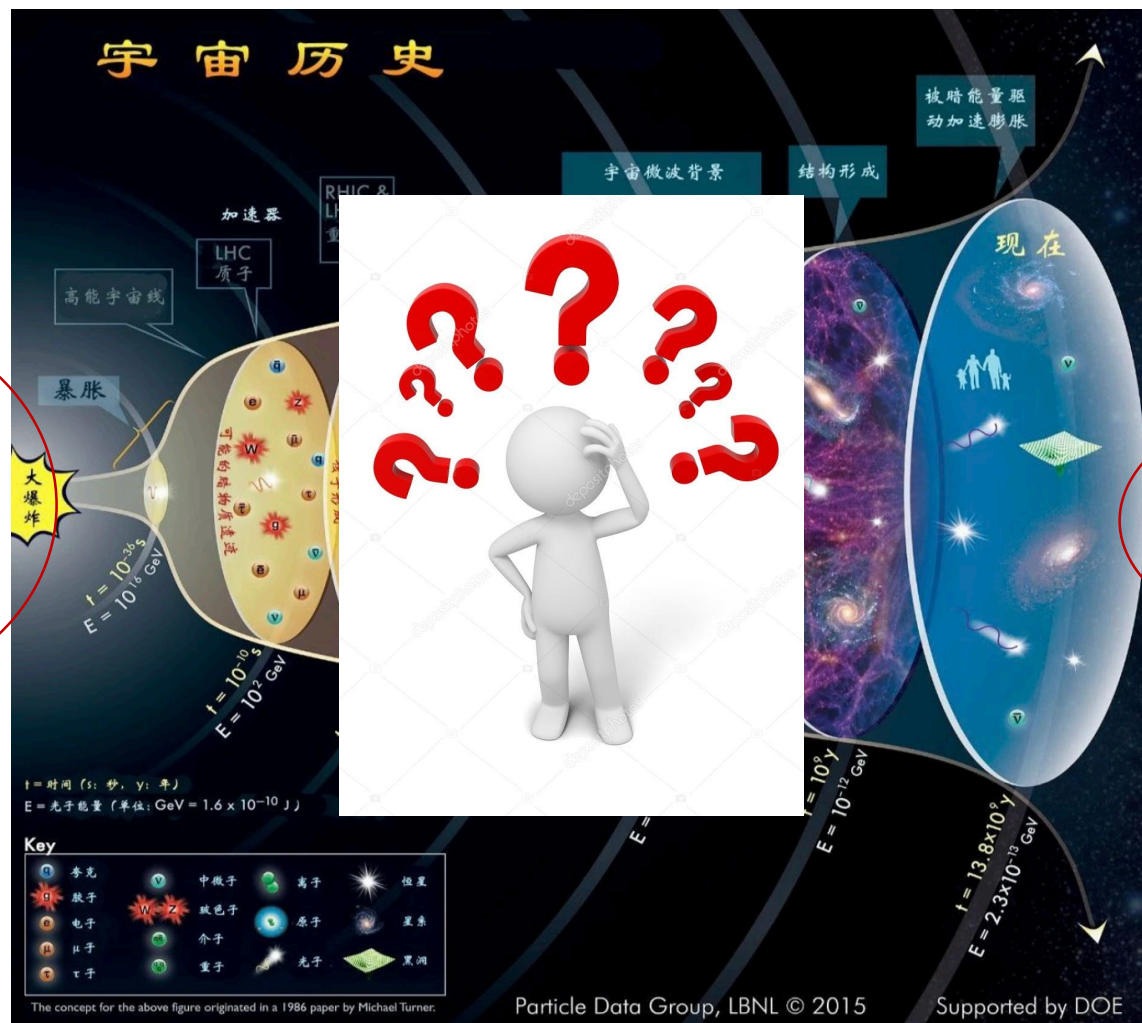


原子核奇特性质与寻找CP对称性破缺新机遇

杨晓菲

北京大学物理学院
核物理与核技术全国重点实验室





物质与
反物质数
量相等

几乎没有
反物质

现代宇宙学观测表明，可见的宇宙中正物质的总量比反物质多出了一个微小的比例（ $\sim 10^{-9}$ ），即正反物质是不对称的，由此导致了当今丰富多彩的物质世界。

报告内容

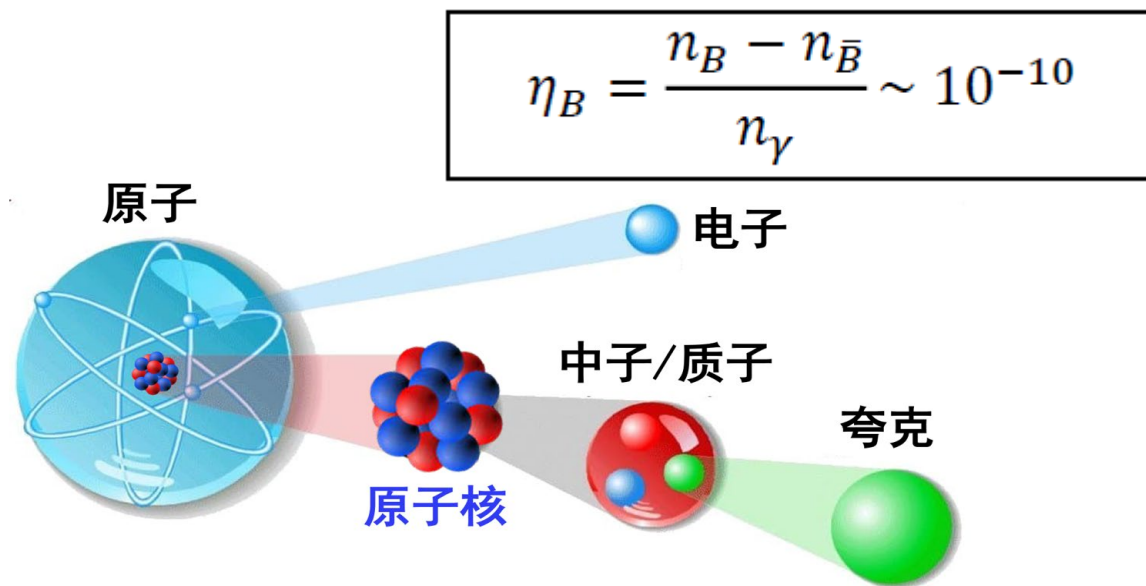
1. P,T 破缺 (研究背景)
2. 重核(放射性)分子的优势
3. 国际放射性分子研究现状
4. 国内放射性分子研究近期发展
5. 总结及展望

1. 研究背景-正反物质不对称

Sakharov条件:

- 重子数破缺
- C和**CP对称性破缺** ★
- 偏离热平衡

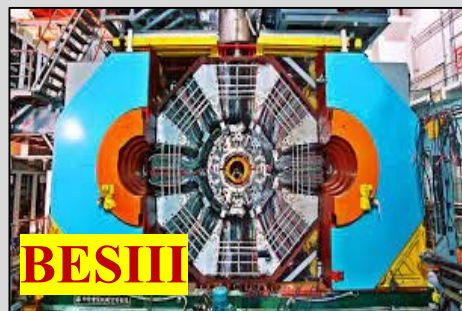
Soviet Physics Uspekhi, **34**, 392 (1991).



宇宙演化后, CP破缺现象应在基本粒子及其相互作用体系中体现



LHCb



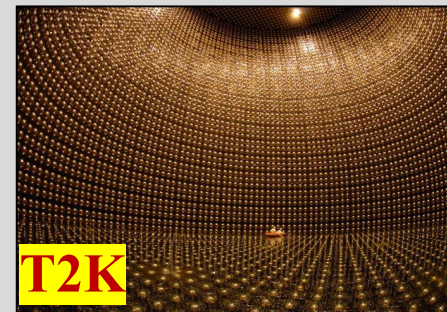
BESIII

高能粒子物理实验



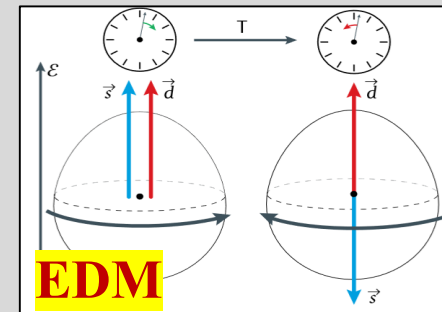
RHIC

重离子碰撞实验



T2K

中微子实验



EDM

低能EDM测量实验

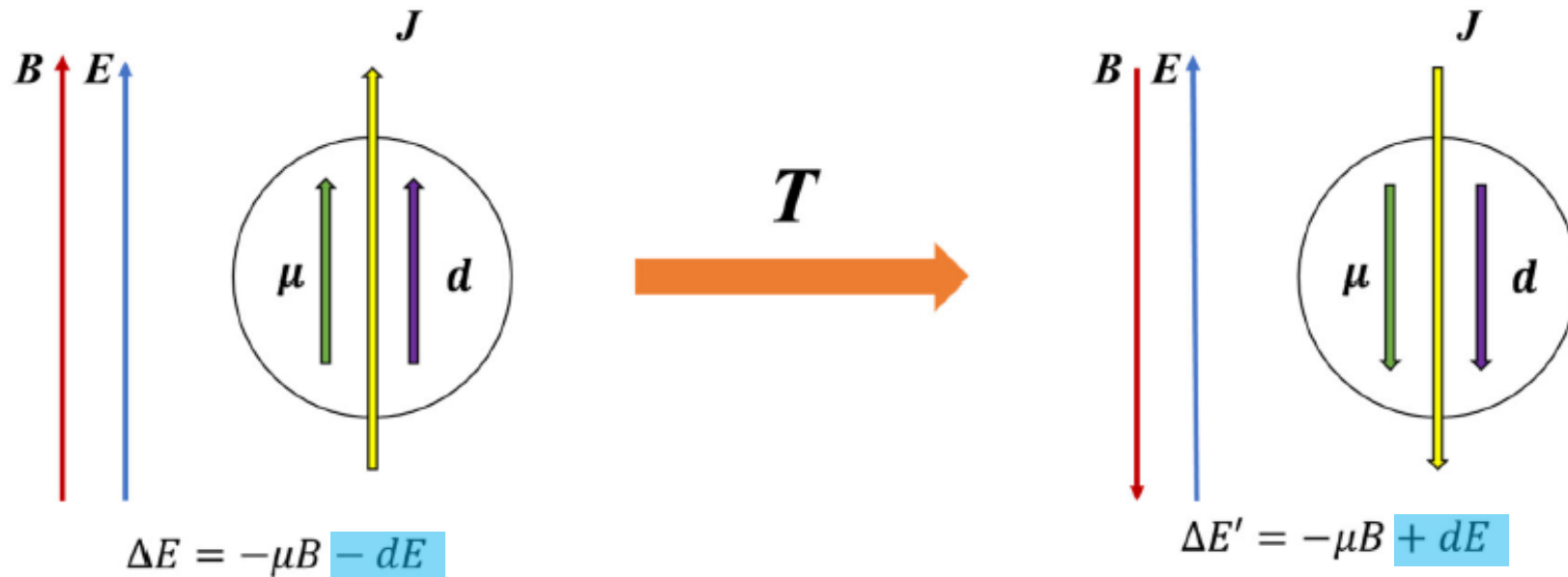
1. 研究背景-EDM的存在-CP破缺/P破缺

$$H = -\boldsymbol{\mu} \cdot \mathbf{B} - \mathbf{d} \cdot \mathbf{E} = -\mu \frac{\mathbf{J} \cdot \mathbf{B}}{J} - d \frac{\mathbf{J} \cdot \mathbf{E}}{J}$$

$$\boldsymbol{\mu} = \frac{1}{2} \int \mathbf{r} \times \mathbf{J}_e(\mathbf{r}) d^3\mathbf{r} = \mu \frac{\langle \mathbf{J} \rangle}{J} \quad \mathbf{d} = \int \mathbf{r} \rho_e(\mathbf{r}) d^3\mathbf{r} = d \frac{\langle \mathbf{J} \rangle}{J}$$

时间反演T操作下:

$$\begin{aligned} J &\rightarrow -J \\ B &\rightarrow -B \\ E &\rightarrow E \end{aligned}$$



空间反演P操作下:

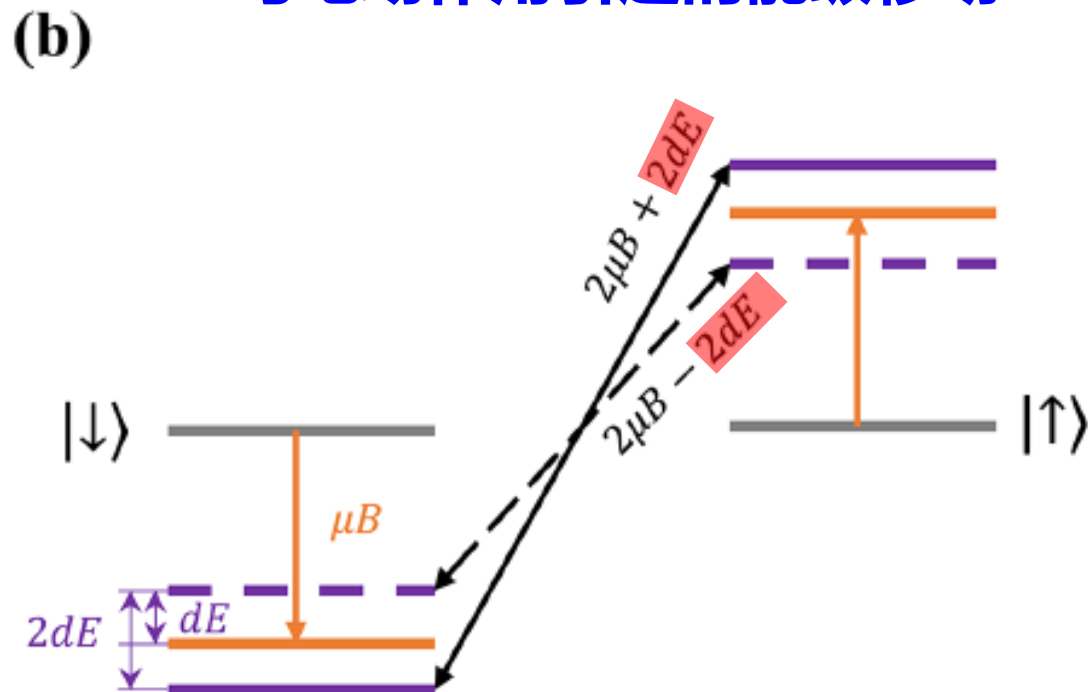
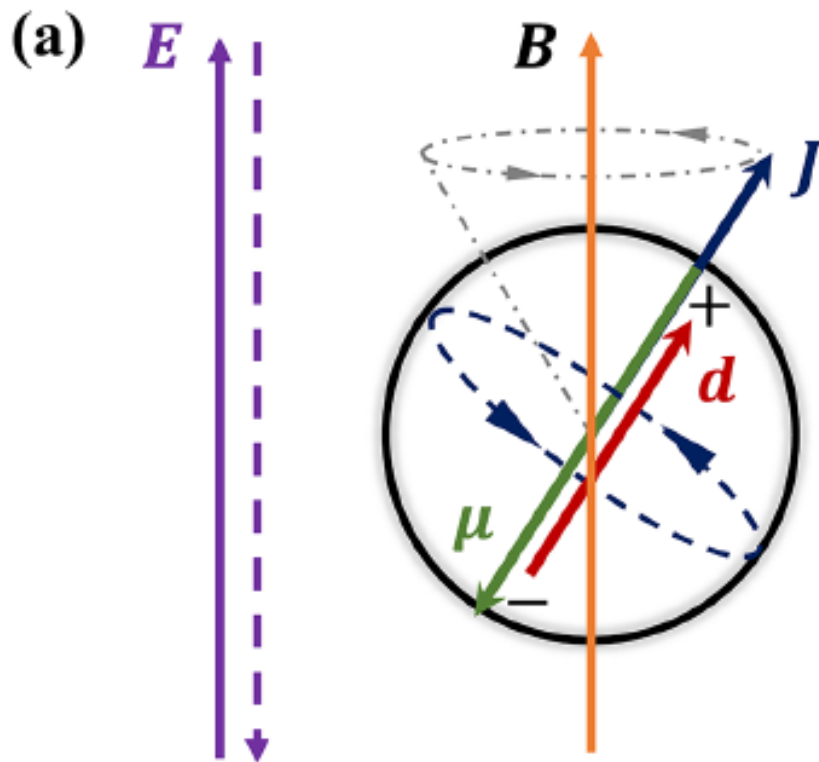
$$\begin{aligned} J &\rightarrow J \\ B &\rightarrow B \\ E &\rightarrow -E \end{aligned}$$

EDM d 的存在破坏了系统的哈密顿量的时间反演和空间反演对称性
T破缺 => CP破缺; P破缺

1. 研究背景-EDM测量原理

$$\mathcal{H} = -\boldsymbol{\mu} \cdot \boldsymbol{B} - \boldsymbol{d} \cdot \boldsymbol{E}$$

d 与电场作用引起的能级移动

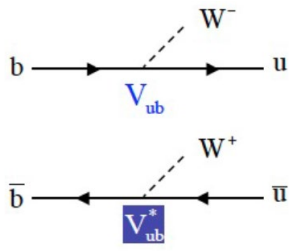


- 体系 $\boldsymbol{\mu}$ 和 $\boldsymbol{d}$ 在电磁场中引起系统的自旋进动频率变化(a) 与能级移动(b)
- 反转E方向, 测量对应的能级的移动 ($\Delta E_{\text{shift}} = 4dE$), 既可提取 d

1. 研究背景-标准模型中CP破缺

弱相互作用

-正反夸克的CKM矩阵互为复共轭，相位反号引起CP破坏

$$V_{CKM} = \begin{bmatrix} V^{ud} & V^{us} & V^{ub} \\ V^{cd} & V^{cs} & V^{cb} \\ V^{td} & V^{ts} & V^{tb} \end{bmatrix}$$


CP-破坏效应 $\propto \text{Im}(V_{us}V_{cs}^*V_{cb}V_{ub}^*) \neq 0$

物质-反物质
光子数

$\sim 10^{-18}$

CKM

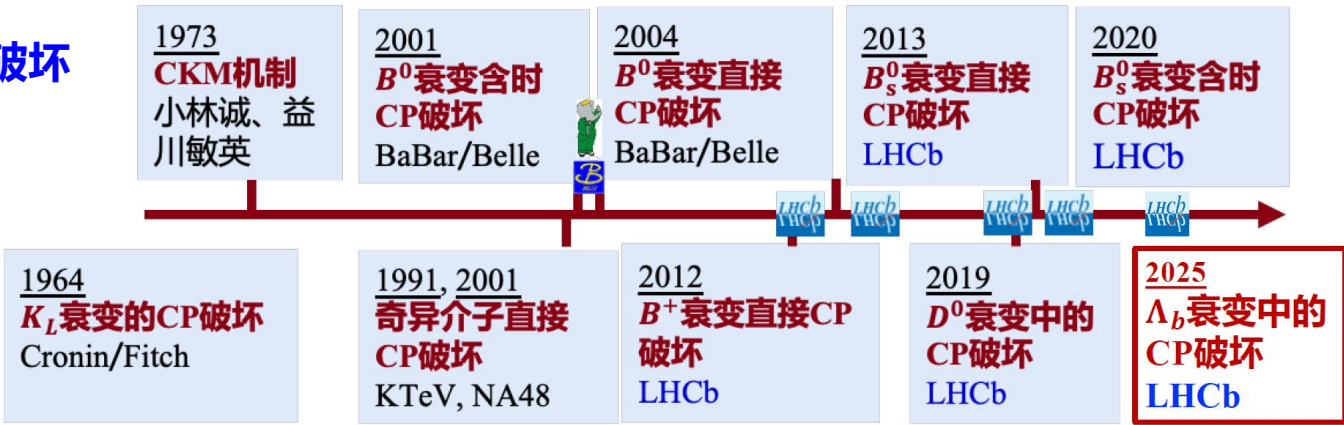
$\ll$

10^{-10}

观测

强相互作用-QCD的θ项(强CP破缺参数)

$$\mathcal{L}_{\bar{\theta}} = -\frac{\alpha_s}{16\pi^2} \bar{\theta} \text{Tr}(G^{\mu\nu} \tilde{G}_{\mu\nu})$$

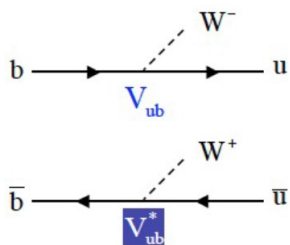


目前还没有实验证据！！

1. 研究背景-标准模型中CP破缺

□ 弱相互作用

-正反夸克的CKM矩阵互为复共轭，相位反号引起CP破坏

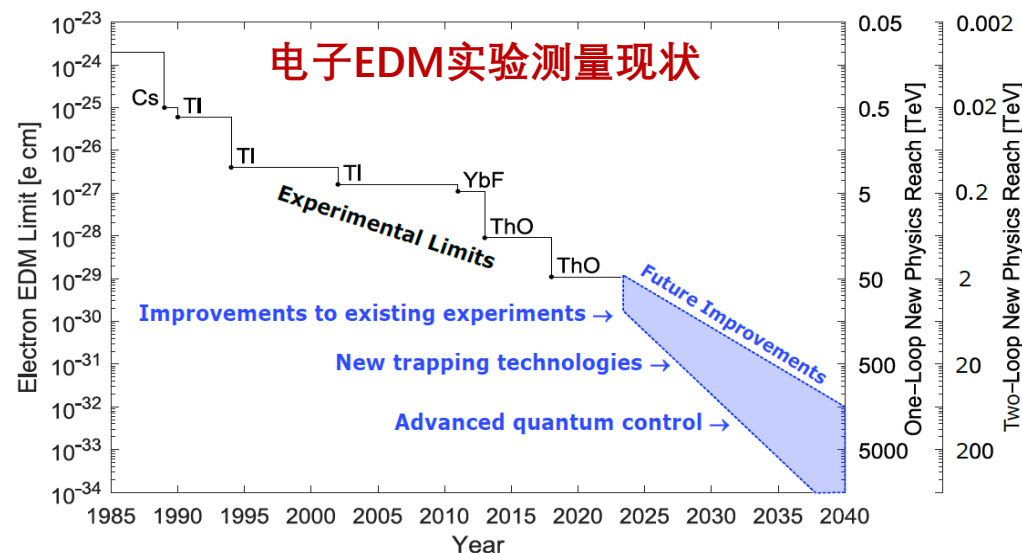
$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$


$$\text{CP-破坏效应} \propto \text{Im}(V_{us}V_{cs}^*V_{cb}V_{ub}^*) \neq 0$$

$$\mathbf{d}_e^{\text{CKM}} = \frac{eG_F}{\pi^2} \left(\frac{\alpha_{\text{EM}}}{2\pi}\right)^3 m_e \bar{\delta} \approx 10^{-38} \text{ e cm}$$

□ 强相互作用-QCD的 $\bar{\theta}$ 项(强CP破缺参数)

$$\mathcal{L}_{\bar{\theta}} = -\frac{\alpha_s}{16\pi^2} \bar{\theta} \text{Tr}(G^{\mu\nu} \tilde{G}_{\mu\nu})$$



R. Alarcon et al., 2022, <https://arxiv.org/abs/2203.08103>

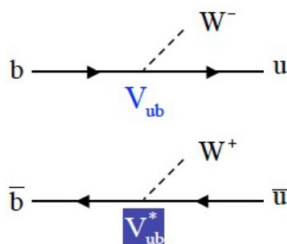
T. E. Chupp et al. Rev. Mod. Phys. 91, 015001 (2019)

