwietz, Grande, Phys. Rev. A 84, 052703 (2011)

- **Semi-empirical formula**

$$-\frac{dE^{\mathrm{ion}}}{dx} = \frac{4\pi Z_p^2 e^4}{m_e v^2} N Z_t L$$

Javanainen, Nucl. Instr. Meth. B 285, 158 (2012)

Gaussian distribution with $\bar{q}$ and width

(i) A general fitting formula by Nikolaev and Dmitriev (ND)

Phys. Lett. A 28, 277 (1968)

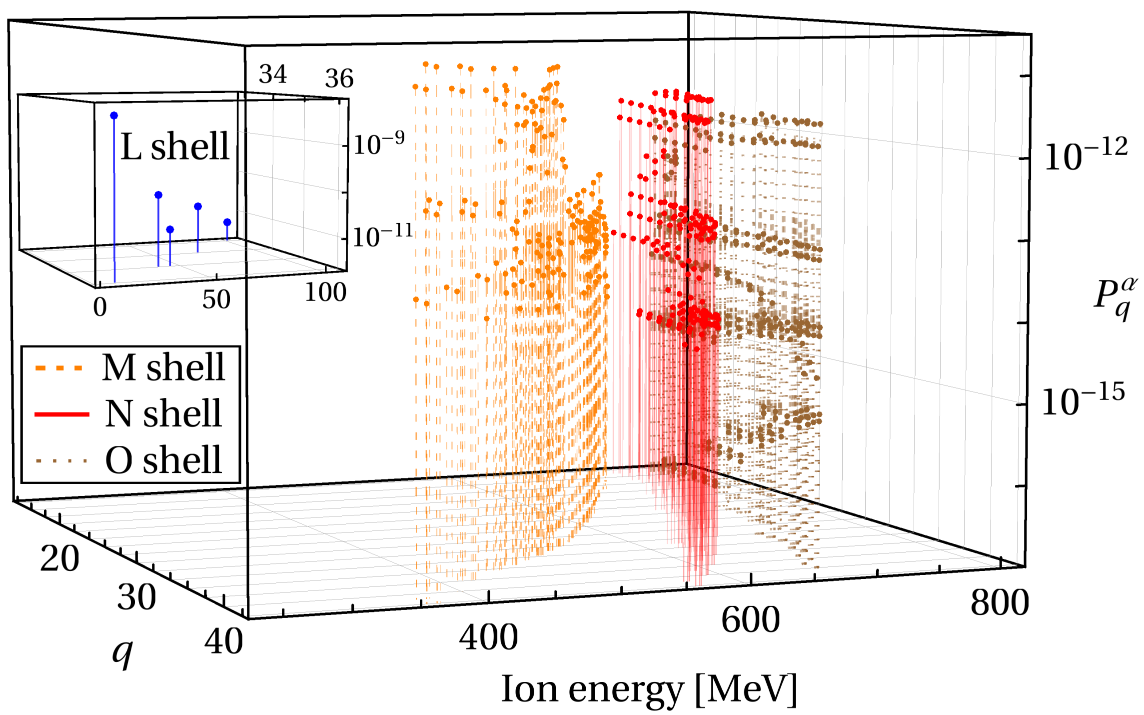
(ii) A multi-parameter least-square fit by Schiwietz and Grande (SG)

Nucl. Instr. Meth. B 175-177, 125 (2001)

Wu, Keitel, Pálffy, Phys. Rev. Lett. 122, 212501 (2019)

First Claimed NEEC evidence

NEEC理论计算



$$P_q^\alpha = n_e S_q^\alpha(E_{q,\alpha}) \frac{m_i}{m_e} \frac{1}{-\left(\frac{E^{\rm ion}}{dx}\right)\Big|_{E^{\rm ion}_{q,\alpha}}}$$