目前还没有实验证据！！

1. 研究背景-标准模型中CP破缺

弱相互作用

-正反夸克的CKM矩阵互为复共轭，相位反号引起CP破坏

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$


$$\text{CP-破坏效应} \propto \text{Im}(V_{us}V_{cs}^*V_{cb}V_{ub}^*) \neq 0$$

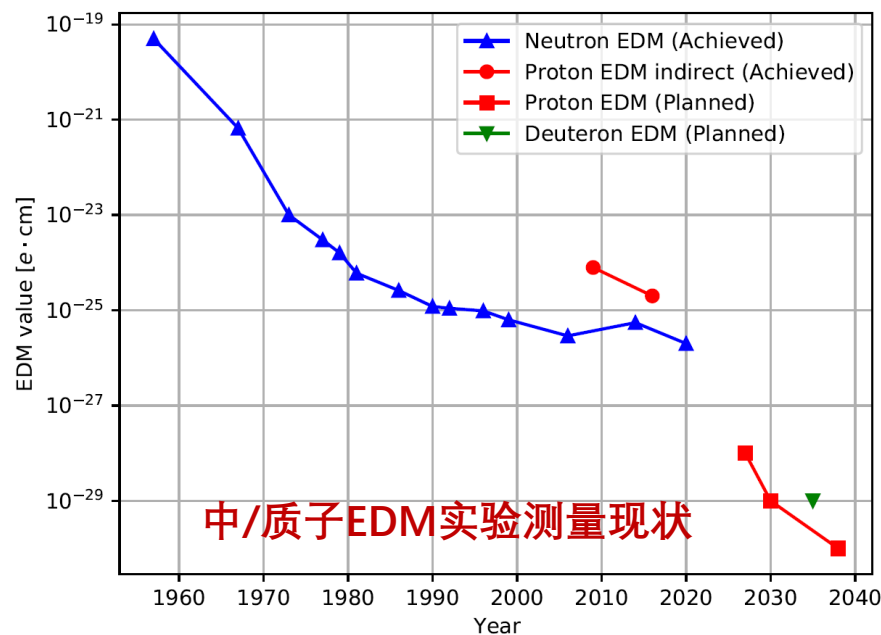
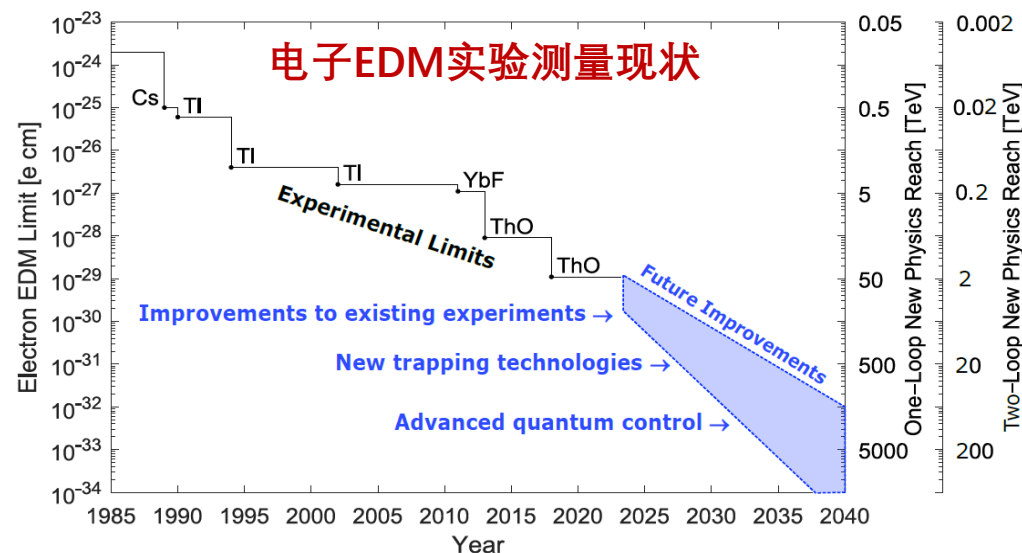
$$d_e^{\text{CKM}} = \frac{eG_F}{\pi^2} \left(\frac{\alpha_{\text{EM}}}{2\pi}\right)^3 m_e \bar{\delta} \approx 10^{-38} \text{ e cm}$$

强相互作用-QCD的 $\bar{\theta}$ 项(强CP破缺参数)

$$\mathcal{L}_{\bar{\theta}} = -\frac{\alpha_s}{16\pi^2} \bar{\theta} \text{Tr}(G^{\mu\nu} \tilde{G}_{\mu\nu})$$

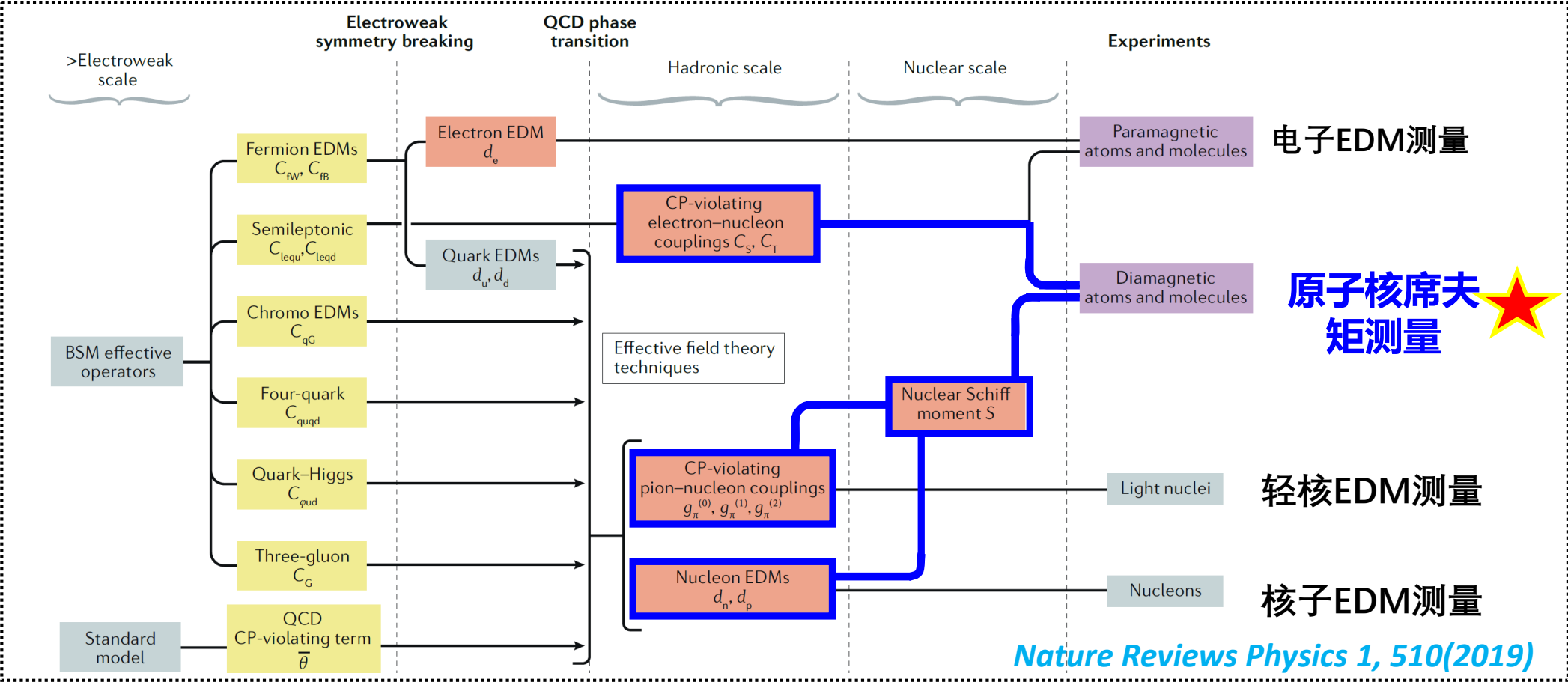
$$d_n^{\bar{\theta}} \sim 10^{-16} \bar{\theta} \text{ e cm}$$

$$\bar{\theta} < 10^{-10}$$



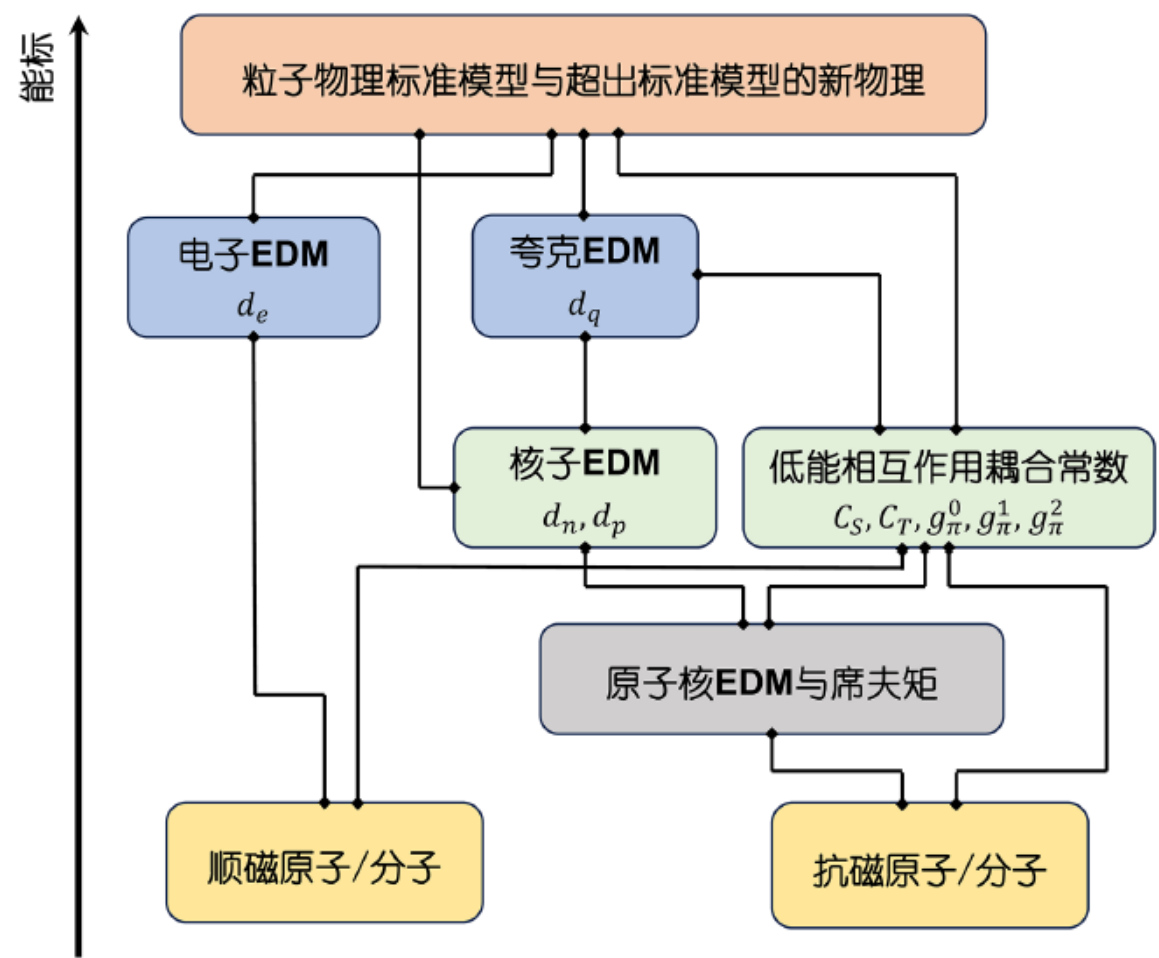
1. 研究背景-EDM测量与CP破缺机制

高能基本粒子层次和低能复杂体系（核子、原子核、原子和分子等）的探测相互关联和互补



未来最关键的是实验上能在某个能区率先取得测量突破

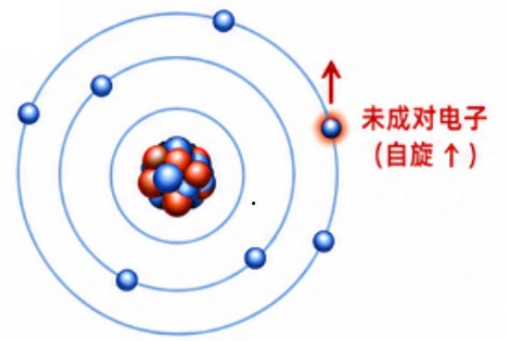
1. 研究背景-EDM测量与CP破缺机制



❑ **顺磁原子/分子:** 电子未完全配对，系统具有非零的总电子自旋，对电子EDM 灵敏；

-测量电子EDM

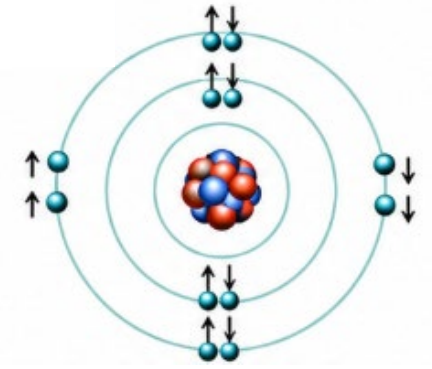
例: Cs (Z=55)
Tl (Z=81)



❑ **抗磁原子/分子:** 电子完全配对总电子自旋为0，体系中只存在非零核自旋，对核子EDM 或核力中可能存在的CP 破缺敏感

-测量核希夫矩

例: ¹⁹⁹Hg (Z=80)
²²⁵Ra (Z=88)



梅文聪, 杨晓菲, 叶沿林. 科学通报, 71, 979–992 (2026).

1. 研究背景-核与核外电子相互作用

• 电磁多极超精细结构

电磁多极展开：

$$H_{\text{hf}} = \sum_k \hat{T}_{\text{N}}^k \cdot \hat{T}_{\text{e}}^k$$

- K=1 磁偶极超精细相互作用

K=2 电四极超精细相互作用

K=3 磁八极超精细相互作用

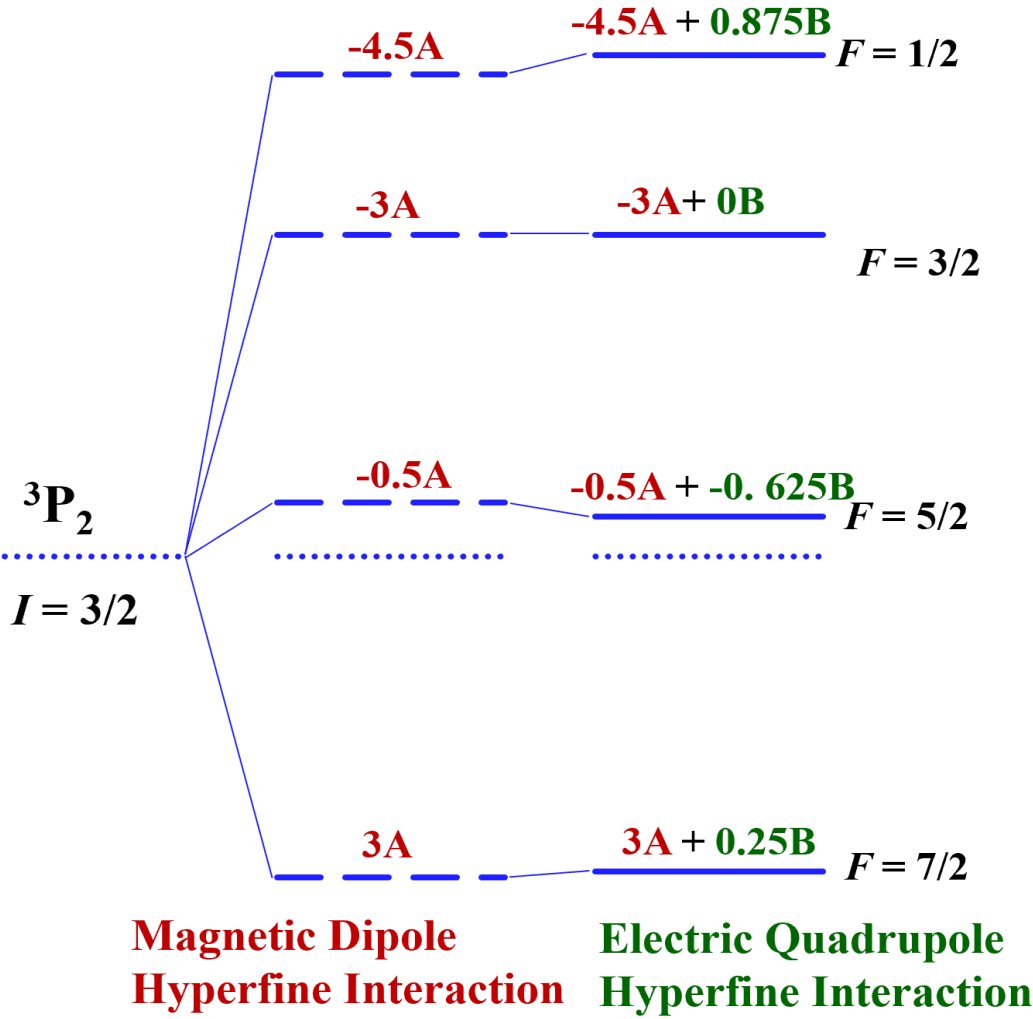
K=4 电十六极超精细相互作用

.....

实验有观测

- 电偶极超精细相互作用 (EDM)
- 磁四极超精细相互作用 (MQM)

对称性破缺

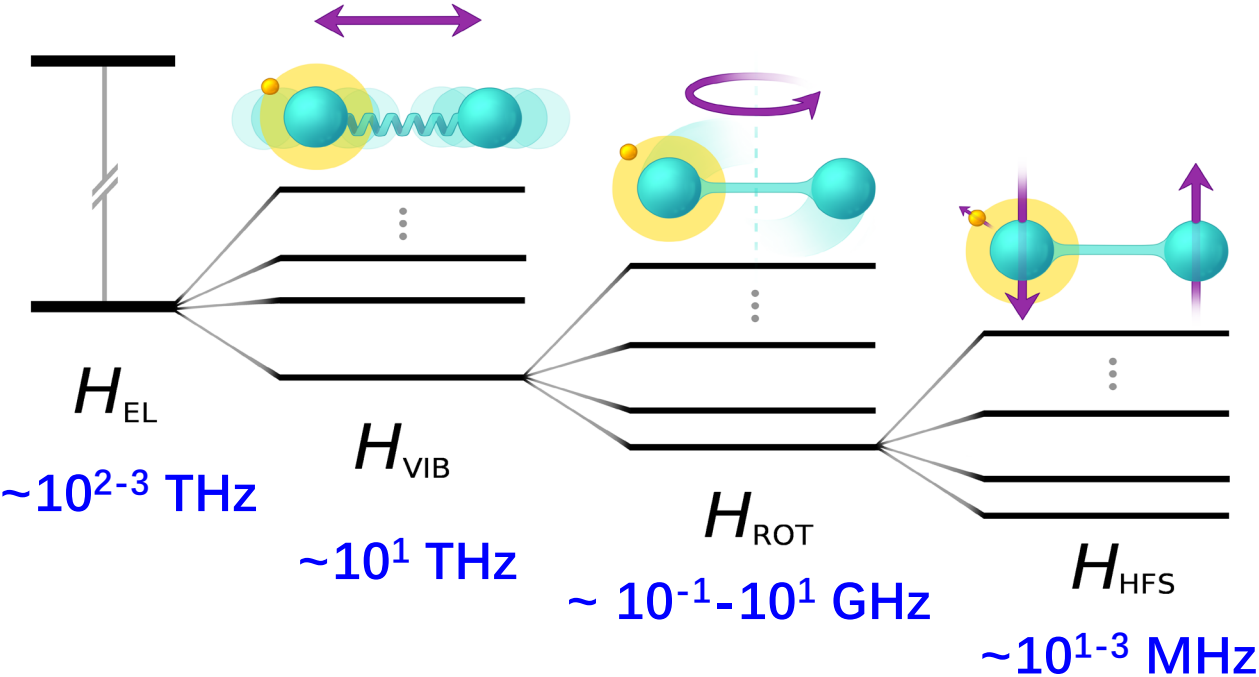


1. 研究背景-核与核外电子相互作用

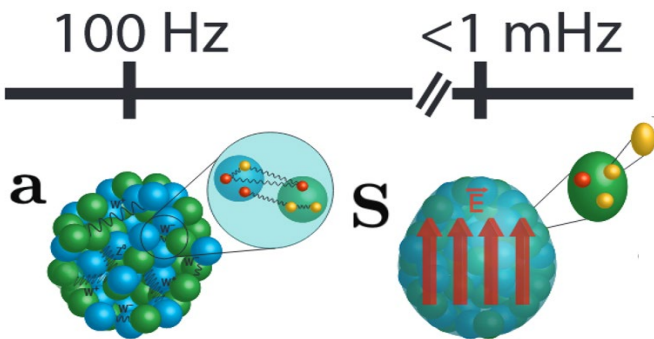
原子核的效应

$$H_{\text{MOL}} = H_{\text{EL}} + H_{\text{VIB}} + H_{\text{ROT}} + H_{\text{HFS}} + \dots + H_{\text{PV}} + H_{\text{PTV}} + \dots$$

$\sim 2 \text{ eV}$ $\sim 10^{-2} \text{ eV}$ $\sim 10^{-5} \text{ eV}$ $\sim 10^{-8} \text{ eV}$ $< 10^{-12} \text{ eV}$ $< 10^{-18} \text{ eV}$



P/CP对称性破缺



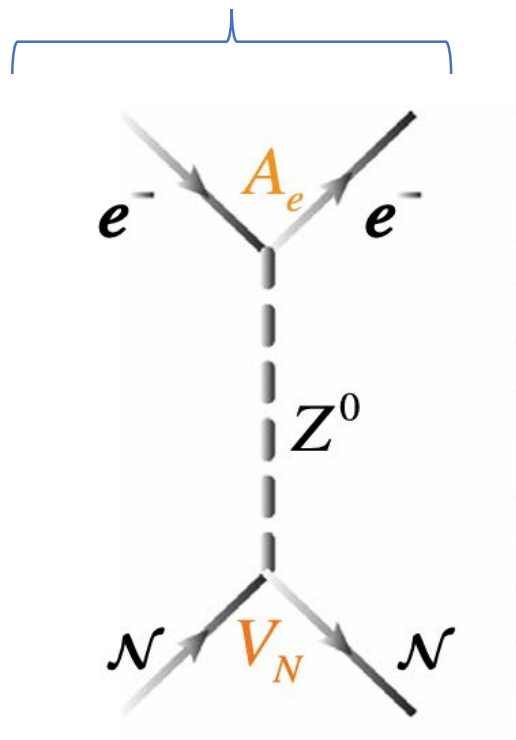
原子核电磁矩

Anapole moment Schiff moment

Nature Physics 20, 741-749 (2024); *Report on the Progress in Physics*, 87, 084301(2024); *PPNP* 129, 104005 (2023)

1. 研究背景-P 破缺与anapole moment(环形偶极矩)

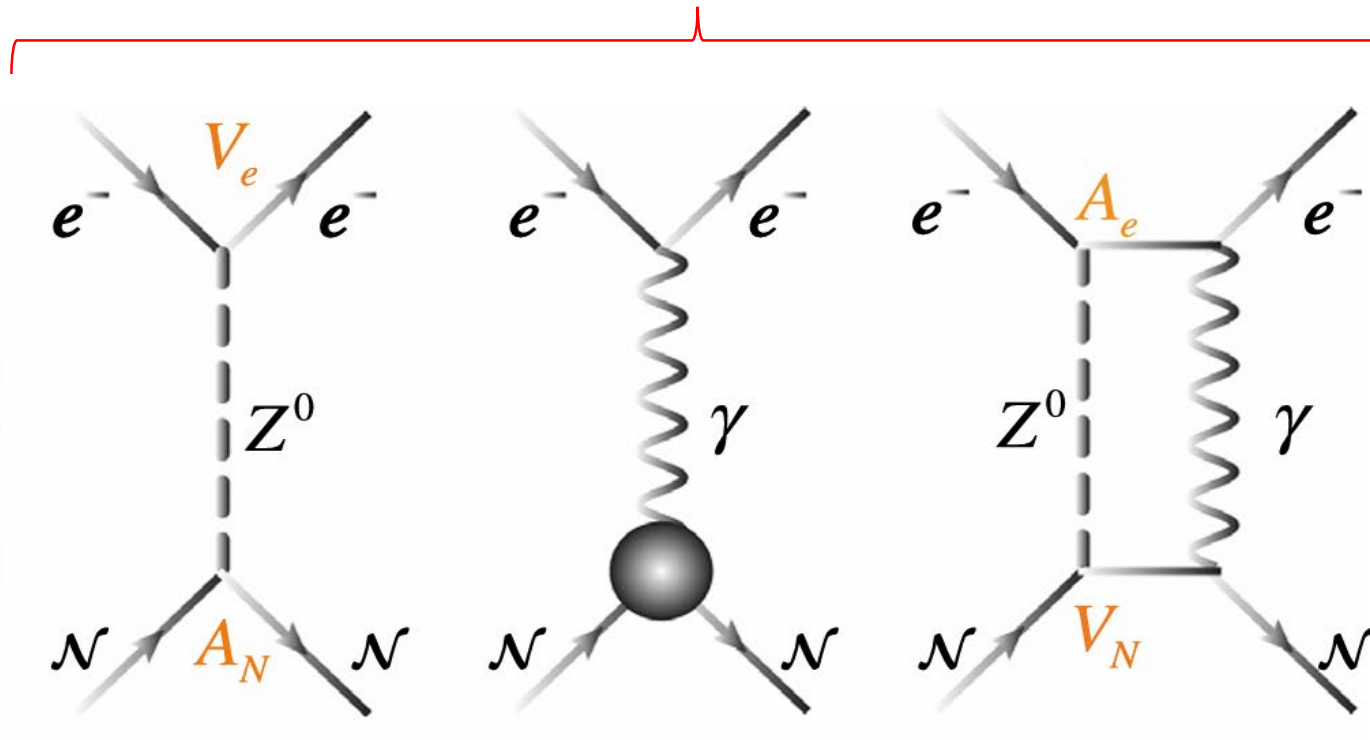
NSI-PV 核自旋无关的P破缺



$$H_W = \underbrace{Q_W}_{\text{circled}} \frac{G_F}{\sqrt{8}} \gamma_5 \rho(r)$$

电子与原子核整体间弱作用

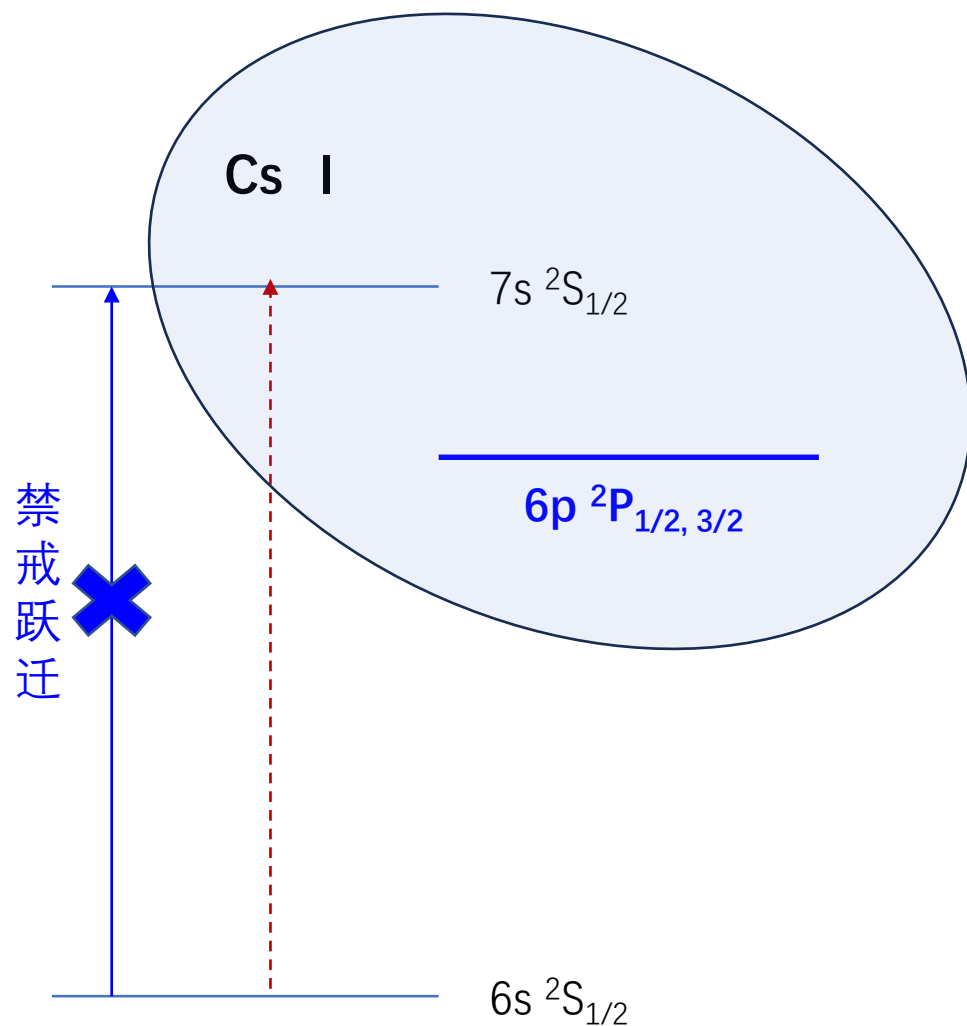
NSD-PV 核自旋相关的P破缺



$$H_{\text{NSD}} = \frac{G_F}{\sqrt{2}} (\eta_{\text{axial}} + \underbrace{\eta_{\text{NAM}}}_{\text{circled}} + \eta_{\text{hf}}) (\boldsymbol{\alpha} \cdot \mathbf{I}) \rho(r)$$

核子间PV弱作用诱导出核内环形涡旋状电流, 产生AM与核外电子作用

1. 研究背景-P 破缺与anapole moment(环形偶极矩)-测量原理



C.S. Wood et al., Science 275, 1759 (1997)

$$H_{PV}: \quad H_W = Q_W \frac{G_F}{\sqrt{8}} \gamma_5 \rho(r)$$
$$H_{NSD} = \frac{G_F}{\sqrt{2}} (\eta_{\text{axial}} + \eta_{\text{NAM}} + \eta_{\text{hf}}) (\boldsymbol{\alpha} \cdot \mathbf{I}) \rho(r)$$

□ H_{PV} 导致原子能级的组态混合

$$|\widetilde{7S}\rangle = |7S\rangle + \sum_n \frac{\langle n|H_{PV}|7S\rangle}{E_{|7S\rangle} - E_{|n\rangle}} |n\rangle, \quad |n\rangle = |6P\rangle, |7P\rangle, \dots$$

□ 增强效应:

重元素: 电子轨道收缩, $\langle n|H_{PV}|7S\rangle$ 更强

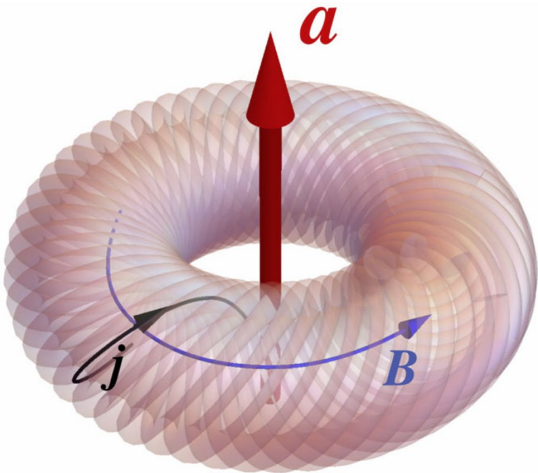
分子系统: 存在能级间距更小的宇称双重态

$$\frac{\langle n|H_{PV}|7S\rangle}{E_{|7S\rangle} - E_{|n\rangle}}$$
$$\frac{\langle n|H_{PV}|7S\rangle}{E_{|7S\rangle} - E_{|n\rangle}}$$

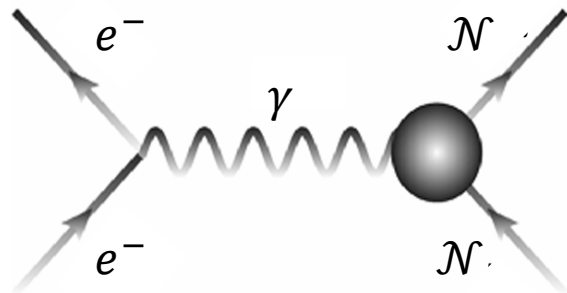
$|\widetilde{6S}\rangle$ 和 $|\widetilde{7S}\rangle$ 之间存在允许的E1跃迁: $\mathcal{A}_{\text{PNC}}$

1. 研究背景-P 破缺与anapole moment(环形偶极矩)

原子核Anapole矩 (宇称破缺效应)



原子核Anapole矩与电子相互作用



- 核子-核子弱作用
- 强子体系中的PV
- 核结构与弱作用耦合
- ...
- ...

部分双原子分子离子对探测核AM的相对灵敏度

分子种类	W_A (Hz)	分子种类	W_A (Hz)
$^{11}\text{BF}^+$	1	$^{227}\text{AcBr}^+$	1644
$^{29}\text{SiO}^+$	13	$^{227}\text{AcI}^+$	1677
$^{205}\text{TlF}^+$	4472	$^{229}\text{ThO}^+$	2506
$^{227}\text{AcH}^+$	1649	$^{229}\text{ThS}^+$	1752
$^{227}\text{AcF}^+$	1655	$^{229}\text{ThSe}^+$	1588
$^{227}\text{AcCl}^+$	1632	$^{229}\text{ThTe}^+$	1323

[1] W. C. Haxton. *Science* 275, 5307 (1997)
[2] M. S. Safronova et al. *RMP* 90, 025008 (2018)
[3] J. Karthein, et al. *PRL* 133, 033003 (2024)

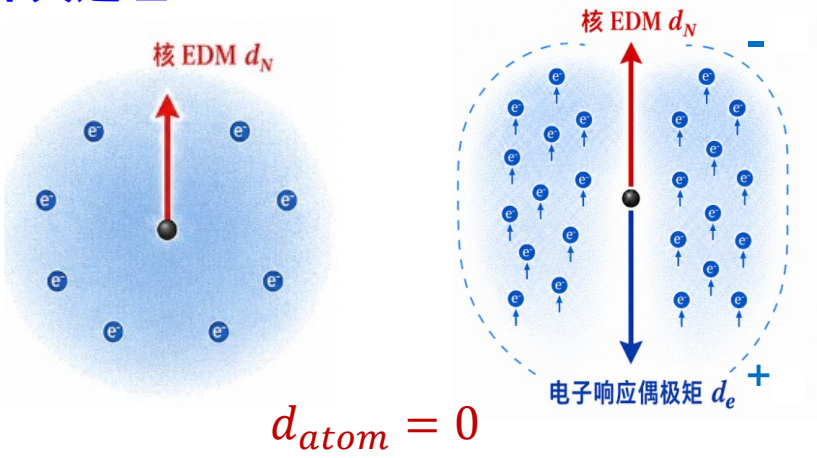
1. 研究背景-CP破缺与Schiff moment席夫矩

席夫定理

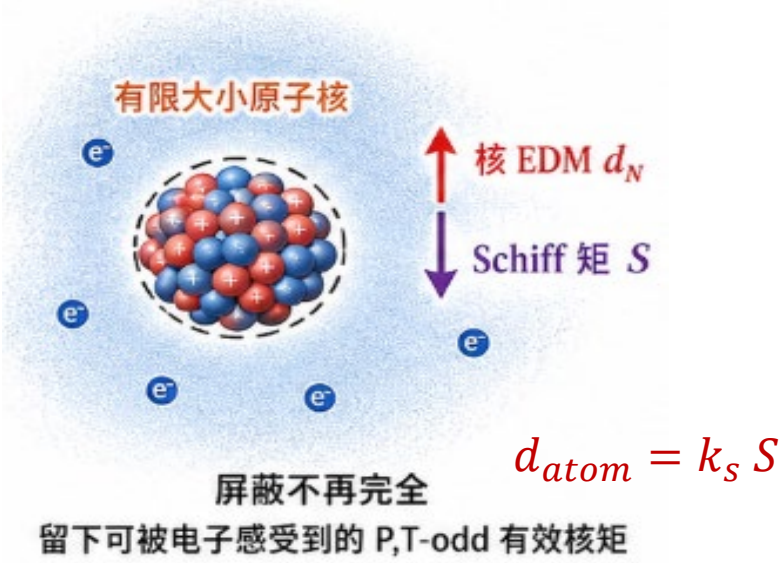
L.I. Schiff, Phys. Rev. 132, 2194 (1963)

$$d_{atom} = \tilde{d}_{atom} + d_{nucleus} = 0 \quad \text{非相对论电子/核为点电荷}$$

Schiff 定理： 在由点状原子核和非相对论电子组成的中性体系中，电子云会重新分布并完全屏蔽核 EDM 的效应。



原子核席夫矩



$$d_{atom} = \tilde{d}_{atom} + d_{nucleus} \neq 0 \quad \text{相对论运动电子/核电荷分布/形变}$$

原子核的席夫矩

$$S_{intr} = \frac{1}{10} \int r^2 \mathbf{r} \rho_e d^3r - \frac{1}{6Z} \int \rho_e r^2 d^3r \times \int \mathbf{r} \rho_e d^3r$$

$$\propto eZR^3 \beta_2 \beta_3 \quad (\text{内禀坐标系})$$

1. 研究背景-CP破缺与Schiff moment席夫矩

八极形变原子核的席夫矩

八极形变原子核可形成近简并的正负宇称双重态

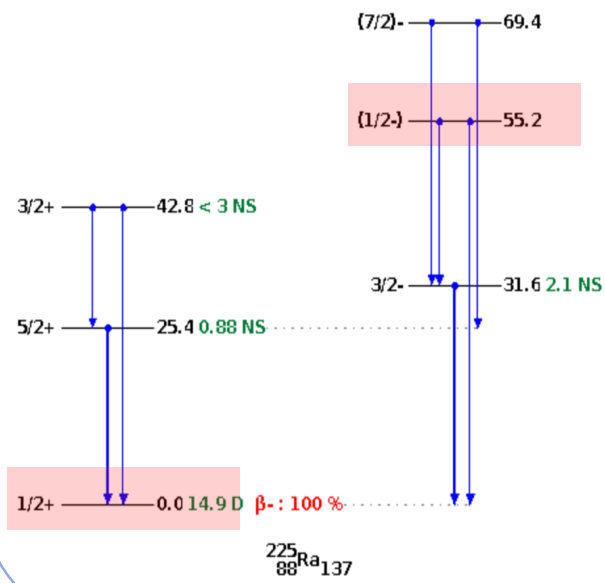
$$|\psi^\pm\rangle = \frac{1}{\sqrt{2}} (|\Omega_+\rangle \pm |\Omega_-\rangle)$$

P,T-破缺相互作用会混合正负宇称态

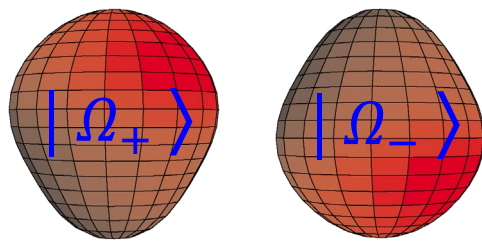
$$|\psi\rangle = |\psi_+\rangle + \alpha |\psi_-\rangle \quad \alpha \sim \frac{\langle \psi_+ | V^{PT,V} | \psi_- \rangle}{E_- - E_+}$$

对²²⁵Ra: $E_- - E_+$ 为55.2 keV
态混合显著增强

²²⁵Ra低能级结构



Parity doublet



$$\psi^- = (|\Omega_+\rangle - |\Omega_-\rangle)/\sqrt{2}$$
$$\psi^+ = (|\Omega_+\rangle + |\Omega_-\rangle)/\sqrt{2}$$

55 keV

$$S = \langle \psi^\pm | S_z | \psi^\pm \rangle = 0$$

$$S = \langle \psi | S_z | \psi \rangle = 2\alpha \frac{I}{I(I+1)} S_{\text{intr}} \quad \rightarrow$$

实验室系核席夫矩估算

$$S \approx 1.0 \times 10^{-4} \frac{I}{I+1} \beta_2 (\beta_3)^2 Z A^{2/3} \frac{[\text{keV}]}{E_- - E_+} e \eta [\text{fm}^3]$$

Rev. Mod. Phys. 90, 025008(2018); Rev. Mod. Phys. 91, 015001(2019)

η : 表征强子层面P,T 破缺强度的无量纲参数

报告内容

1. P,T 破缺 (研究背景)
2. 重核(放射性)分子的优势
3. 国际放射性分子研究现状
4. 国内放射性分子研究近期发展
5. 总结及展望

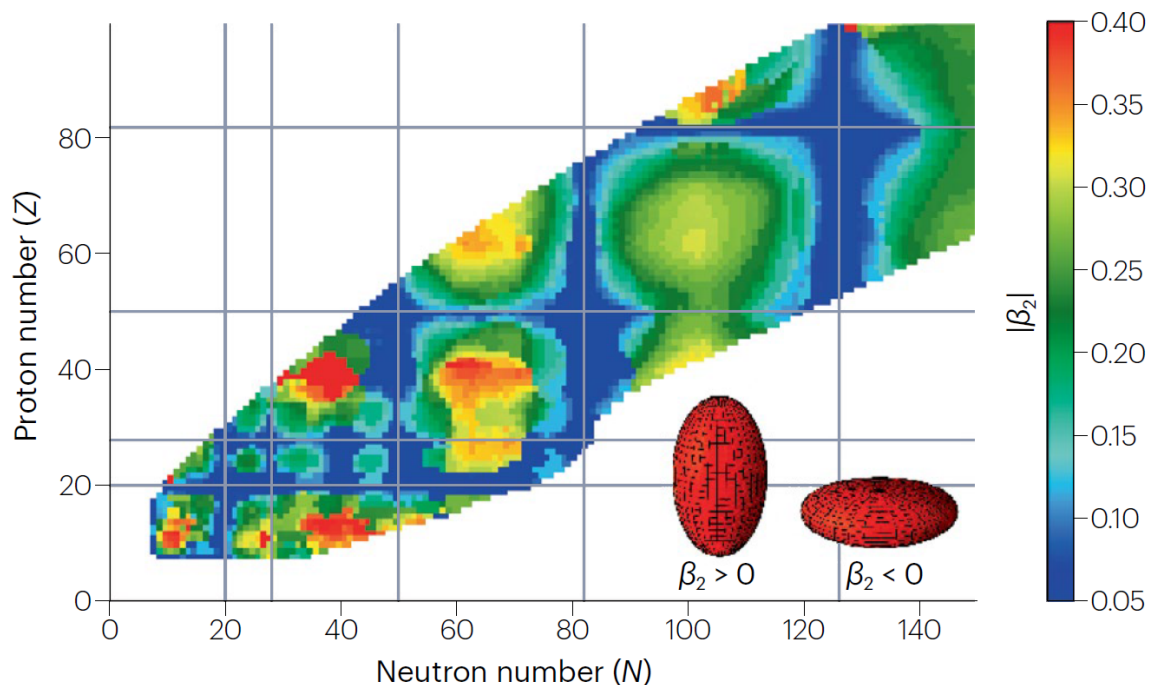
2. 重核分子的优势 八极形变重核优势

^{223}Fr , ^{225}Ra , ^{227}Ac , ^{227}Th , ^{229}Pa

$Z \sim 88$, $N \sim 134$

$$S \approx 1.0 \times 10^{-4} \frac{I}{I+1} \beta_2 (\beta_3)^2 Z A^{2/3} \frac{[\text{keV}]}{E_- - E_+} e \eta [\text{fm}^3]$$

a Ground-state quadrupole deformation



b Ground-state octupole deformation

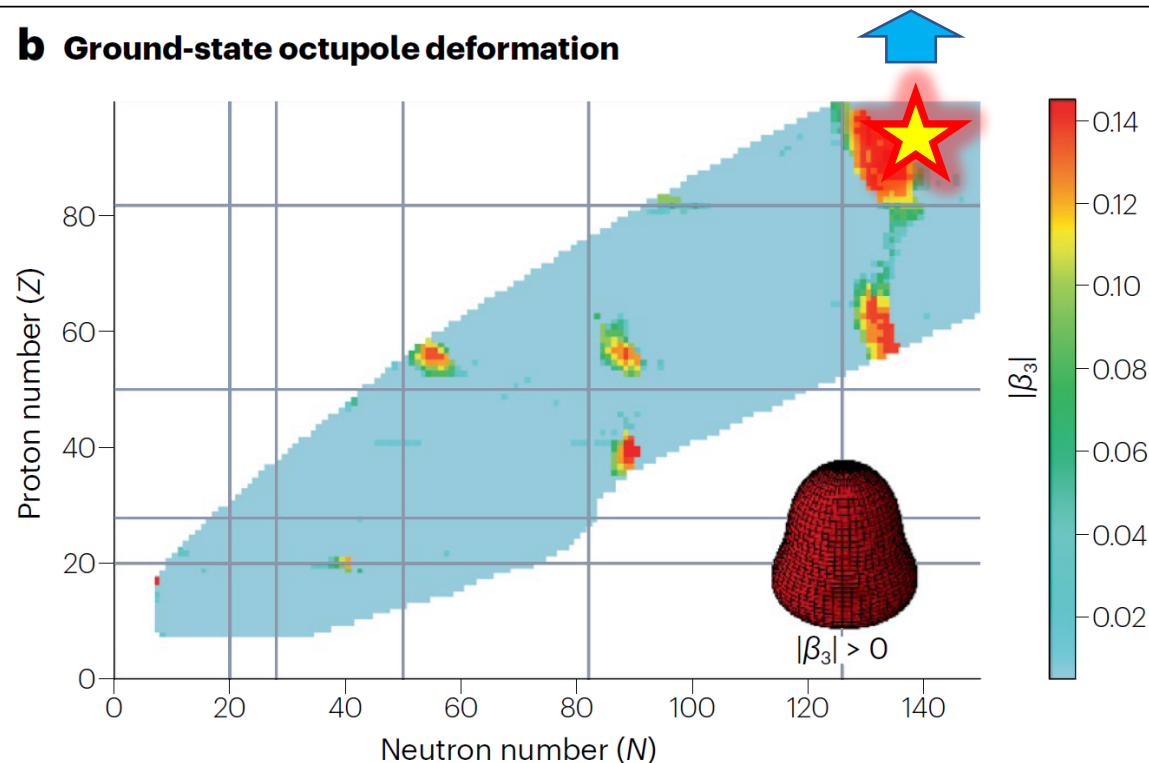


Fig. 1 | Quadrupole and octupole deformation across the nuclear chart.

The parameters β_2 and β_3 characterize deviations of a nucleus from spherical symmetry. **a**, The quadrupole deformation parameter β_2 corresponds to elongated

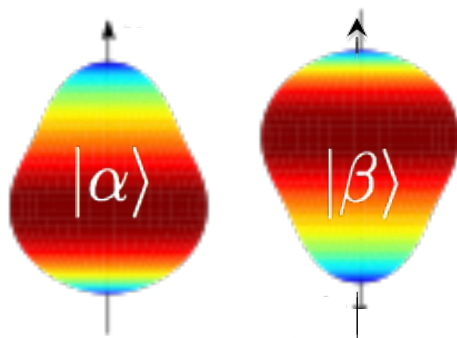
(prolate) or flattened (oblate) shapes, respectively. **b**, The octupole deformation parameter β_3 describes pear-like shapes that do not exhibit reflection symmetry. Data replotted from ref. 142. Figure courtesy of Jose Miguel Munoz Arias.

2. 重核分子的优势 八极形变重核优势

$$H_{\text{MOL}} = H_{\text{EL}} + H_{\text{VIB}} + H_{\text{ROT}} + \dots + H_{\text{HFS}} + H_{\text{PV}} + H_{\text{PTV}}$$



Nature 497(2013)199



²²⁵Ra

$$\Delta E = 55 \text{ keV}$$

原子	席夫矩 S (10^{-17} e.f.m^3)	系数 k_s (10^{-17} cm/fm^3)
¹²⁹ Xe	1.75	0.38
¹⁷¹ Yb	-1.4	-1.9
¹⁹⁹ Hg	-1.4	-2.5
²²⁵ Ra	300-1100	-8.5

*PRL*76(1996)4316; *RRC* 68 (2003)035502/*PRA*101(2020)042504

$$\begin{aligned} S(^{225}\text{Ra})/S(^{199}\text{Hg}) &\sim 10^{2-3} \\ d(^{225}\text{Ra})/d(^{199}\text{Hg}) &\sim 10^3 \end{aligned} \quad \downarrow \quad d_a \propto k_s S$$

$$H = (\mu \vec{J} \cdot \vec{B} + d \vec{J} \cdot \vec{E})/J \quad \text{八极形变核增强 } \times 10^3$$

$$S \approx 1.0 \times 10^{-4} \frac{I}{I+1} \beta_2 (\beta_3)^2 Z A^{2/3} \frac{[\text{keV}]}{E_- - E_+} e \eta [\text{fm}^3]$$

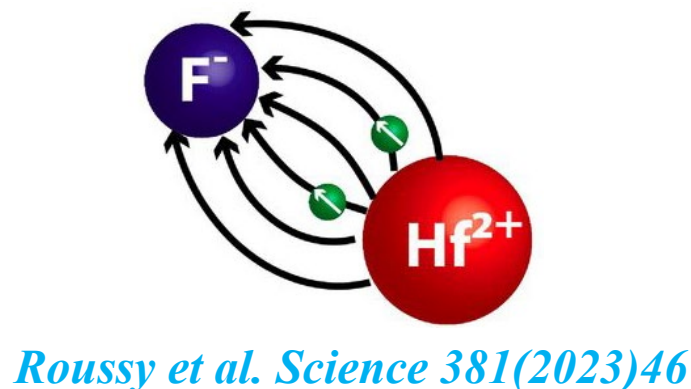
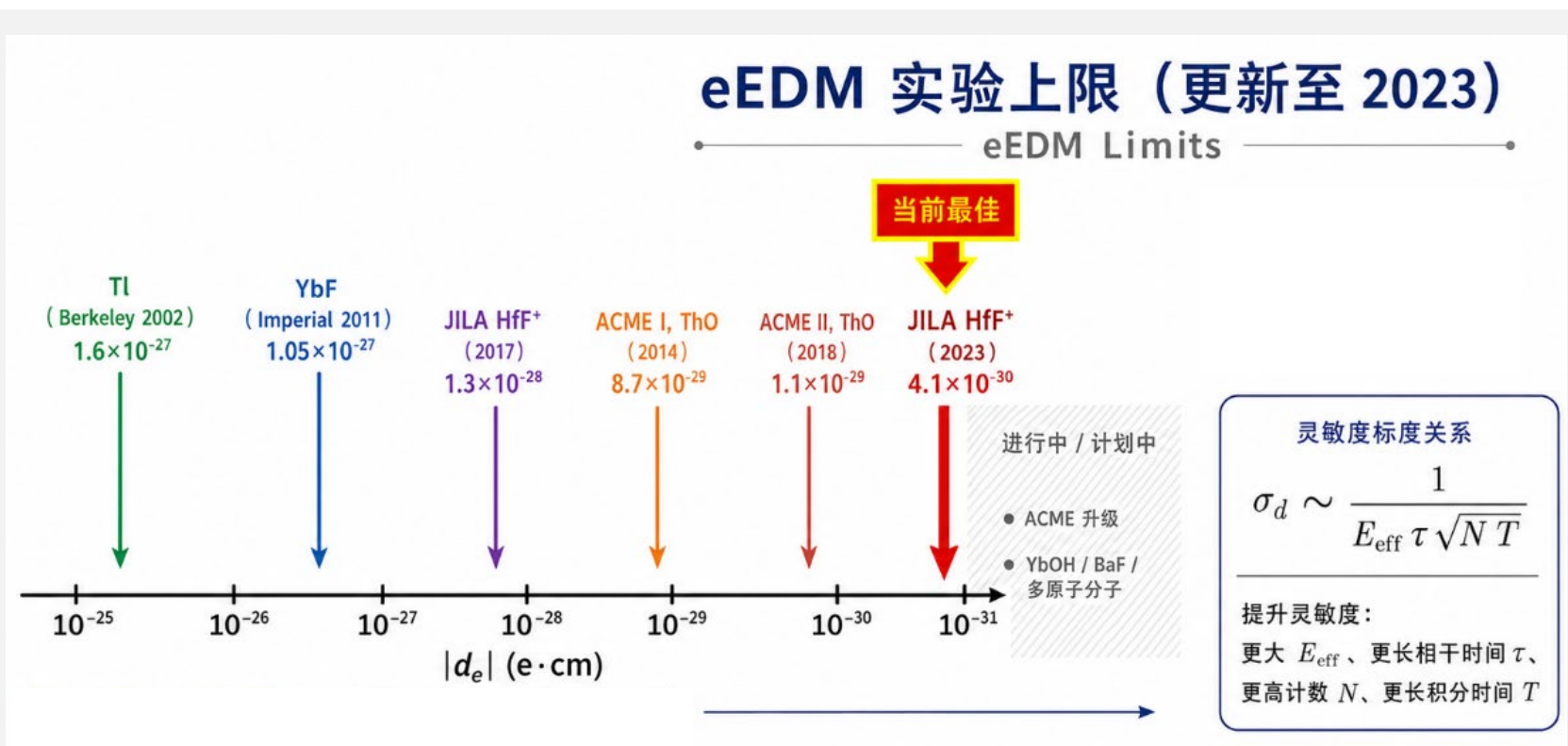
Nature Reviews Physics 1, 510(2019); *Rev. Mod. Phys.* 90, 025008(2018); *Rev. Mod. Phys.* 91, 015001(2019)