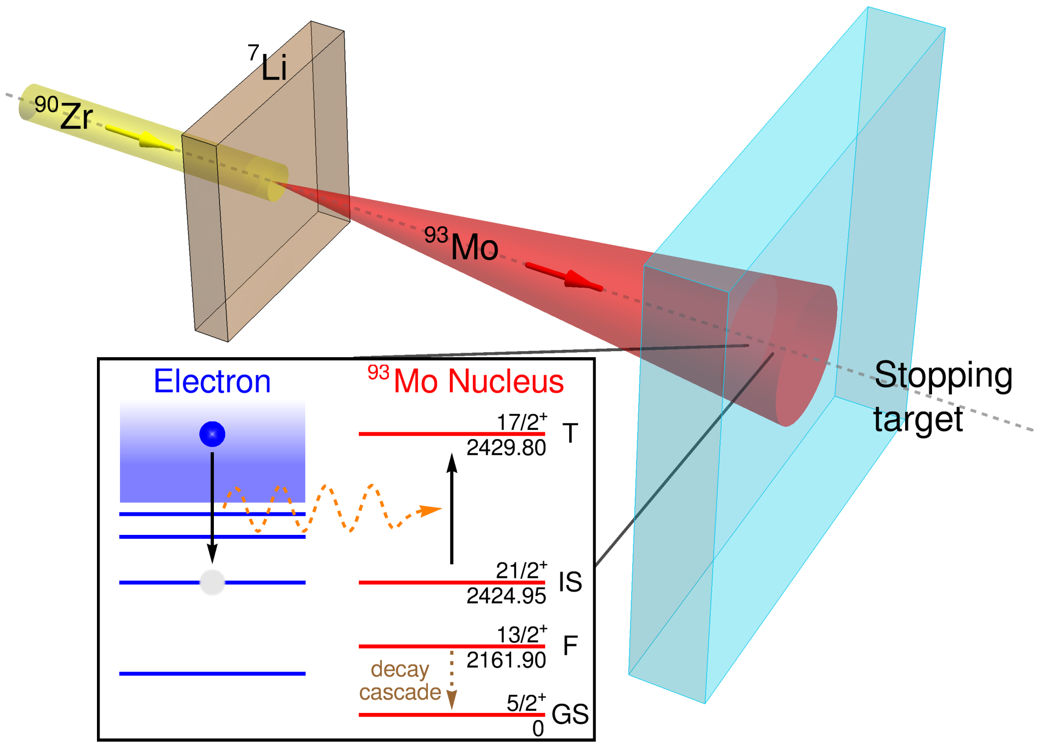
- 考虑648个通道
- L, M, N, O 壳层

$$P = \sum_{q,\alpha} f_q(E^{\rm ion}_{q,\alpha}) P_q^\alpha(E^{\rm ion}_{q,\alpha})$$

- NEEC probability $P \sim 10^{-11} \ll P_{\rm exc} = 0.01$
- NEEC probability in Pb target $\approx 5 \times 10^{-11}$

Wu, Keitel, Pálffy, Phys. Rev. Lett. 122, 212501 (2019)