八极形变重核(例²²⁵Ra)的优势: 灵敏度~3个量级提升

2. 重核分子的优势 分子优势

$$H_{\text{MOL}} = H_{\text{EL}} + H_{\text{VIB}} + H_{\text{ROT}} + \dots + H_{\text{HFS}} + H_{\text{PV}} + H_{\text{PTV}} + D_e E_{\text{eff}}$$

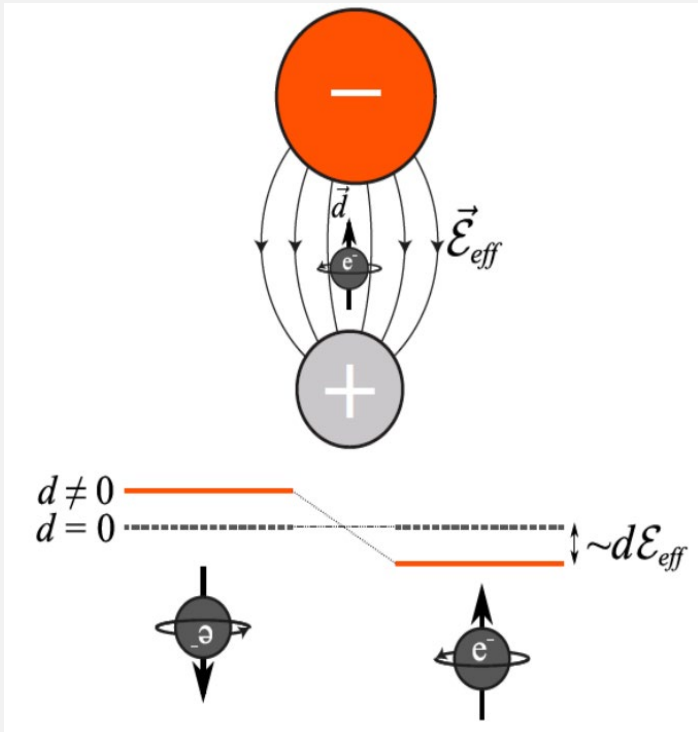
当前最严格上限: $d_e < 4.1 \times 10^{-30} e \cdot \text{cm}$ (90% C.L. JILA HfF⁺, *Science* 381, 46 (2023))



2. 重核分子的优势 分子优势

$$H_{\text{MOL}} = H_{\text{EL}} + H_{\text{VIB}} + H_{\text{ROT}} + \dots + H_{\text{HFS}} + H_{\text{PV}} + H_{\text{PTV}} + D_e E_{\text{eff}}$$

当前最严格上限: $d_e < 4.1 \times 10^{-30} \text{ e. cm}$ (90% C.L. JILA HfF⁺, *Science* 381, 46 (2023))



例: ThO (eEDM)

$E_{\text{eff}} \sim 80 \text{ GV/cm}$

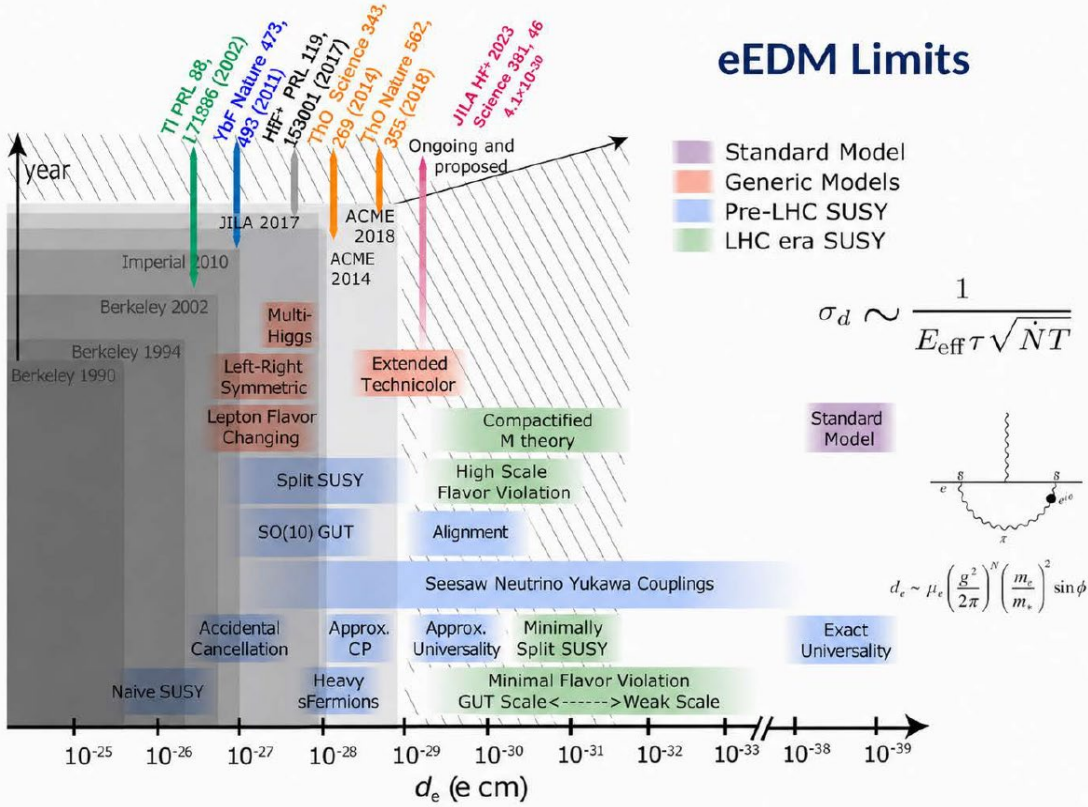
例: HfF (eEDM)

$E_{\text{eff}} \sim 20 \text{ GV/cm}$

$$H = (\mu \vec{J} \cdot \vec{B} + d \vec{J} \cdot \vec{E})/J$$

分子增强 $\times 10^4$

Nature 562, 355 (2018)
Science 381, 46 (2023)



科大卢征天老师团队最新¹⁷¹Yb测量: $E = 300 \text{ kV/cm}$

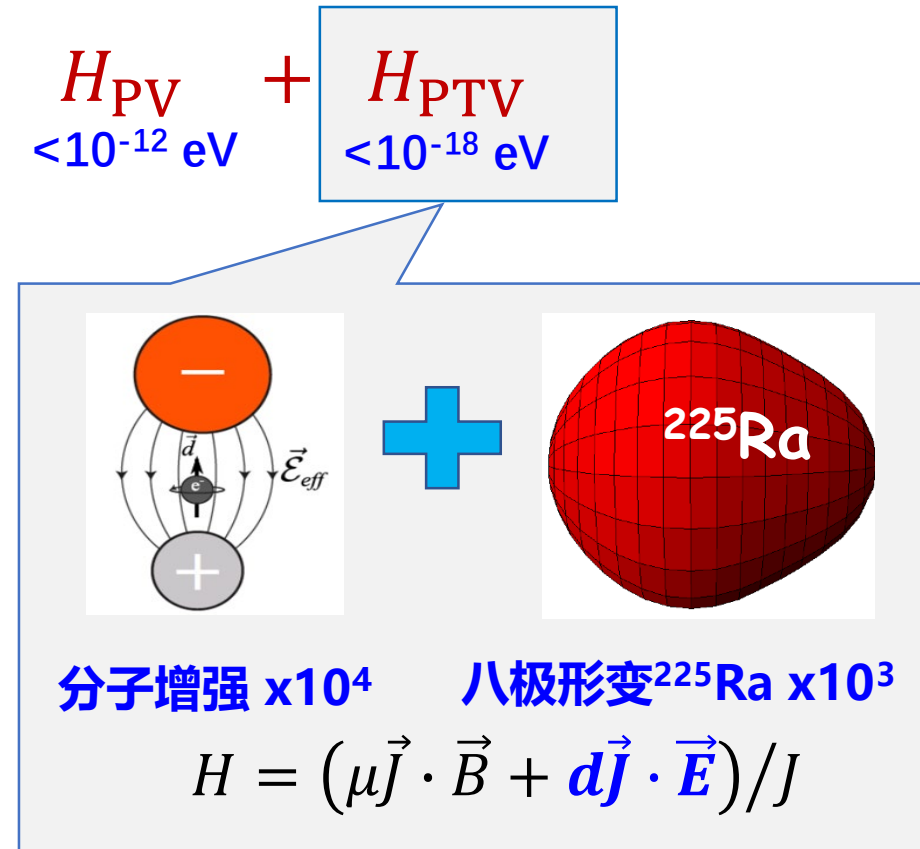
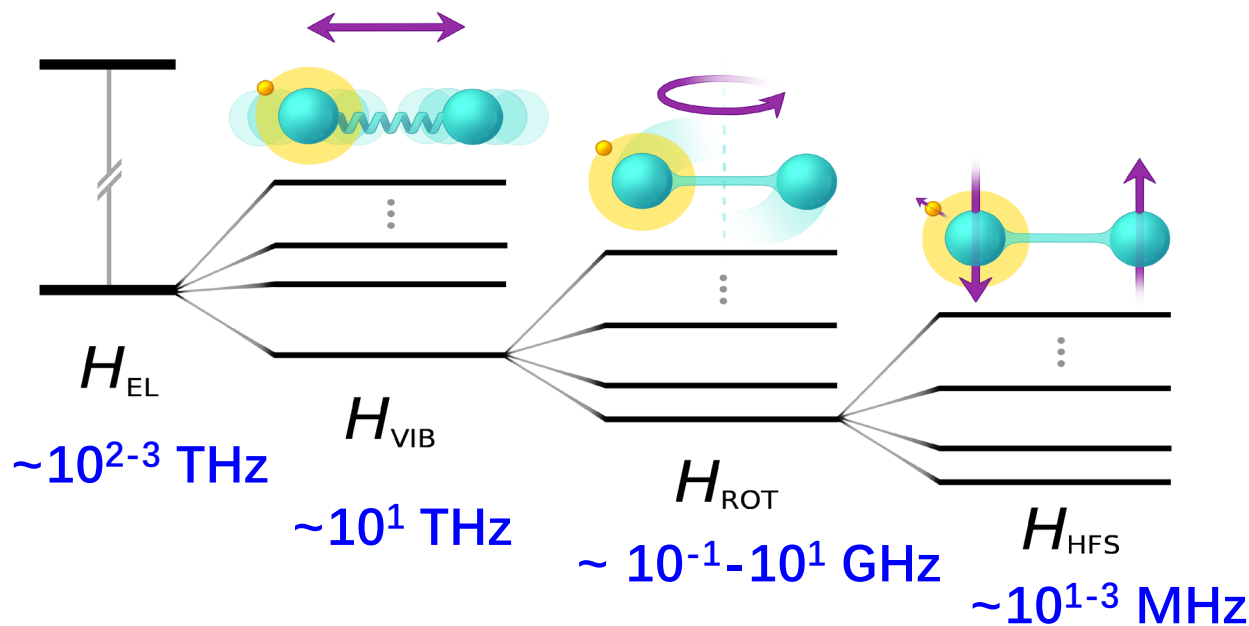
重核分子的优势: 灵敏度~4个量级提升

2. 重核分子的优势

八极形变重核+分子(放射性分子)优势

$$H_{\text{MOL}} = H_{\text{EL}} + H_{\text{VIB}} + H_{\text{ROT}} + \cdots + H_{\text{HFS}} + H_{\text{PV}} + H_{\text{PTV}}$$

$\sim 2 \text{ eV}$ $\sim 10^{-2} \text{ eV}$ $\sim 10^{-5} \text{ eV}$ $\sim 10^{-8} \text{ eV}$ $< 10^{-12} \text{ eV}$ $< 10^{-18} \text{ eV}$

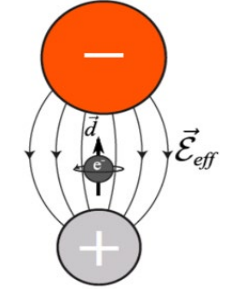


八极形变重核+分子优势：灵敏度~7个量级提升

2. 重核分子的优势

八极形变重核+分子(放射性分子)优势

$$\mathcal{H} = -\mu \cdot B - d \cdot E$$



极性分子内
强有效电场

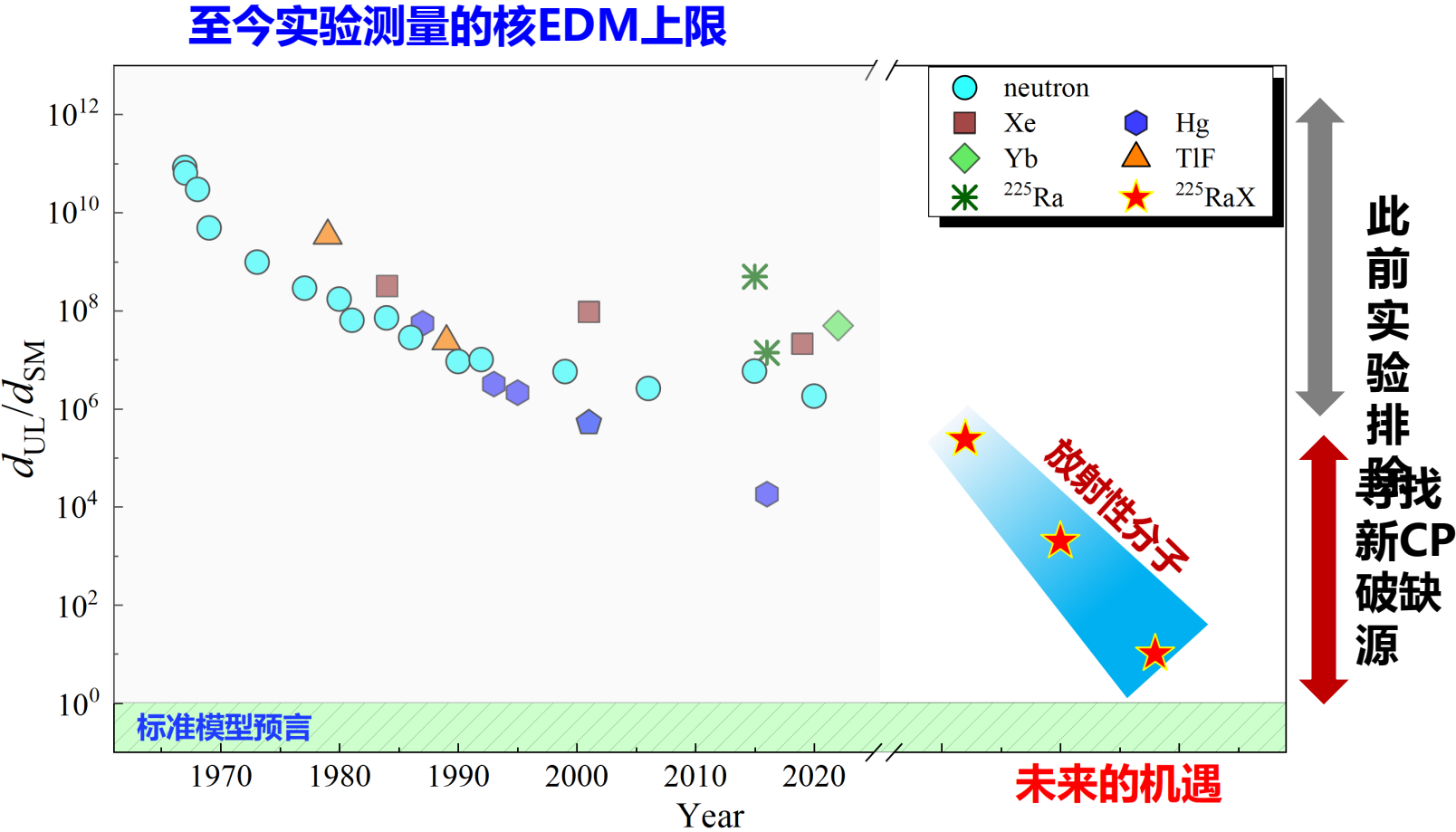
E 提升 10^4

+



八极形变重核
强EDM效应

d 提升 10^3



Nature Review Physics (2026); *Nature Physics* 20, 741-749 (2024); *Report on the Progress in Physics*, 87, 084301(2024)

2. 重核分子的优势

八极形变重核+分子(放射性分子)优势

表 1 原子核席夫矩测量实验的候选八极形变重核, 以及其原子序数、自旋、宇称、半衰期、八极形变参数和理论计算给出的原子核席夫矩预测值^{a)}

Table 1 Candidate octupole-deformed nuclei for nuclear Schiff moment measurement experiments, along with their atomic number, spin, parity, half-life, octupole deformation parameters, and predicted values of the nuclear Schiff moment

核素	<i>Z</i>	<i>I</i> ^π	$\tau_{1/2}$	β_3	$ S_{\text{intr}} (e \text{ fm}^3)$	$ S_{\text{lab}} (\bar{\theta} e \text{ fm}^3)$
²²¹ Fr	87	5/2 ⁻	4.801 min	0.13	11	0.20
²²³ Fr	87	3/2 ⁻	22.00 min	0.18	19	0.60
²²⁵ Ra	88	1/2 ⁺	14.82 d	0.18	23	1.2
²²⁵ Ac	89	3/2 ⁻	9.9190 d	0.18	22	2.7
²²⁷ Ac	89	3/2 ⁻	21.772 a	0.037	5.1	0.19
²²⁹ Th	90	5/2 ⁺	7916 a	0.115	-	2.0
²²⁹ Pa	91	5/2 ⁺	1.55 d	0.049	7.9	56
²³⁷ Np	93	5/2 ⁺	2.144 × 10 ⁶ a	0.0054	1.1	0.0034

a) 表中原子序数、自旋、宇称、半衰期等基本性质来自NUBASE2020数据库^[58], 原子核八极形变参数及席夫矩的理论计算值取自文献^[59,60]

表 2 部分候选放射性分子的电子态对原子核席夫矩探测的灵敏度^{a)}

Table 2 Sensitivity of some candidate radioactive molecules for detecting the nuclear Schiff moment

分子	分子点群	电子态	电子总自旋	$ W_S (e/4\pi\epsilon_0 a_0^4)$
RaF	<i>C</i> _{∞v}	X ² Σ _{1/2}	1/2	25560
RaO	<i>C</i> _{∞v}	X ¹ Σ ₀	0	45192
RaOH ⁺	<i>C</i> _{∞v}	X ¹ Σ ₀	0	~30000
RaOCH ₃ ⁺	<i>C</i> _{3v}	X ¹ Σ ₀	0	56300
AcF	<i>C</i> _{∞v}	X ¹ Σ ₀	0	8400
ThF ⁺	<i>C</i> _{∞v}	X ³ Δ ₁	1	45600
ThO	<i>C</i> _{∞v}	X ¹ Σ ₀	0	17085
ThOH ⁺	<i>C</i> _{∞v}	X ¹ Σ ₀	0	~30000

a) 表中理论计算值取自文献^[60,65~69,71]

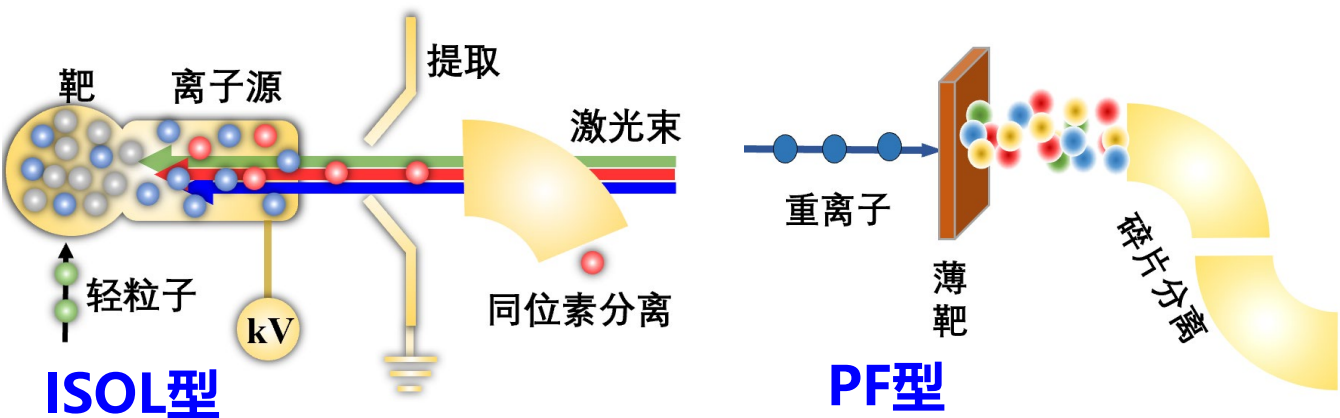
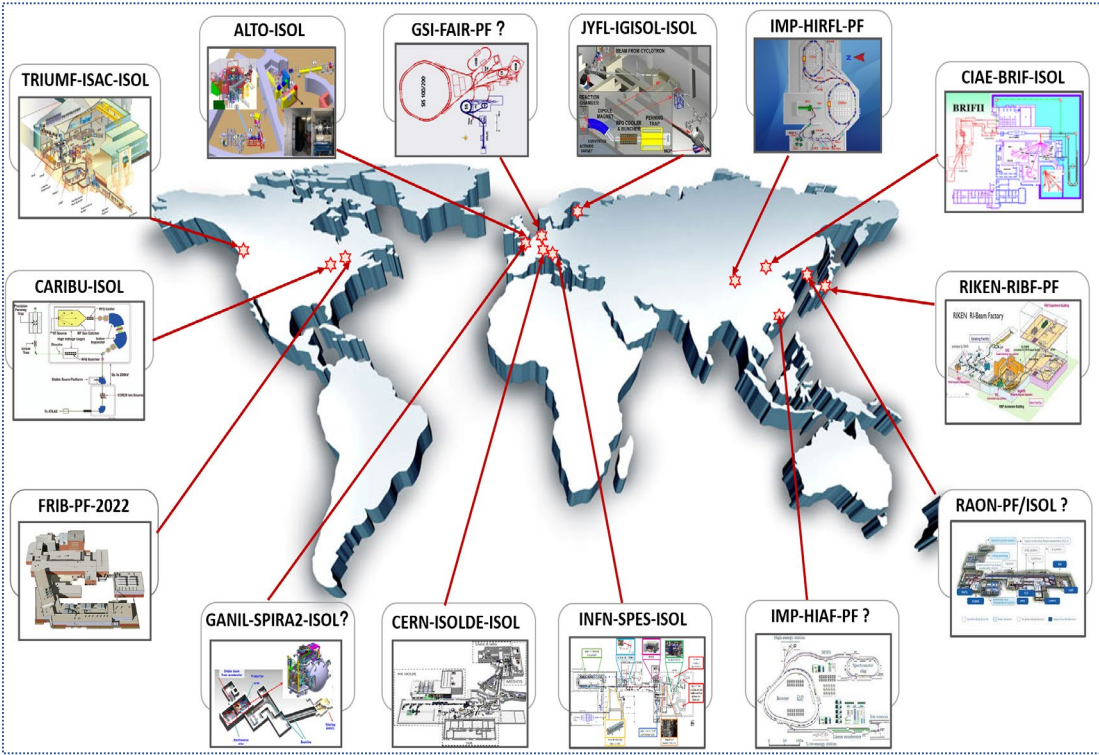
报告内容

1. P,T 破缺 (研究背景)
2. 重核(放射性)分子的优势
3. 国际放射性分子研究现状
4. 国内放射性分子研究近期发展
5. 总结及展望

3. 国际放射性分子研究现状 放射性分子研究的挑战 (放射性分子制备?)

226Pa 1.8 min $\alpha=74\%$ $\varepsilon+\beta+=26\%$	227Pa 38.3 min $\alpha=85\%$ $\varepsilon=15\%$	228Pa 19.8 h $\varepsilon+\beta+=98.15\%$ $\alpha=1.85\%$	229Pa 1.55 d $\varepsilon=99.49\%$ $\alpha=0.51\%$	230Pa 17.4 d $\varepsilon+\beta+=92.2\%$ $\beta^-=7.8\%$ $\alpha=3.5e-3\%$	231Pa 3.27e+4 y 100% $\alpha=100\%$ 24Ne=1.34e-9%
225Th 8.72 min $\alpha=90\%$ $\varepsilon=10\%$	226Th 30.69 min $\alpha=100\%$	227Th 18.69 d $\alpha=100\%$	228Th 1.91 y $\alpha=100\%$ 200=1.13e-11%	229Th 7907.5 y $\alpha=100\%$	230Th 7.54e+4 y 0.02% $\alpha=100\%$ 24Ne=5.8e-11%
224Ac 2.78 h $\varepsilon+\beta+=90.9\%$ $\alpha=9.1\%$	225Ac 9.919 d $\alpha=100\%$ 14C=5.3e-10%	226Ac 29.37 h $\beta^-=83\%$ $\varepsilon=17\%$ $\alpha=0.006\%$	227Ac 21.77 y $\beta^-=98.62\%$ $\alpha=1.38\%$	228Ac 6.15 h $\beta^-=100\%$	229Ac 62.7 min $\beta^-=100\%$
223Ra 11.44 d $\alpha=100\%$ 14C=8.9e-8%	224Ra 3.63 d $\alpha=100\%$ 14C=4e-9%	225Ra 14.8 d $\beta^-=100\%$	226Ra 1600 y $\alpha=100\%$ 14C=2.6e-9%	227Ra 42.2 min $\beta^-=100\%$	228Ra 5.75 y $\beta^-=100\%$
222Fr 14.2 min $\beta^-=100\%$	223Fr 21.99 min $\beta^-=99.994\%$ $\alpha=0.006\%$	224Fr 3.33 min $\beta^-=100\%$	225Fr 4 min $\beta^-=100\%$	226Fr 49 s $\beta^-=100\%$	227Fr 2.47 min $\beta^-=100\%$

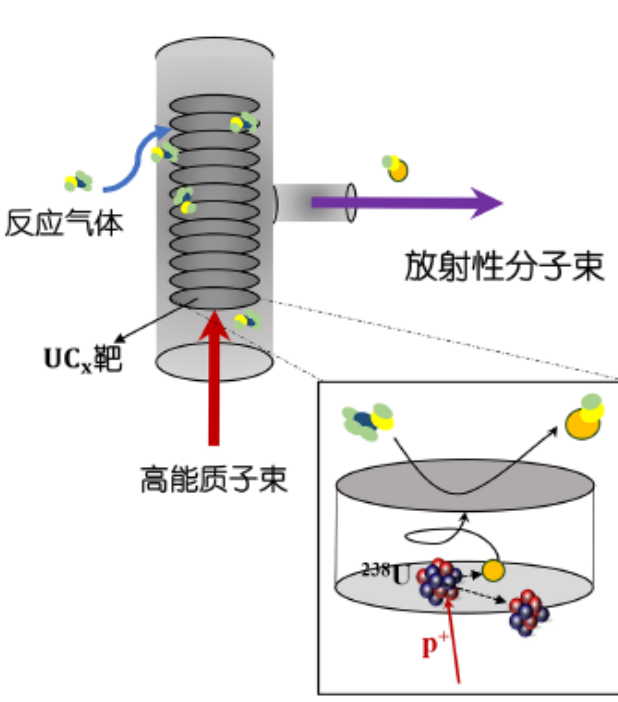
223Fr: 22.99 min; 227Th: 18.69 d
需要依赖加速器等产生



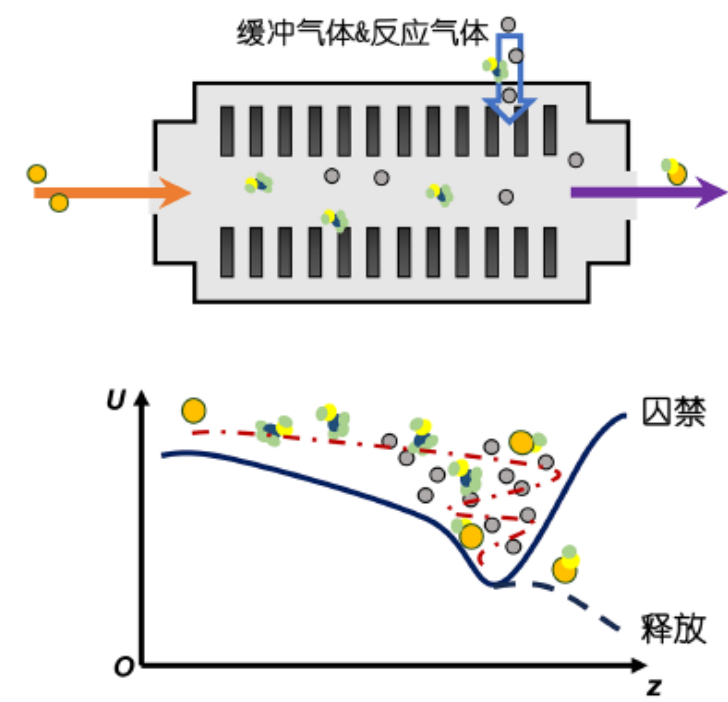
3. 国际放射性分子研究现状 放射性分子研究的挑战 (放射性分子制备?)

226Pa 1.8 min $\alpha=74\%$ $\varepsilon+\beta+=26\%$	227Pa 38.3 min $\alpha=85\%$ $\varepsilon=15\%$	228Pa 19.8 h $\varepsilon+\beta+=98.15\%$ $\alpha=1.85\%$	229Pa 1.55 d $\varepsilon=99.49\%$ $\alpha=0.51\%$	230Pa 17.4 d $\varepsilon+\beta+=92.2\%$ $\beta^-=7.8\%$ $\alpha=3.5e-3\%$	231Pa 3.27e+4 y 100% $\alpha=100\%$ 24Ne=1.34e-9%
225Th 8.72 min $\alpha=90\%$ $\varepsilon=10\%$	226Th 30.69 min $\alpha=100\%$	227Th 18.69 d $\alpha=100\%$	228Th 1.91 y $\alpha=100\%$ 20O=1.13e-11%	229Th 7907.5 y $\alpha=100\%$	230Th 7.54e+4 y 0.02% $\alpha=100\%$ 24Ne=5.8e-11%
224Ac 2.78 h $\varepsilon+\beta+=90.9\%$ $\alpha=9.1\%$	225Ac 9.919 d $\alpha=100\%$ 14C=5.3e-10%	226Ac 29.37 h $\beta^-=83\%$ $\varepsilon=17\%$ $\alpha=0.006\%$	227Ac 21.77 y $\beta^-=98.62\%$ $\alpha=1.38\%$	228Ac 6.15 h $\beta^-=100\%$	229Ac 62.7 min $\beta^-=100\%$
223Ra 11.44 d $\alpha=100\%$ 14C=8.9e-8%	224Ra 3.63 d $\alpha=100\%$ 14C=4e-9%	225Ra 14.8 d $\beta^-=100\%$	226Ra 1600 y $\alpha=100\%$ 14C=2.6e-9%	227Ra 42.2 min $\beta^-=100\%$	228Ra 5.75 y $\beta^-=100\%$
222Fr 14.2 min $\beta^-=100\%$	223Fr 21.99 min $\beta^-=99.994\%$ $\alpha=0.006\%$	224Fr 3.33 min $\beta^-=100\%$	225Fr 4 min $\beta^-=100\%$	226Fr 49 s $\beta^-=100\%$	227Fr 2.47 min $\beta^-=100\%$

(a)在ISOL靶源内产生



(b) 在离子阱内产生



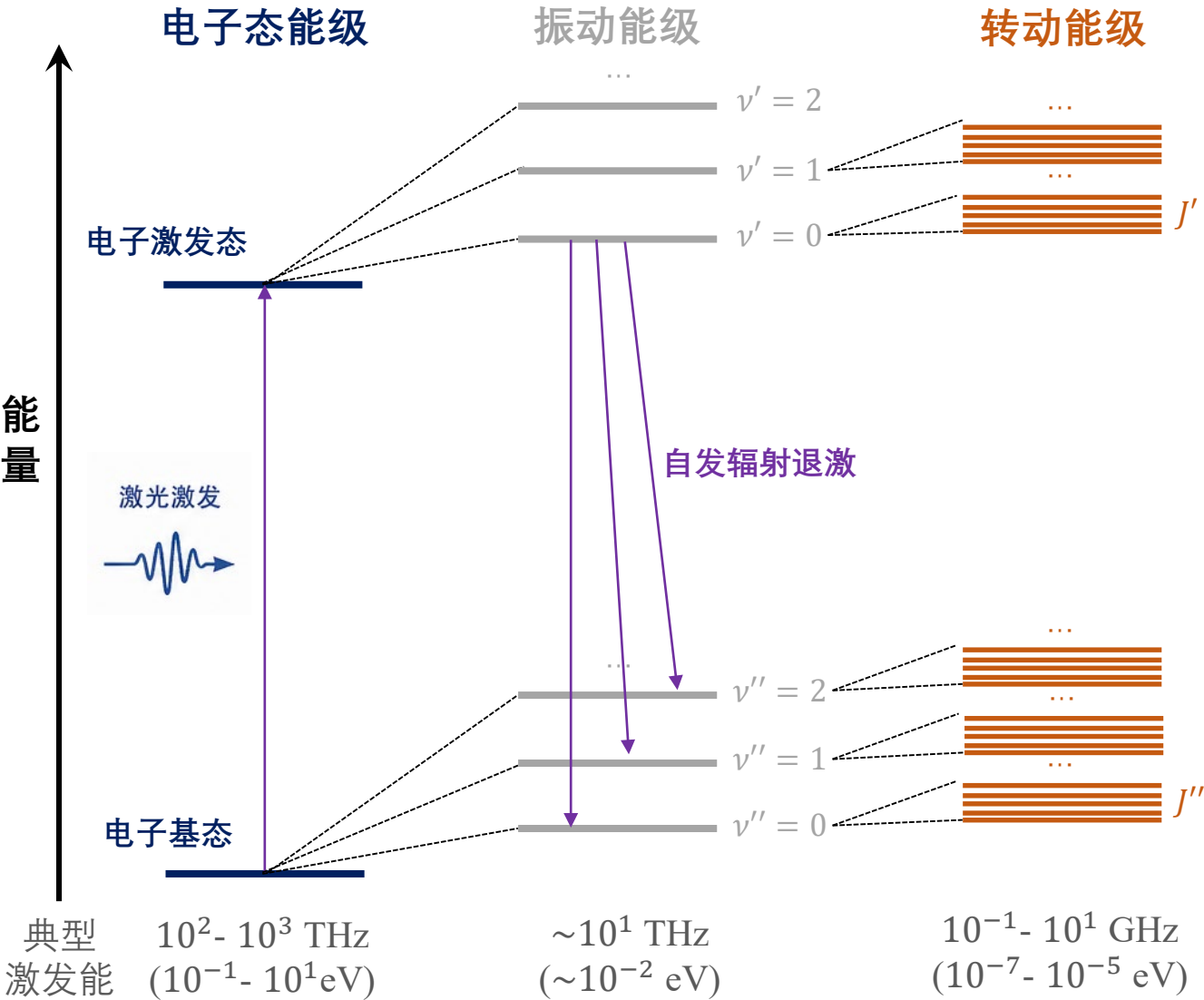
223Fr: 22.99 min; 227Th: 18.69 d
需要依赖加速器等产生

梅文聪, 杨晓菲, 叶沿林 科学通报, 71, 979–992 (2026).

3. 国际放射性分子研究现状 放射性分子研究的挑战 (放射性分子光谱测量?)

分子丰富的内态自由度带来了复杂的能级结构

精密操纵和测量的难度显著提高



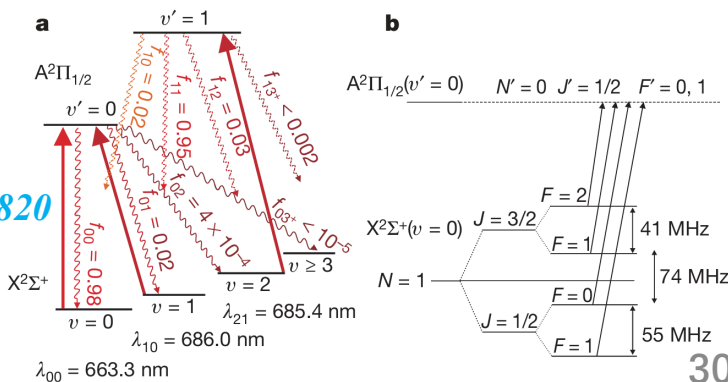
在复杂的分子体系中开展EDM实验

- 如何实现分子的冷却/囚禁?
- 如何实现分子初态的高效制备?
- 如何实现分子末态的高保真度读取?
- ...

实验设计高度依赖分子光谱信息

- 电子态、振转能级及超精细结构
- 跃迁强度及分支比
- 激发态能级寿命
- ...

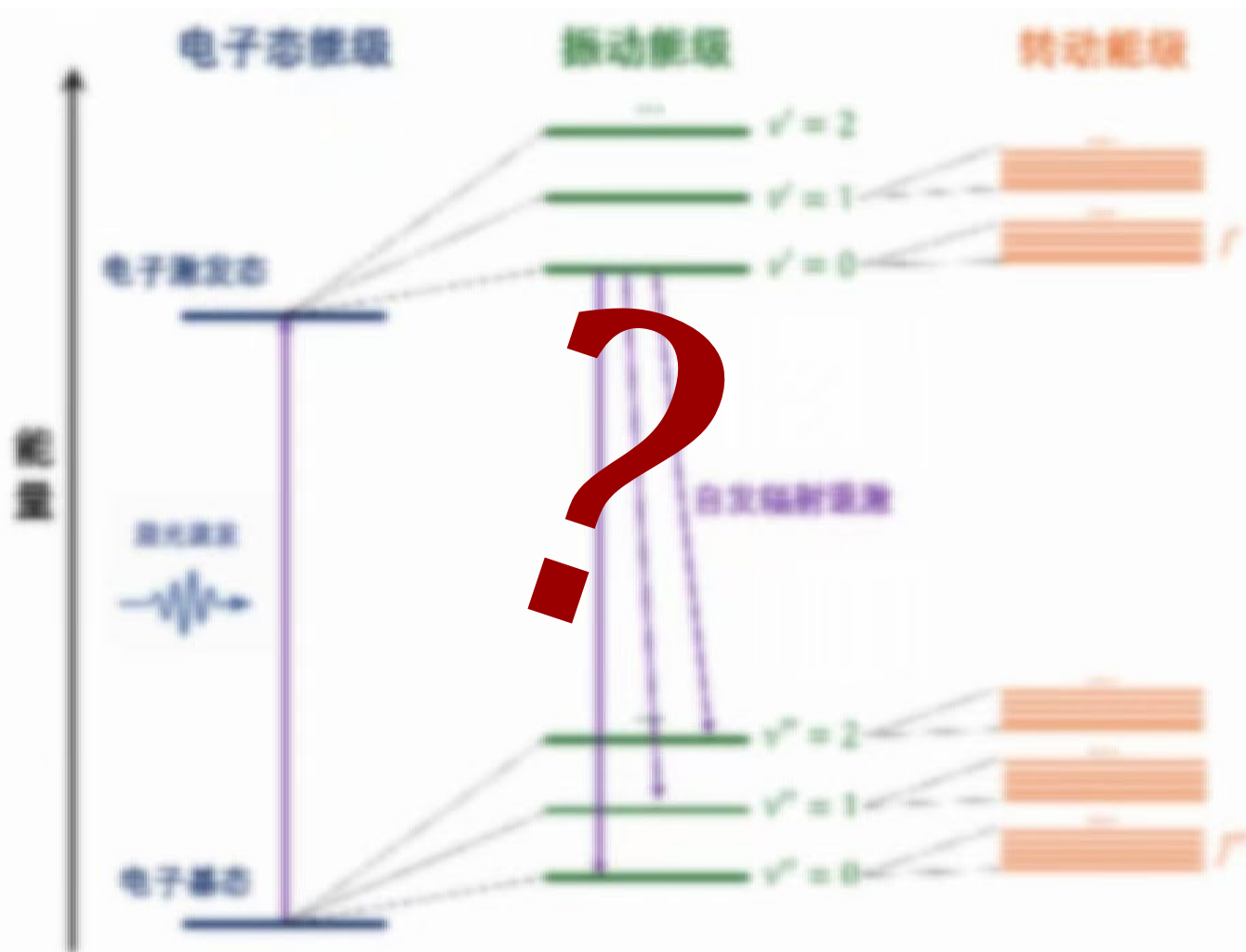
e.g. SrF分子
激光冷却
Nature 467(2010)820



3. 国际放射性分子研究现状 放射性分子研究的挑战 (放射性分子光谱测量?)

分子丰富的内态自由度带来了复杂的能级结构

精密操纵和测量的难度显著提高



在复杂的分子体系中开展EDM实验

- 如何实现分子的冷却/囚禁?
- 如何实现分子初态的高效制备?
- 如何实现分子末态的高保真度读取?
- ...

实验设计高度依赖分子光谱信息

- 电子态、振转能级及超精细结构
- 跃迁强度及分支比
- 激发态能级寿命
- ...

**对核EDM灵敏的放射性
分子光谱数据此前完全空白!!**

3. 国际放射性分子研究现状

CRIS国际合作组

<https://isolde-cris.web.cern.ch/collaboration.html>



- 英国曼彻斯特大学
- 比利时鲁汶大学
- 中国北京大学
- 美国麻省理工学院



MANCHESTER
1824

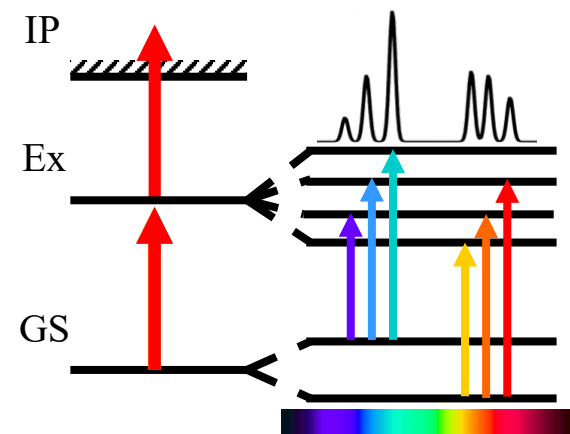
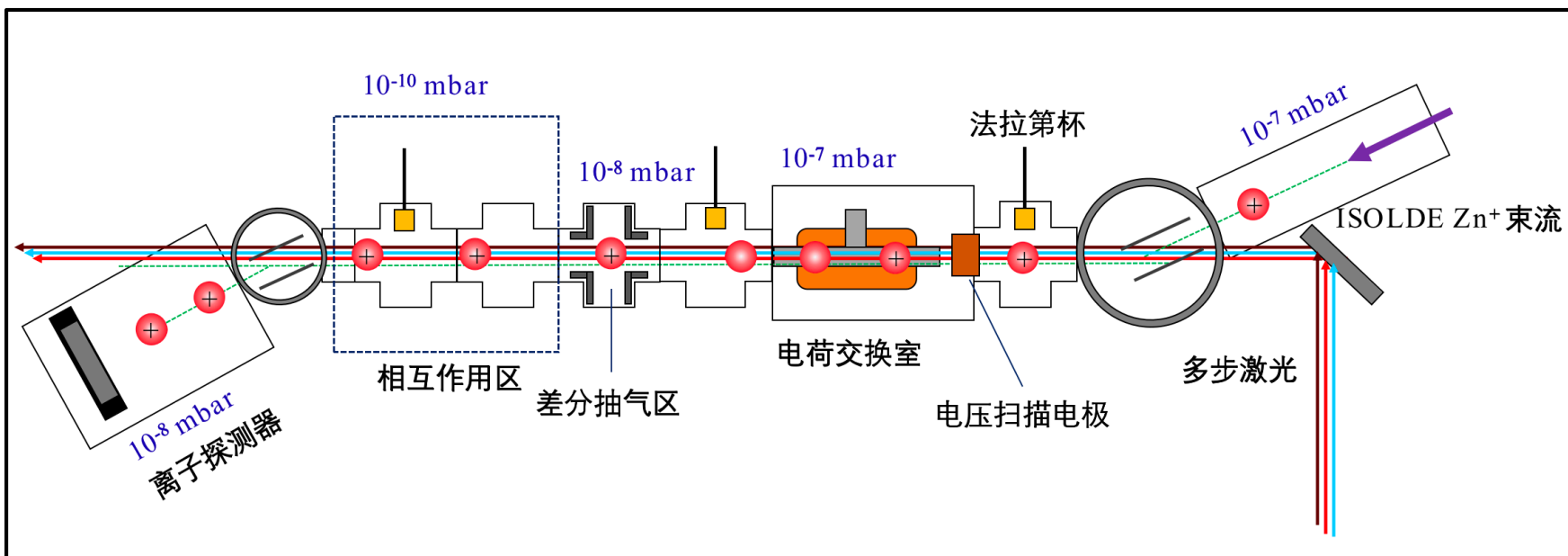
KU LEUVEN



北京大学
PEKING UNIVERSITY



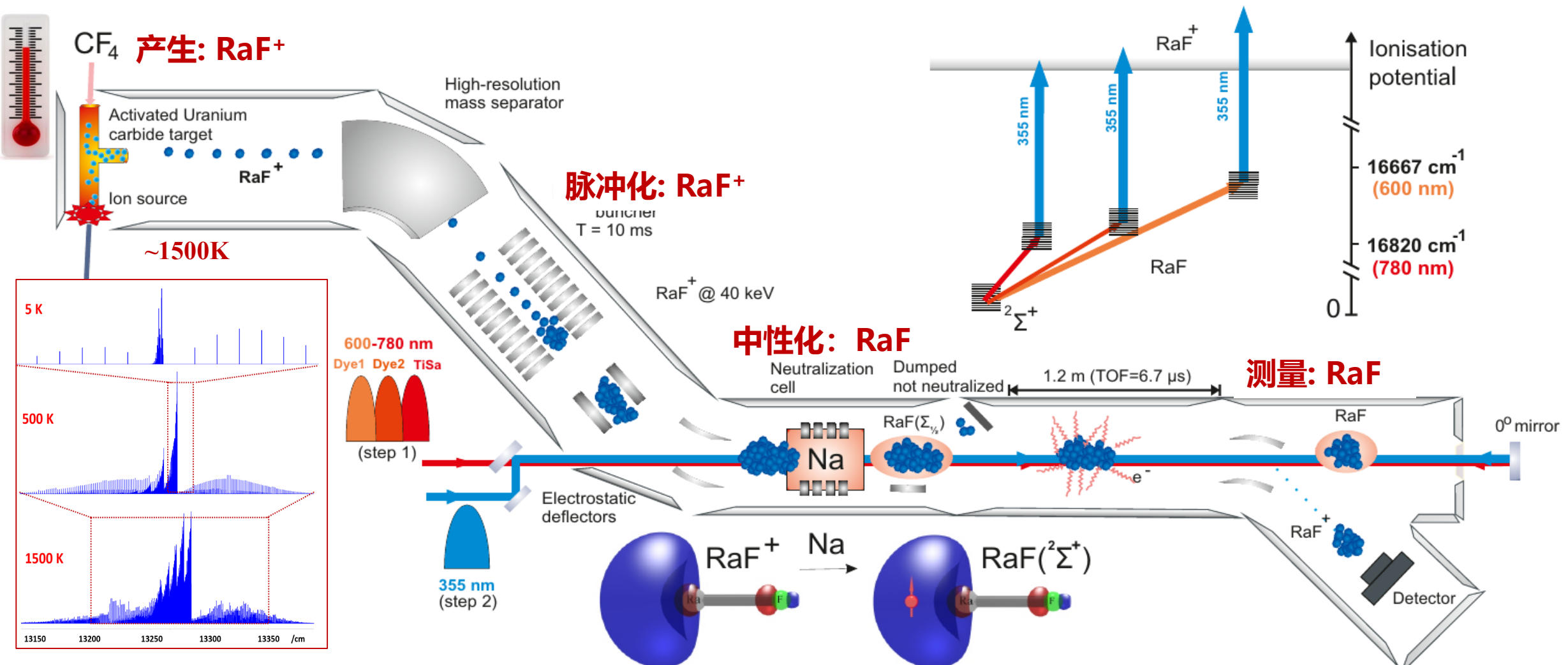
Massachusetts
Institute of
Technology



2018年我们合作组，国际首个针对放射性分子RaF的光谱实验测量成功，引起国际上的广泛关注

3. 国际放射性分子研究现状

CRIS collaboration @ ISOLDE-CERN <https://isolde-cris.web.cern.ch/>



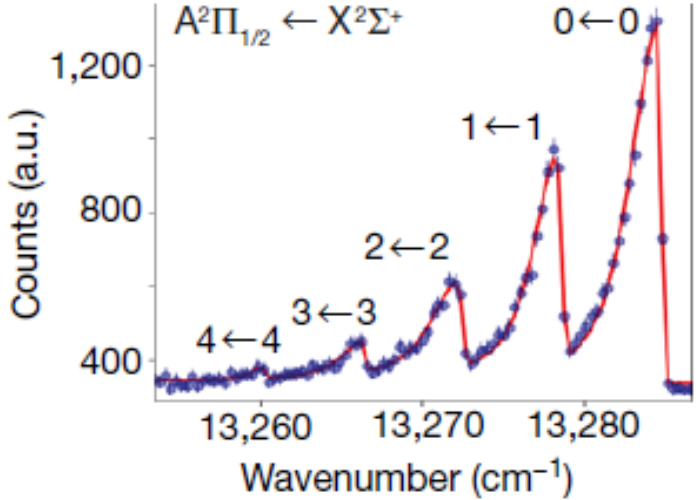
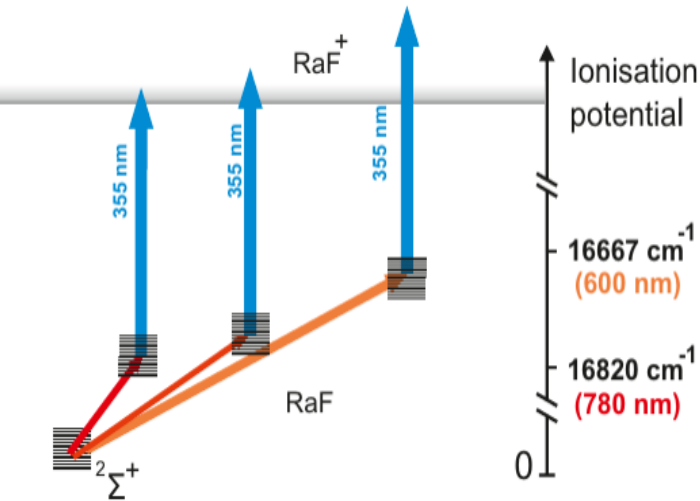
3. 国际放射性分子研究现状 RaF 放射性分子



$$H_{\text{MOL}} = \boxed{H_{\text{EL}}} + H_{\text{VIB}} + H_{\text{ROT}} + H_{\text{HFS}} + \dots + H_{\text{PV}} + H_{\text{PTV}}$$