First Claimed NEEC evidence



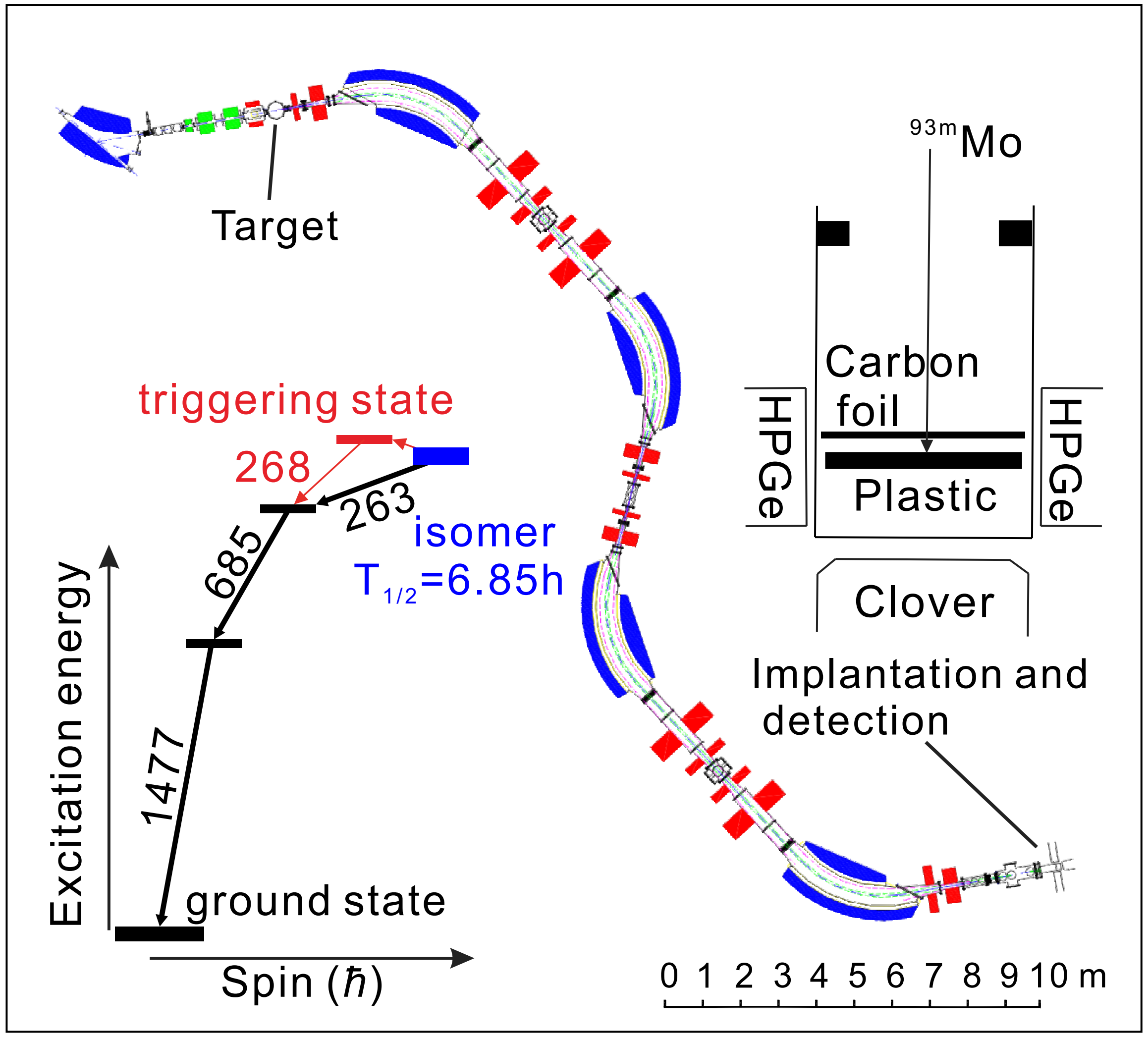
^{93m}Mo产生和衰变观测区域没有有效分离从而可能引起污染?

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

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

First Claimed NEEC evidence

使用Isomer Beam重新观测NEEC



- $^{12}C(^{86}Kr, 5n)^{93m}Mo$
- ^{93m}Mo离子能量：460 MeV
- 分离^{93m}Mo产生和衰变观测区域
- 低伽马本底
- 激发几率上限：$P_{exc} < 2 \times 10^{-5}$
- NEEC几率理论比值：
  $P(460\ \mathrm{MeV})/P(840\ \mathrm{MeV}) \sim 8\%$