$\sim 2 \text{ eV}$ $\sim 10^{-2} \text{ eV}$ $\sim 10^{-5} \text{ eV}$ $\sim 10^{-8} \text{ eV}$ $< 10^{-12} \text{ eV}$ $< 10^{-18} \text{ eV}$

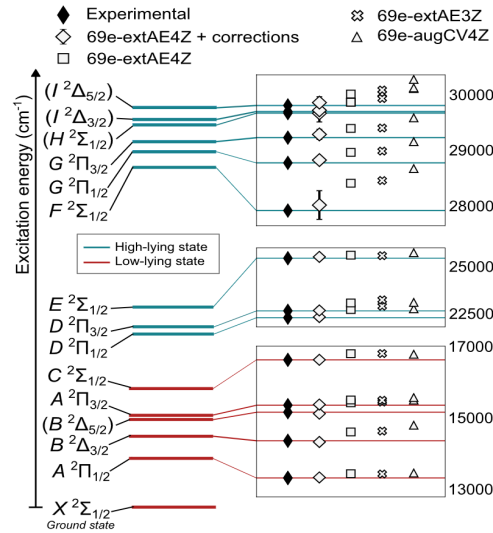
✓
Nature 581, 396 (2020)
Nat. Comm. 16, 2139 (2025)



Spectroscopy of short-lived radioactive molecules

R. F. Garcia Ruiz , R. Berger , J. Billowes, C. L. Binnersley, M. L. Bissell, A. A. Breier, A. J. Brinson, K. Chrysalidis, T. E. Cocolios, B. S. Cooper, K. T. Flanagan, T. F. Giesen, R. P. de Groote, S. Franchoo, F. P. Gustafsson, T. A. Isaev, Á. Koszorus, G. Neyens, H. A. Perrett, C. M. Ricketts, S. Rothe, L. Schweikhard, A. R. Vernon, K. D. A. Wendt, ... X. F. Yang + Show authors

Nature 581, 396–400 (2020) | Cite this article



Electron correlation and relativistic effects in the excited states of radium monofluoride

M. Athanasakis-Kaklamanakis , S. G. Wilkins , L. V. Skripnikov, Á. Koszorus, A. A. Breier, O. Ahmad, M. Au, S. W. Bai, I. Belošević, J. Beralk, R. Berger, C. Bernerd, M. L. Bissell, A. Borschevsky, A. Brinson, K. Chrysalidis, T. E. Cocolios, R. P. de Groote, A. Dorne, C. M. Fajardo-Zambrano, R. W. Field, K. T. Flanagan, S. Franchoo, R. F. Garcia Ruiz, ... C. Zülch + Show authors

Nature Communications 16, Article number: 2139 (2025) | Cite this article

3. 国际放射性分子研究现状 RaF 放射性分子



$$H_{\text{MOL}} = H_{\text{EL}} + H_{\text{VIB}} + H_{\text{ROT}} + H_{\text{HFS}} + \dots + H_{\text{PV}} + H_{\text{PTV}}$$

$\sim 2 \text{ eV}$ $\sim 10^{-2} \text{ eV}$ $\sim 10^{-5} \text{ eV}$ $\sim 10^{-8} \text{ eV}$ $< 10^{-12} \text{ eV}$ $< 10^{-18} \text{ eV}$



PRL 127, 033001 (2021)

PHYSICAL REVIEW LETTERS

Highlights Recent Accepted Collections Authors Referees Search Press About Staff

Featured in Physics

Editors' Suggestion

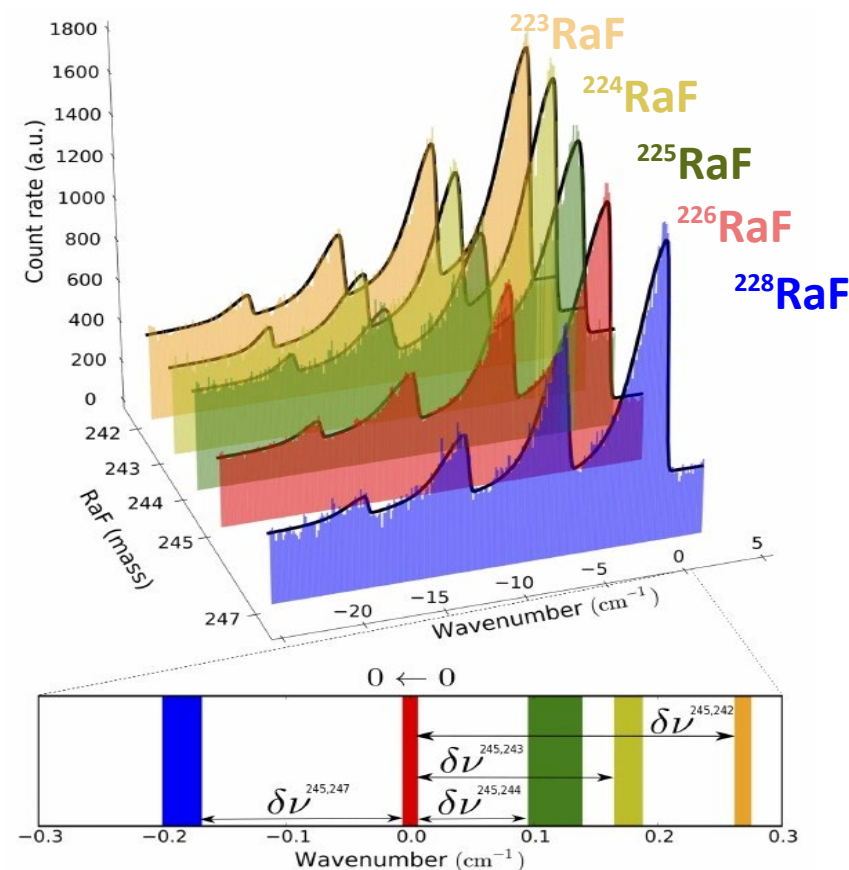
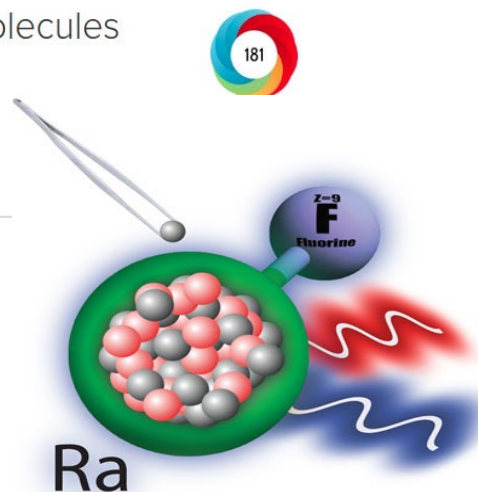
Open Access

Isotope Shifts of Radium Monofluoride Molecules

S. M. Udrescu *et al.*

Phys. Rev. Lett. **127**, 033001 – Published 14 July 2021

Physics See Viewpoint: Sizing up Exotic Nuclei with Radioactive Molecules



3. 国际放射性分子研究现状 RaF 放射性分子



$$H_{\text{MOL}} = H_{\text{EL}} + H_{\text{VIB}} + H_{\text{ROT}} + H_{\text{HFS}} + \dots + H_{\text{PV}} + H_{\text{PTV}}$$

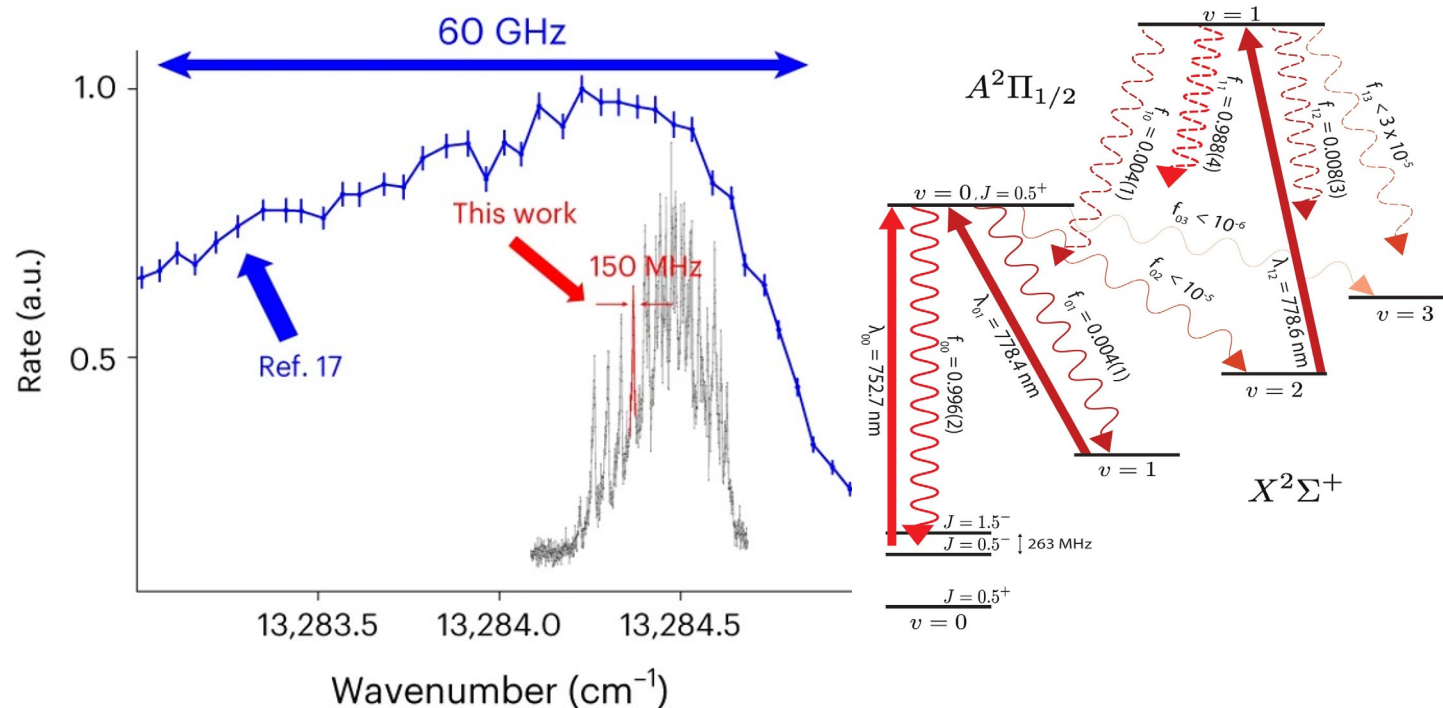
$\sim 2 \text{ eV}$ $\sim 10^{-2} \text{ eV}$ $\sim 10^{-5} \text{ eV}$ $\sim 10^{-8} \text{ eV}$ $< 10^{-12} \text{ eV}$ $< 10^{-18} \text{ eV}$

Nature Phys 20, 202 (2024)

Precision spectroscopy and laser-cooling scheme of a radium-containing molecule

[S. M. Udrescu](#), [S. G. Wilkins](#), [A. A. Breier](#), [M. Athanasakis-Kaklamanakis](#), [R. F. Garcia Ruiz](#), [M. Au](#),
[Belošević](#), [R. Berger](#), [M. L. Bissell](#), [C. L. Binnersley](#), [A. J. Brinson](#), [K. Chrysalidis](#), [T. E. Cocolios](#), [R. P. de Groen](#),
[A. Dorne](#), [K. T. Flanagan](#), [S. Franchoo](#), [K. Gaul](#), [S. Geldhof](#), [T. F. Giesen](#), [D. Hanstorp](#), [R. Heinke](#), [Á. Koszoru](#),
[S. Kujanpää](#), ... [C. Zülch](#) [+ Show authors](#)

[Nature Physics](#) **20**, 202–207 (2024) | [Cite this article](#)



3. 国际放射性分子研究现状 RaF 放射性分子

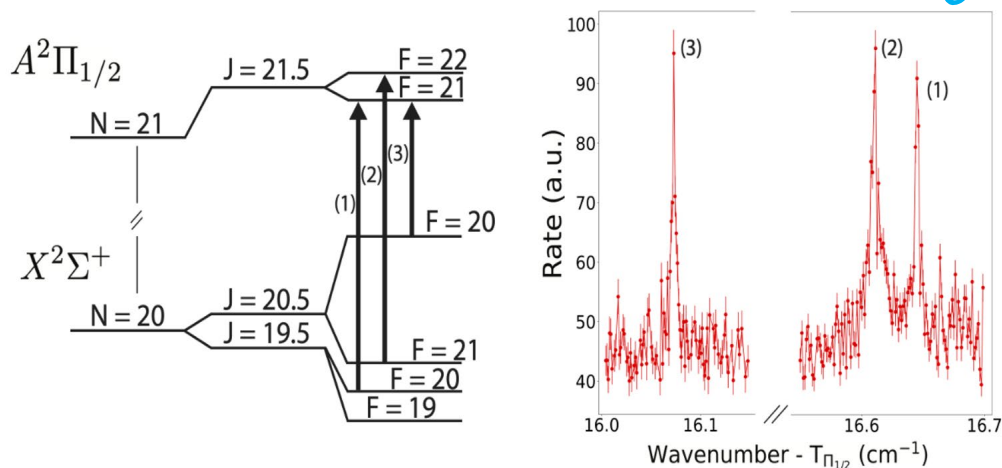


$$H_{\text{MOL}} = H_{\text{EL}} + H_{\text{VIB}} + H_{\text{ROT}} + \boxed{H_{\text{HFS}}} + \dots + H_{\text{PV}} + H_{\text{PTV}}$$

$\sim 2 \text{ eV}$ $\sim 10^{-2} \text{ eV}$ $\sim 10^{-5} \text{ eV}$ $\sim 10^{-8} \text{ eV}$ $< 10^{-12} \text{ eV}$ $< 10^{-18} \text{ eV}$

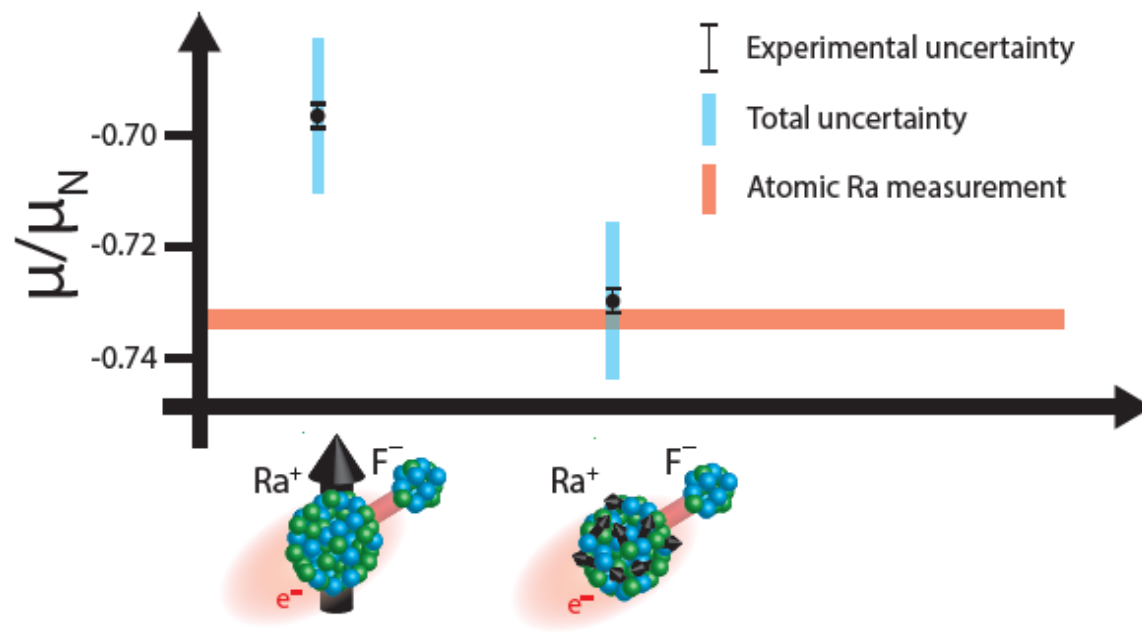
Science 390, 386 (2025)

^{225}RaF 超精细结构谱



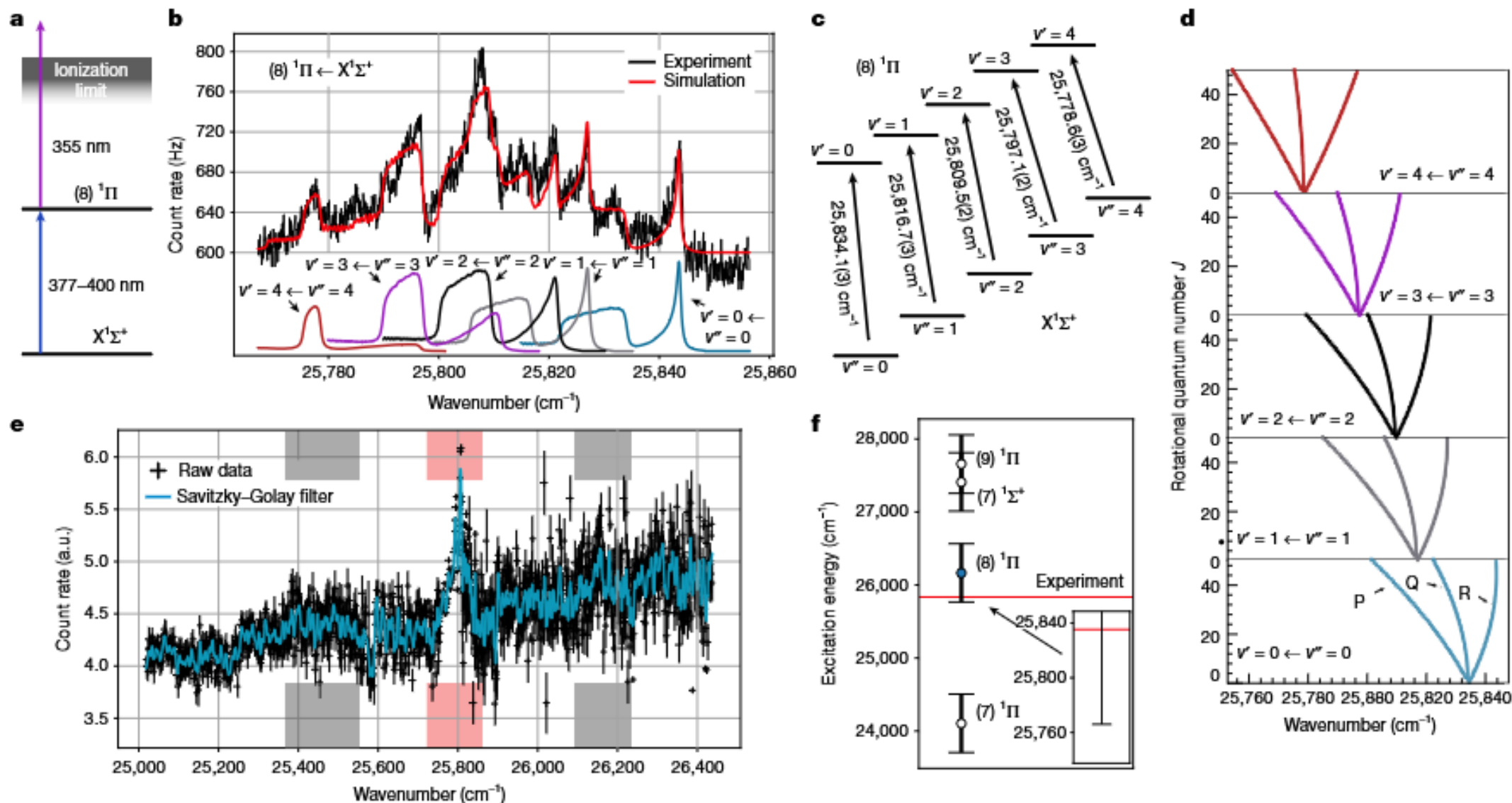
Observation of the distribution of nuclear magnetization in a molecule

S. G. Wilkins^{1,*}, S. M. Udrescu^{1,*}, M. Athanasakis-Kaklamanakis^{2,3}, R. F. Garcia Ruiz^{1,8}, M. Au^{4,5}, I. Belošević⁶, R. Berger⁷, M. L. Bissell⁸, A. A. Breier⁹, A. J. Brinson¹, K. Chrysalidis⁴, T. E. Cocolios³, R. P. de Groot³, A. Dorne³, K. T. Flanagan^{8,10}, S. Franchoo¹¹, K. Gaul⁷, S. Geldhof³, T. F. Giesen⁹, D. Hanstorp¹², R. Heinke⁴, T. Isaev¹³, Á. Koszorus², S. Kujanpää¹⁴, L. Lalanne³, G. Neyens³, M. Nichols¹², H. A. Perrett⁸, J. R. Reilly⁸, L. V. Skripnikov¹⁵, S. Rothe⁴, B. van den Borne³, Q. Wang¹⁵, J. Wessolek⁸, X. F. Yang¹⁶, C. Zülch⁷



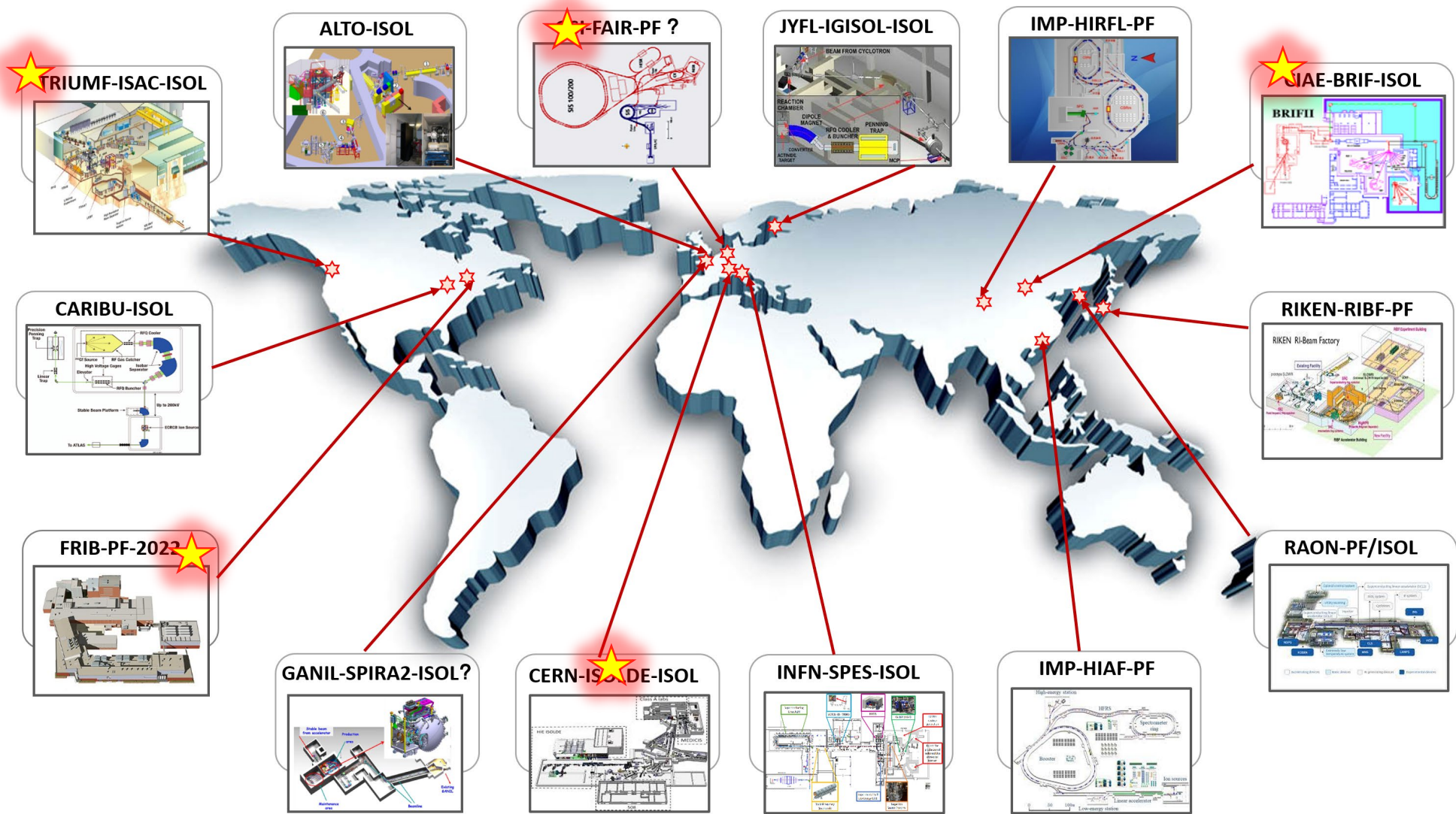
3. 国际放射性分子研究现状 AcF 放射性分子

Nature 648, 562-568 (2025)



3. 国际放射性分子研究现状

已有有成果挂出或项目支持的实验室



3. 国际放射性分子研究现状

已有放射性分子计划和综述



6.4.2. Atomic and Molecular EDMs

Experiments using methods of atomic, molecular, and optical (AMO) physics are making a major contribution to the search for BSM charge–parity symmetry violation. They are poised to expand both in breadth and depth by studying nuclei in atoms and molecules. The nuclei in suitable candidate systems are sensitive to underlying charge–parity symmetry violating interactions, but their **Schiff moments** and **magnetic quadrupole moments** vary across different nuclei and probe new charge–parity symmetry violating sources in a manner complementary to those probed by the neutron (and proton) EDMs.