S. Guo, B. Ding, X. H. Zhou, Y. B. Wu, ……, Y. H. Zhang, Phys. Rev. Lett. 128, 242502 (2022)

报告提纲

- ☑研究背景
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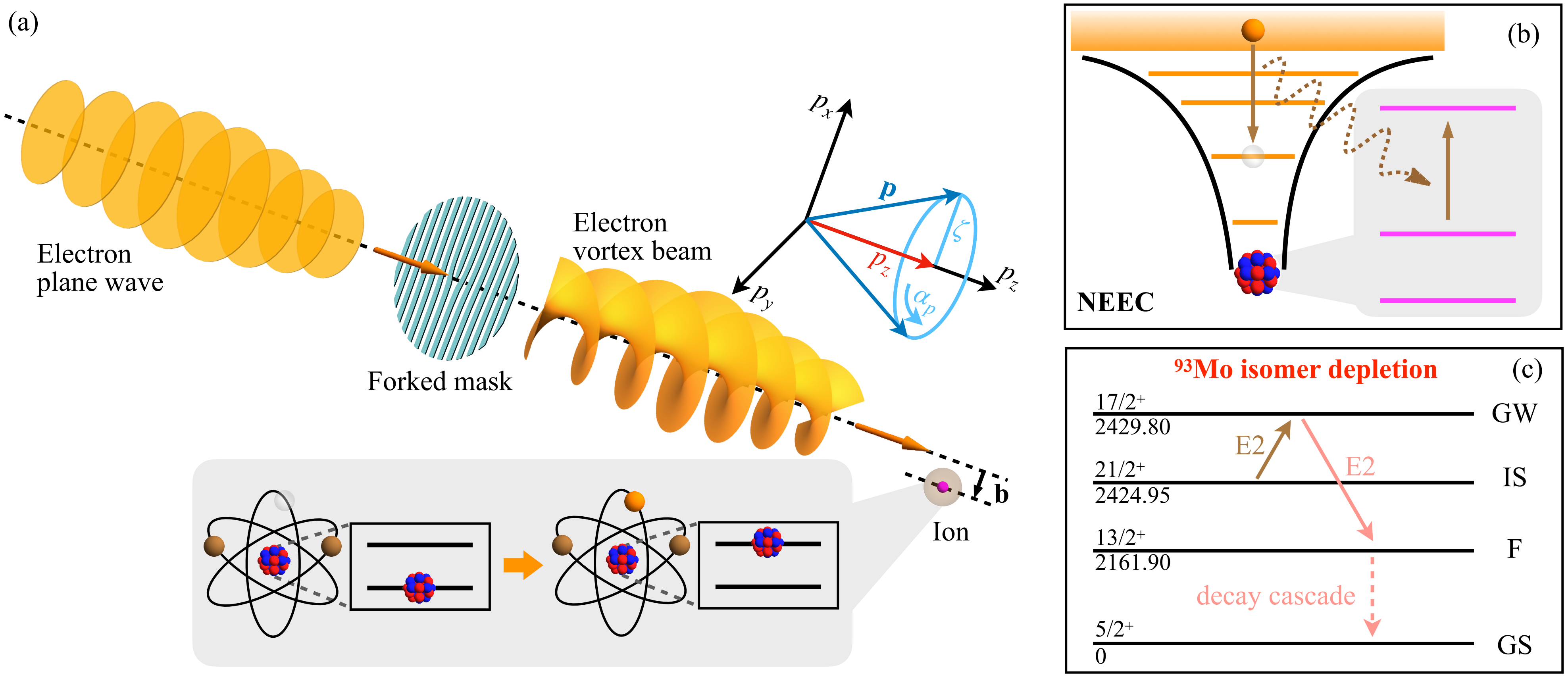
- ☑涡旋电子束
- ☑总结

NEEC-涡旋电子束

通过调节电子波函数来操纵原子核?



Electron vortex beams carry orbital angular momentum (OAM)