DOE, LRP (2023)

A NEW ERA OF DISCOVERY THE 2023 LONG RANGE PLAN FOR NUCLEAR SCIENCE

several orders of magnitude in the near future.

Heavy nuclei with mass numbers larger than about 220 can be nonspherical, and, in certain cases, a reflection-asymmetric, permanent octupole deformation can exist—and those radioactive isotopes can have greatly enhanced nuclear moments. In particular, the Schiff moment in systems such as radium-225 or protactinium-229 provides a striking enhancement of time-reversal symmetry violating effects by a factor of 100–1,000 (radium-225) or more (protactinium-229) over mercury-199.

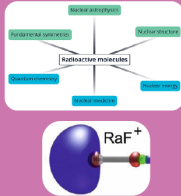
NuPECC, LRP (2024)



Radioactive molecules

Box 6.1: Radioactive molecules: powerful tool and unique laboratory

The production and study of radioactive molecules is fast acquiring momentum at radioactive ion beam facilities across Europe and beyond. The motivation for studying the structure and dynamics of molecules containing short-lived radioactive nuclei is multi-faceted and covers areas of both fundamental and applied science in regions of the nuclear chart where molecular studies have so far been too challenging. For heavy species, gas-phase spectroscopy provides powerful benchmarks of the predictions of ab initio quantum chemistry in regions where relativistic effects are crucial, the chemistry of *s*-electrons is not fully understood, and experimental data is scarce. Meanwhile, producing isotopically pure compounds of the early actinides is important for understanding the isolated molecular dynamics of relevance to nuclear engineering and radioactive waste management. Simultaneously, the optimisation of the ISOL production of molecular beams that are purer and more intense than the constituent atomic beams is also of direct importance for the future of ISOL as a production plant for medical radioisotopes. Finally, some of those radioactive molecules may prove ideal laboratories for searches of physics beyond the Standard Model.



RECENTLY IN THE GLOBAL SPECTROSCOPY CHALLENGE, USED TO THE PRESENCE OF A STRONGER ELECTROMAGNETIC FIELD GRADIENTS WITHIN CERTAIN MOLECULES COMPARED TO THEIR CONSTITUENT ATOMIC SYSTEMS, THE EXTRACTION OF ELECTRIC QUADRUPOLE OR MAGNETIC OCTUPOLE MOMENTS OF ISOTOPES NOT ACCESSIBLE VIA ATOMIC SPECTROSCOPY OR OTHER METHODS COULD BECOME POSSIBLE, OR THE PRECISION OF EXISTING DATA COULD BE SIGNIFICANTLY IMPROVED.

To explore the limits of the Standard Model and its extension theories, precision searches for the CP-violating electric dipole moment of the electron (eEDM) and nuclear Schiff moments are a promising approach, because the magnitude of the moments scales with the level of T breaking in the fundamental forces. Heavy polar molecules are a highly sensitive laboratory for these searches, thanks to the strong electric field (in the order of GV cm⁻¹) that is formed along their internuclear axis and the high polarisability of linear molecules which enables aligning the molecular field along the laboratory axes.

The most stringent upper bounds to the eEDM, down to the 10⁻²⁹ e cm level, have been set from the spectroscopy of ThO and HfF⁺, while ongoing global campaigns for nuclear Schiff moments expect an unprecedented sensitivity in molecule-based searches. The sensitivity of these searches scales with the strength of the internal electric field and thus with the atomic number of the heavy nucleus. Radioactive molecules, such as FrAg, RaF, or the polyatomic RaOCH₃, have thus been highlighted by theory for their expected sensitivity. In nuclear Schiff moment searches, the octupole deformation of heavy nuclei leads to an additional enhancement in sensitivity.

In the near term, laser spectroscopy of radioactive molecules proposed for precision tests is necessary to benchmark the quantum chemistry methods that have indicated their sensitivity to CP-violating properties and to confirm their suitability for precision experiments. At the same time, progress in the delivery of intense and pure molecular beams with existing and novel sources is pivotal for improvement in the achievable experimental precision. In the long term, progress in coupling state-of-the-art precision setups to facilities optimised for the production of radioactive molecules should be followed by proof-of-concept experiments with intensely produced beams. ISOLDE can be expected to host a large number of short- and long-term experimental studies as part of its ongoing programme in molecular production and spectroscopy. Other European facilities that utilise gas-cell sources, such as CERN-ISOL and next-generation installations, should be supported in the development of similar programmes, as the gas-cell environment is ideal for efficient molecular formation.

In parallel, advances in nuclear modelling will be crucial for interpreting results from measurements performed on molecular systems. An accurate description of nuclear magnetisation will be essential for linking the measured hyperfine structures and isotope shifts to nuclear properties. Cross-community efforts by nuclear physicists and quantum chemists will be key to tackling the interdisciplinary nature of the challenges posed in this exciting new field. Close collaboration will also be needed to link our descriptions of fundamental interactions within the nucleus to those used in the domain of high-energy particle physics. Our complementary studies of nuclear moments in the low-energy regime could play a critical role in shaping future descriptions of the fundamentals of nature and directly contribute to around-breaking discoveries.

Report on Progress

Opportunities for fundamental physics research with radioactive molecules

Gordon Arrowsmith-Kron¹, Michail Athanasakis-Kaklamanakis^{2,3}, Mia Au^{4,5}, Jochen Ballou^{1,6}, Robert Berger⁷, Anastasia Borschevsky⁸, Alexander A Breier⁹, Fritz Buchinger¹⁰, Dmitry Budker^{11,12}, Luke Caldwell^{13,14}, Christopher Charles^{15,16}, Nike Dattani^{17,18}, Ruben P de Groote^{19,20}, David DeMille^{21,22}, Timo Dicker^{23,24}, Jacek Dobaczewski^{25,26}, Christoph E Düllmann^{27,28,29}, Ephraim Eliav³⁰, Jonathan Engel³¹, Mingyu Fan³², Victor Flambaum³³, Kieran T Flanagan³⁴, Alyssa N Gaiser³⁵, Ronald F Garcia Ruiz^{35,*}, Konstantin Gaul³⁶, Thomas F Giesen⁹, Jacinda S M Ginges³⁶, Alexander Gottberg³⁵, Gerald Gwinne³⁷, Reinhard Heinke³⁸, Steven Hoekstra^{8,38}, Jason D Holt^{15,39}, Nicholas R Hutzler^{40,*}, Andrew Jayich^{32,*}, Jonas Kartheim³⁵, Kyle G Leach^{1,41}, Kirk W Madison⁴², Stephan Malbrunot-Ettenauer^{15,43}, Takayuki Miyagi¹⁵, Iain D Moore⁴⁴, Scott Moroch³⁵, Petr Navrátil¹⁵, Witold Nazarewicz^{45,*}, Gerda Neyens³⁶, Eric B Norrgard⁴⁶, Nicholas Nussgart¹, Lukáš F Pasteka^{8,47}, Alexander N Petrov^{48,49}, Wolfgang R Plaf^{23,24}, Roy A Ready³², Moritz Pascal Reiter⁵⁰, Mikael Reponen⁴⁴, Sebastian Rothe⁹, Marianna S Safronova^{51,52}, Christoph Scheidegger^{23,24,53}, Andrea Shindler⁵⁴, Jaideep T Singh^{55,*}, Leonid V Skripnikov^{48,49}, Anatoly V Titov^{48,49}, Silviu-Marian Udrescu³⁵, Shane G Wilkins³⁵ and Xiaofei Yang⁵⁶

Radioactive molecules as laboratories of fundamental physics

A. Jadbabaie^{1,9}, S. Ebadi^{1,2}, R. F. Garcia Ruiz³⁵, N. R. Hutzler⁹, A. M. Jayich³² & J. T. Singh⁹

Abstract

Radioactive molecules provide a new platform in the search for new physics, at energy scales complementary to those probed by high-energy particle colliders. By combining enhancements from nuclear properties with the sensitivity and control offered by molecular structure, experiments with radioactive molecules offer great reach in the search for physics beyond the standard model. Progress in this field is being driven by advances in the production and control of radioactive molecules, alongside the development of new experimental tools and theoretical techniques. In this Perspective, we discuss the current status and future prospects of this rapidly developing, interdisciplinary field at the intersection of nuclear physics, atomic and molecular physics and particle physics.

Sections

Introduction

Symmetry-violating nuclear properties

Effective field theories and energy reach

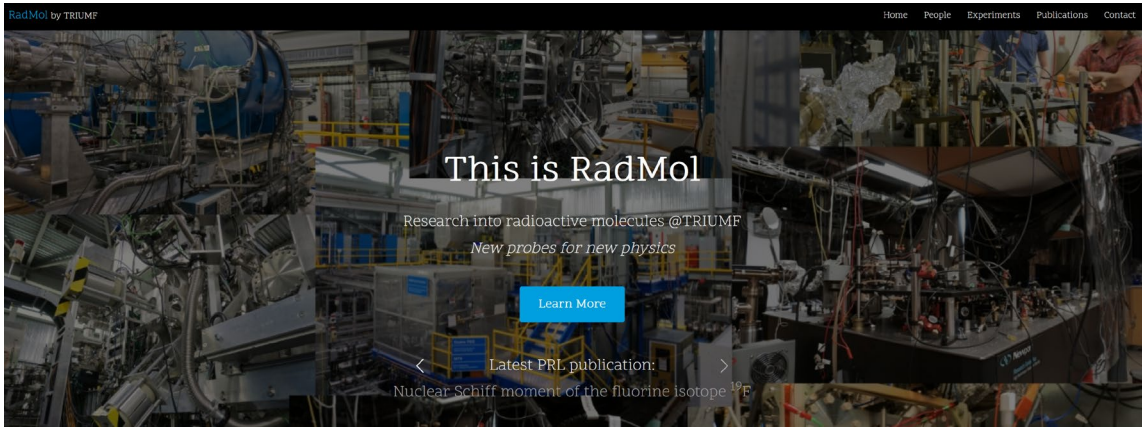
Experimental techniques and challenges

Outlook

3. 国际放射性分子研究现状

已有放射性分子项目和非官方合作组(-2026)

加拿大TRIUMF的RadMol合作组 [上亿经费支持]



欧洲瑞士CERN-FunSY合作组

Fundamental symmetries in nuclei, atoms, and molecules

2026年2月16日至18日
CERN
Europe/Zurich 时区

Contact
✉ mia.au@cern.ch

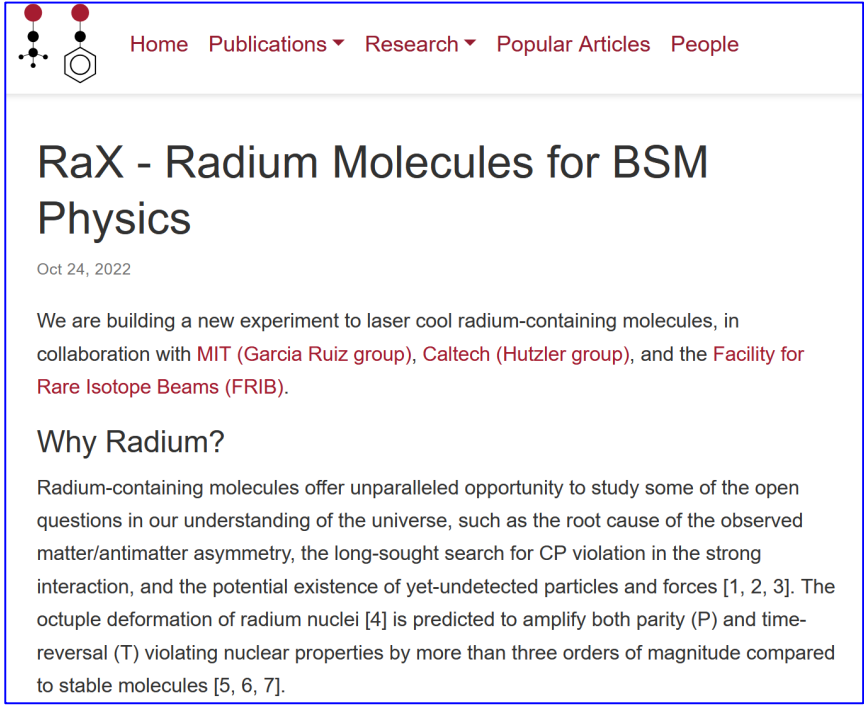
申请
registration form

⚠ 只有注册的参加人才能访问此事件的其余部分。

📞 联系人信息
For further information please contact mia.au@cern.ch

📄 Welcome to the registration site for the workshop on symmetry violation in nuclei, atoms and molecules.
Please note that registration includes the following only: access to all lectures throughout the workshop, coffee and coffee breaks, and visits booked through registration.

美国哈佛MIT等的RaX合作组



英国曼彻斯特大学 Advanced ERC项目ActMol

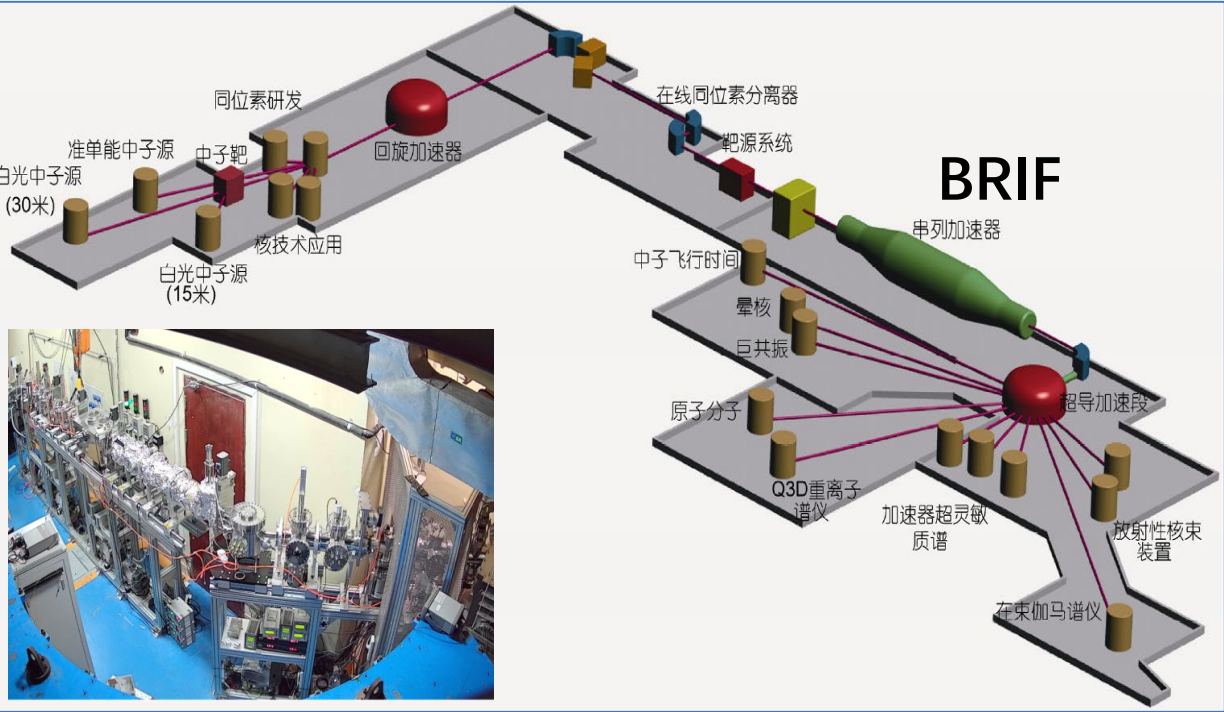
Actinide molecules for exploring the frontiers of fundamental physics (ActMol) aims to identify novel exotic molecules to enable future experiments to search for new physics beyond the standard model. Critical to this project and programmed is the development of a platform to produce intense cold beams of radioactive molecules for future search experiments.

报告内容

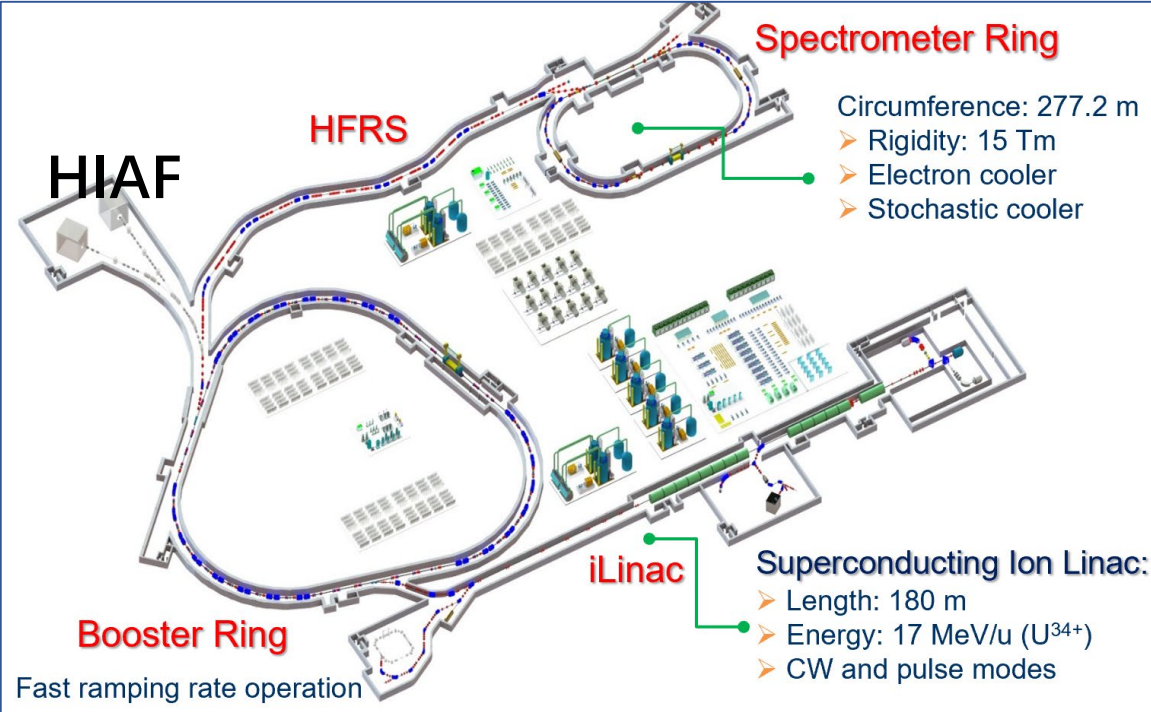
1. P,T 破缺 (研究背景)
2. 重核(放射性)分子的优势
3. 国际放射性分子研究现状
4. 国内放射性分子研究近期发展
5. 总结及展望

4. 国内放射性分子研究近期进展

BRIF:北京放射性同位素装置



HIAF: 强流重离子加速器装置

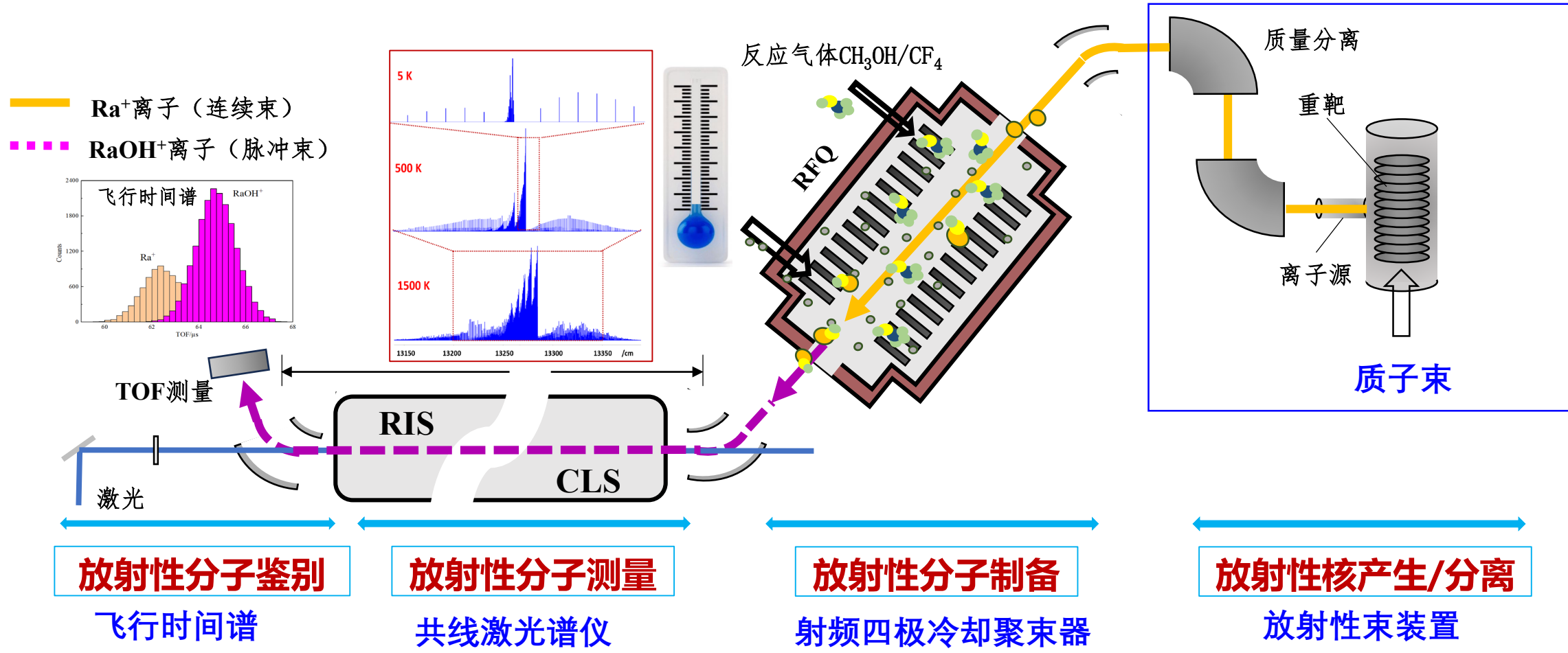


-结合离子阱+激光谱, 制备和测量放射性分子
在国内现有(BRIF@CIAE) 和 下一代(HAIF@IMP)放射性核束装置上应用！

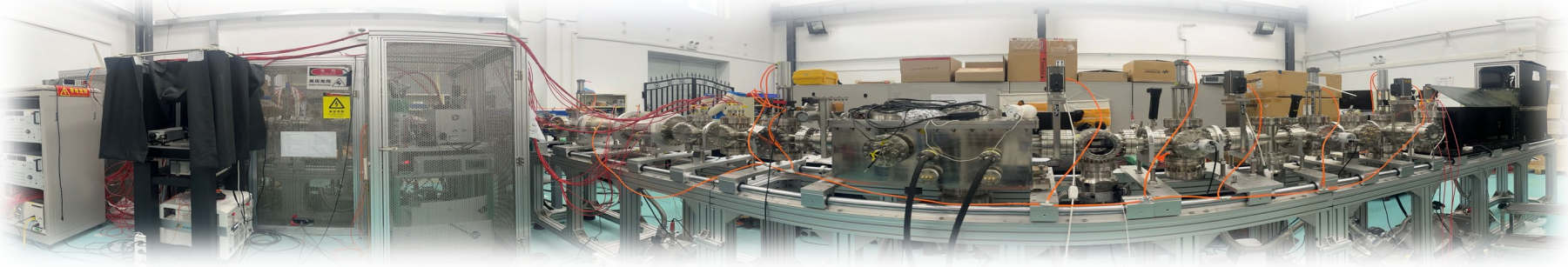
4. 国内放射性分子研究近期进展 放射性分子研究技术路线提出

理论计算表明，含八极形变重核 ^{225}Ra 的多原子放射性分子（如 $^{225}\text{RaOH}^+$ ， $^{225}\text{RaOCH}_3^+$ ）是测量与CP 破缺效应相关原子核席夫矩(S)的更理想的候选者，但目前谱学实验数据完全空白。