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

NEEC-涡旋电子束

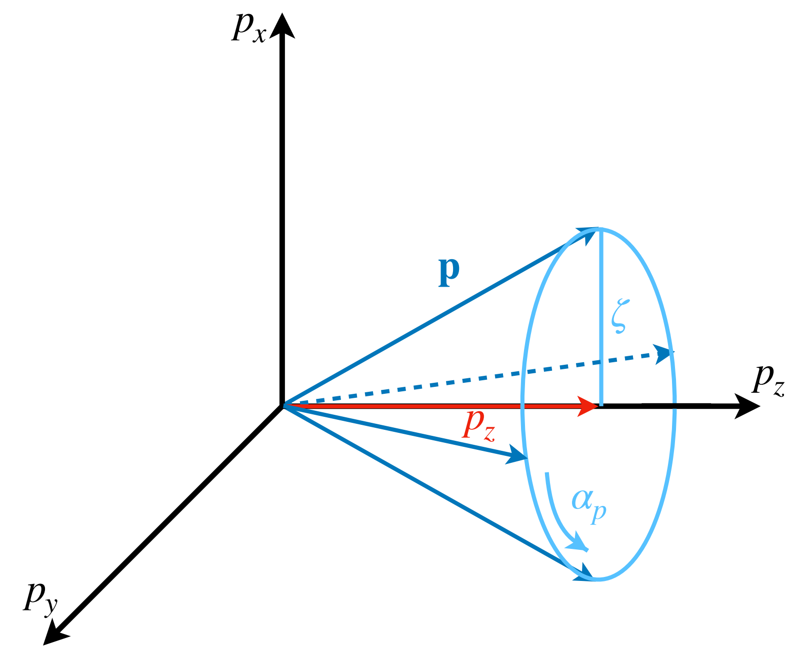
电子波函数

$$\psi(\mathbf{r}) = \int \frac{d^2\mathbf{p}_\perp}{(2\pi)^2} a_{\zeta m}(\mathbf{p}_\perp) u_\mathbf{p} e^{i\mathbf{p}\cdot\mathbf{r}}$$

$$a_{\zeta m}(\mathbf{p}_\perp) = (-i)^m e^{im\alpha_p} \sqrt{2\pi/\zeta}\,\delta(|\mathbf{p}_\perp| - \zeta)$$

m: vortex quantum number related to OAM

$$\mathbf{p} = (\mathbf{p}_\perp, p_z) = (\zeta\cos\alpha_p, \zeta\sin\alpha_p, p_z)$$



$$\psi_{+\frac{1}{2}}(\mathbf{r}) \propto e^{ip_z z}\left[\begin{pmatrix}\sqrt{E_+}\\0\\\cos\theta_0\sqrt{E_-}\\0\end{pmatrix} e^{im\varphi}J_m(\zeta r_\perp) + i\begin{pmatrix}0\\0\\0\\\sin\theta_0\sqrt{E_-}\end{pmatrix} e^{i(m+1)\varphi}J_{m+1}(\zeta r_\perp)\right]$$

$$\psi_{-\frac{1}{2}}(\mathbf{r}) \propto e^{ip_z z}\left[\begin{pmatrix}0\\\sqrt{E_+}\\0\\-\cos\theta_0\sqrt{E_-}\end{pmatrix} e^{im\varphi}J_m(\zeta r_\perp) - i\begin{pmatrix}0\\0\\\sin\theta_0\sqrt{E_-}\\0\end{pmatrix} e^{i(m-1)\varphi}J_{m-1}(\zeta r_\perp)\right]$$

NEEC-涡旋电子束

NEEC - 平面波

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

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

NEEC - 涡旋电子

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

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

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

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

Transitions of electric multipolarity L

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

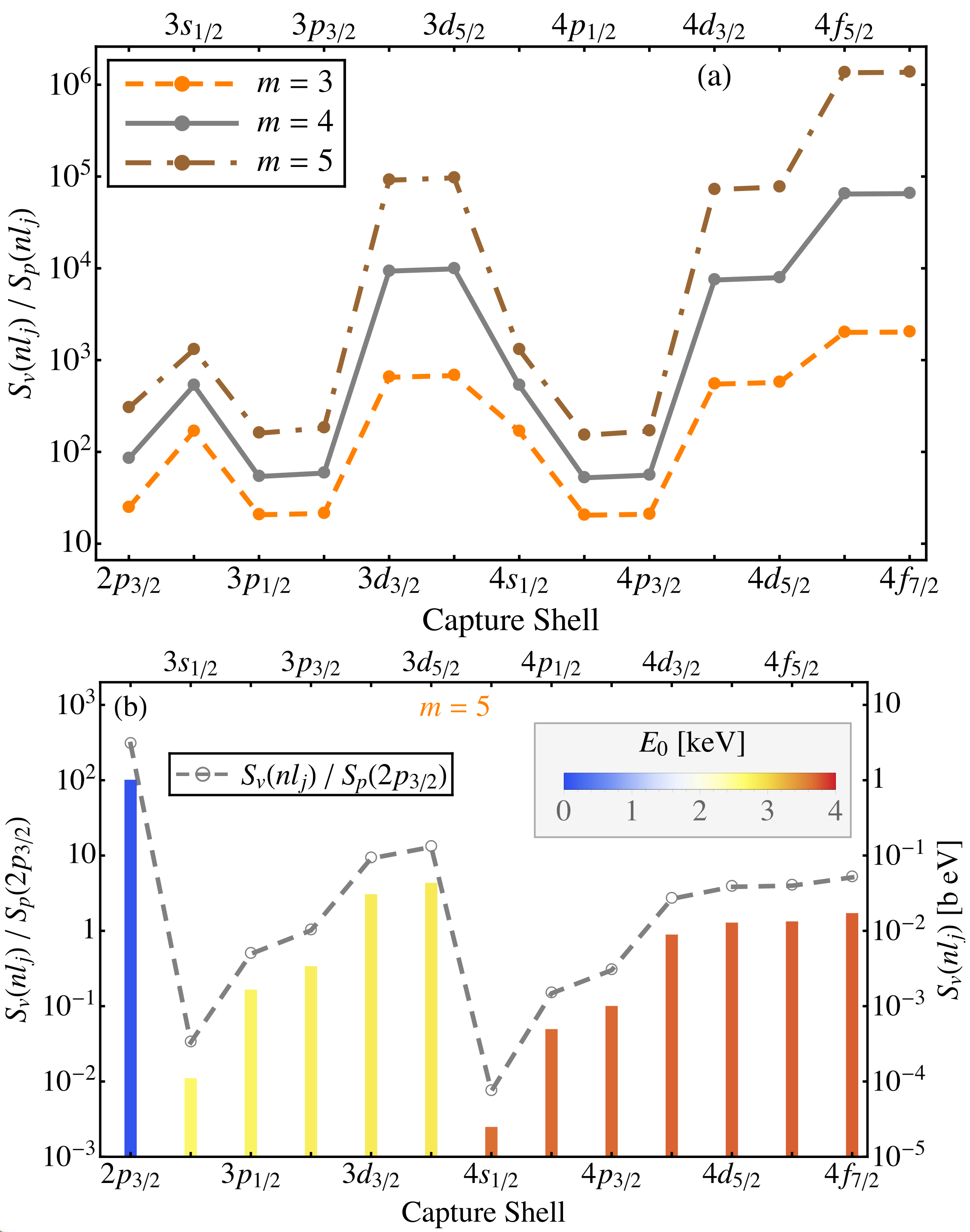
Transitions of magnetic multipolarity L

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

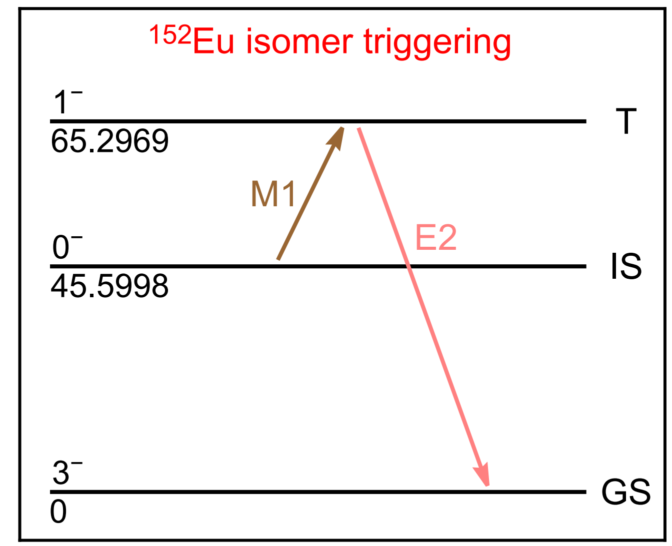
Wu, Gargiulo, Carbone, Keitel, Pálffy, Phys. Rev. Lett. 128, 162501 (2022)

NEEC-涡旋电子束

^{93m}Mo E2 跃迁



^{152m}Eu M1 跃迁



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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总结

首个NEEC实验迹象 — 离子束-固体靶

- NEEC几率 $P \sim 10^{-11} \ll P_{\text{exc}} = 0.01$ (首个NEEC实验迹象)
- 离子能量偏低、低伽马本底条件下重新测量：$P_{\text{exc}} < 2 \times 10^{-5}$

NEEC — 涡旋电子束-离子束

- 相比于平面波，涡旋电子束可以使NEEC截面提高2-6个数量级
- 通过电子波函数的改变影响原子核能级的跃迁

谢谢大家！