基金委原创探索项目[冷却型RFQ分子制备+共线激光谱分子测量]



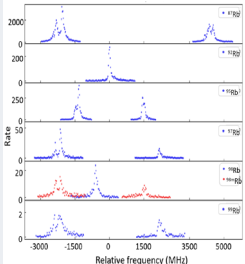
4. 国内放射性分子研究近期进展 设备平台搭建



高分辨高灵敏度激光核谱仪(在线)

2025.07

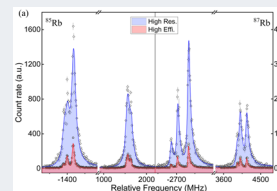
Phy.Rev. Res. 8(26)023286



高分辨高灵敏度激光核谱仪(离线)

2025.02

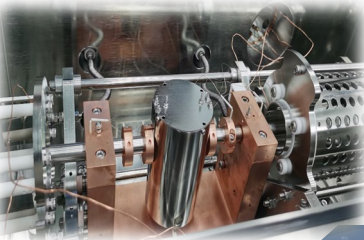
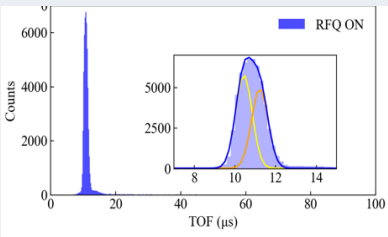
Sci. Bull. 70(2025)2721



射频四极冷却聚束器

2024.01

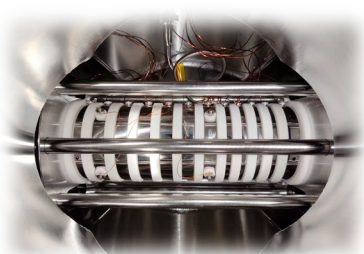
NST 37 (2026)13[封面]



离线共线共振电离谱

2022-2023

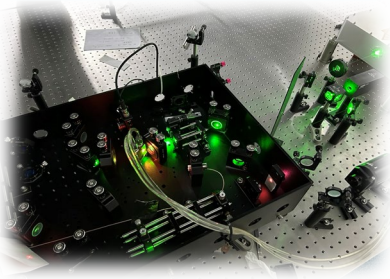
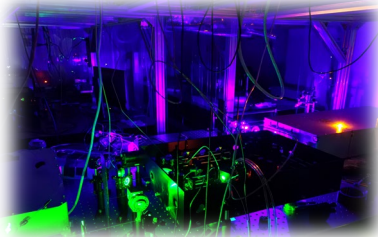
NIMB541(2023)37
NST34(2023)38



离线/在线共线激光谱

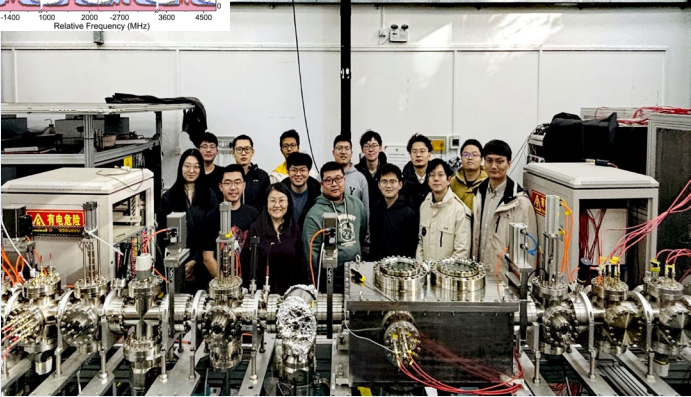
2020-2021

NIMA1032(2022)166622
NST33(2022)9[封面]



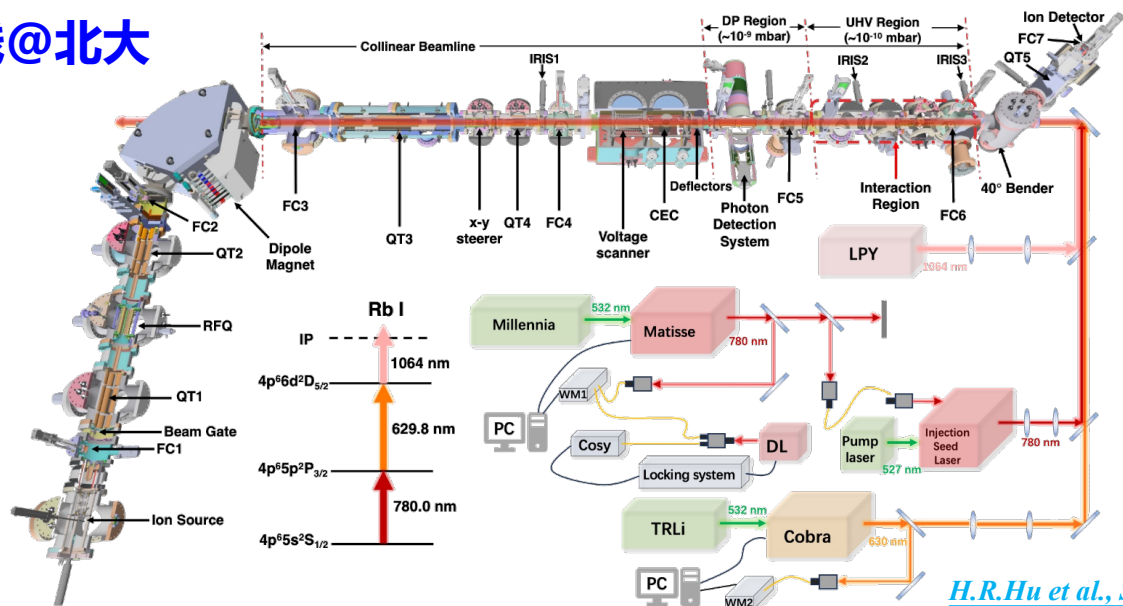
实验室改造

2018-2019

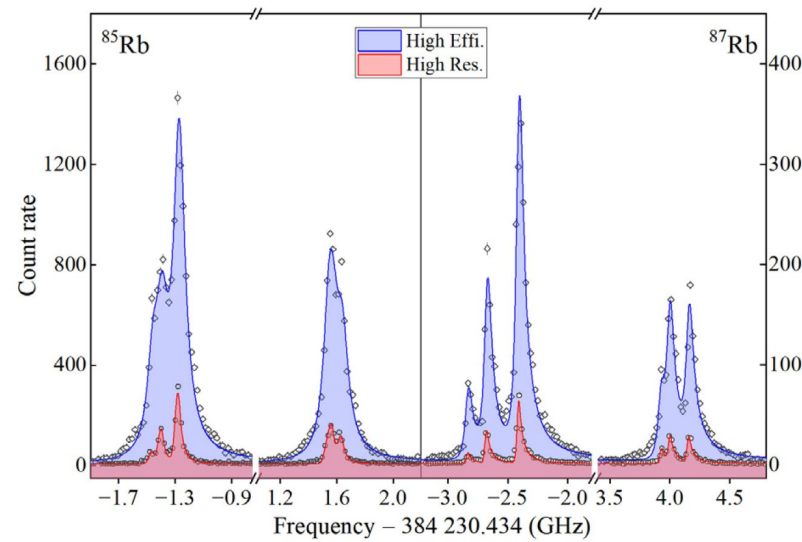


4. 国内放射性分子研究近期进展 设备平台完成

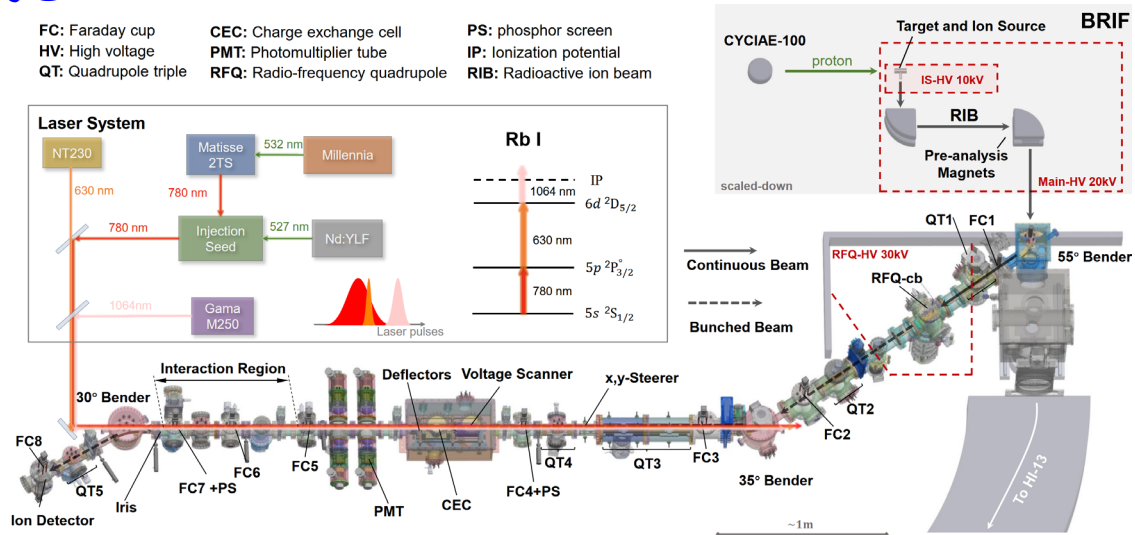
离线@北大



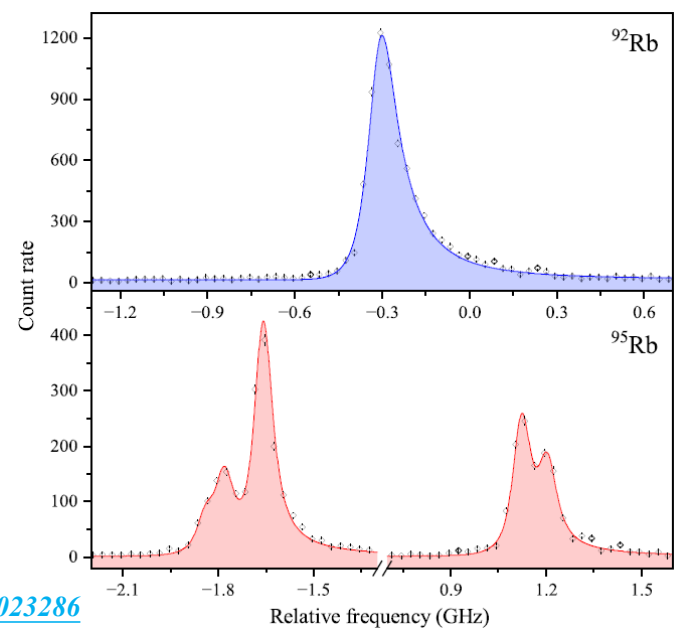
H.R.Hu et al., Sci. Bull. 70(2025)2721



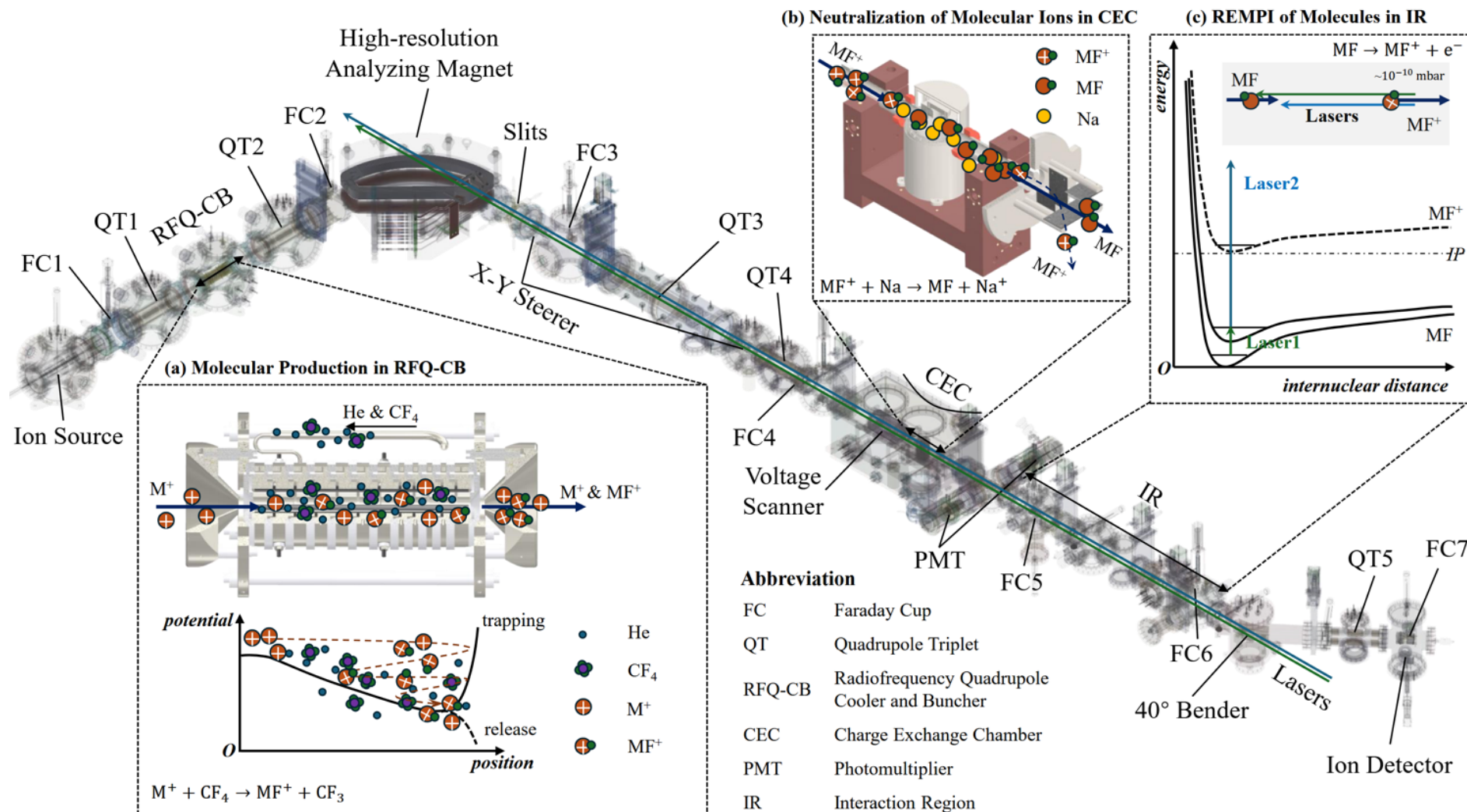
在线@BRIF



W.C. Mei et al., Phy.Rev. Res. 8(26)023286

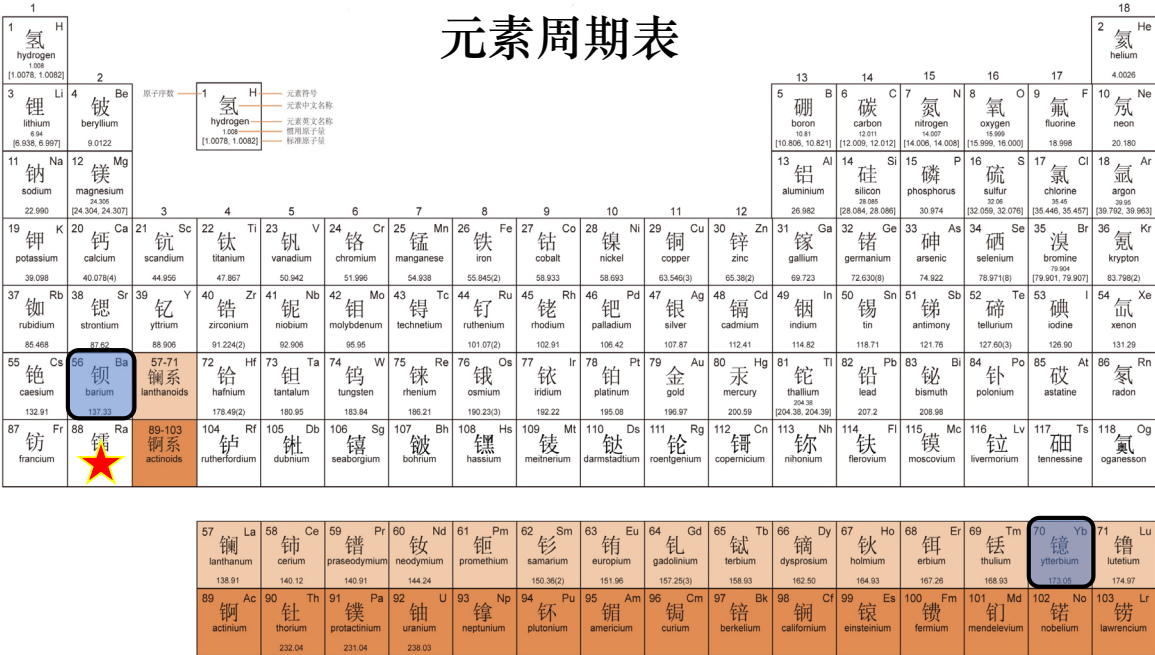


冷却型RFQ分子制备+共线激光谱分子测量技术路线



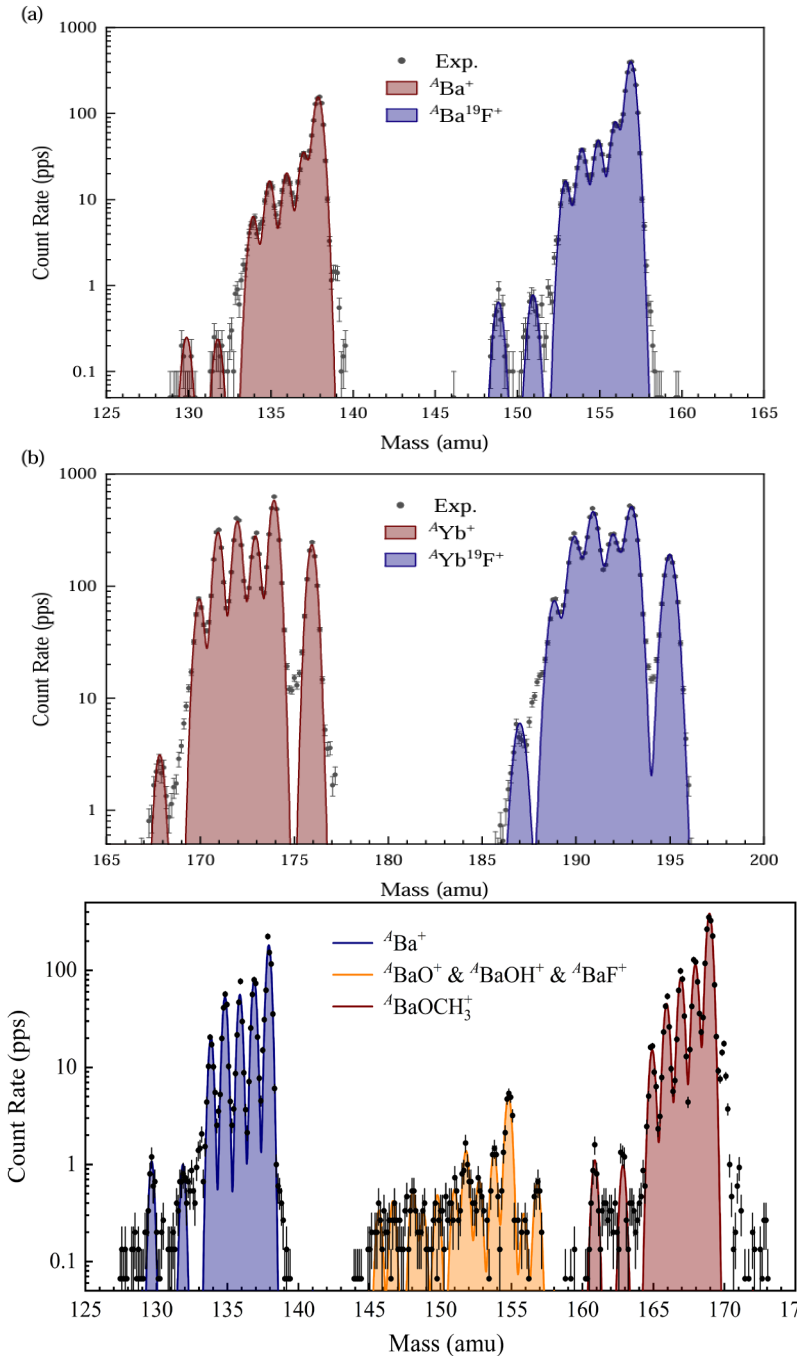
4. 国内放射性分子研究近期进展 离线技术路线验证@PKU

冷却型RFQ分子制备+共线激光谱分子测量技术路线

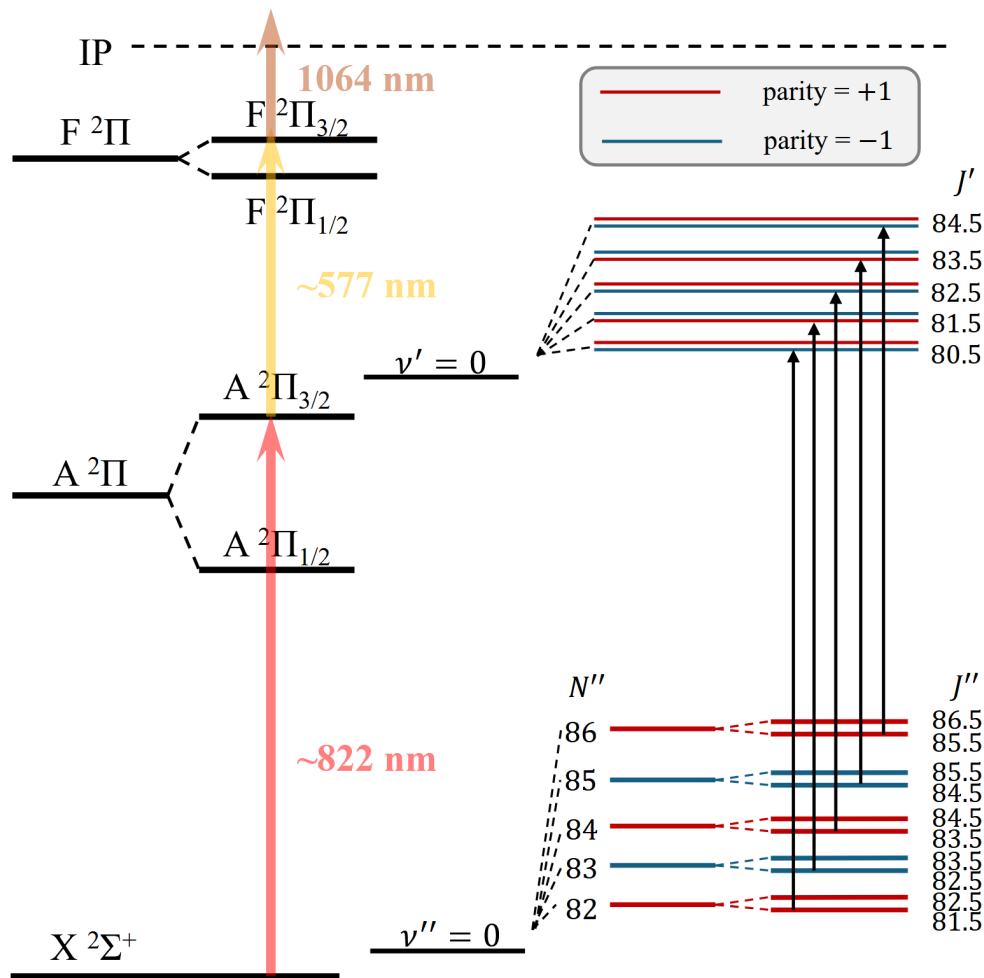


化学热力学计算：反应焓变 ΔH

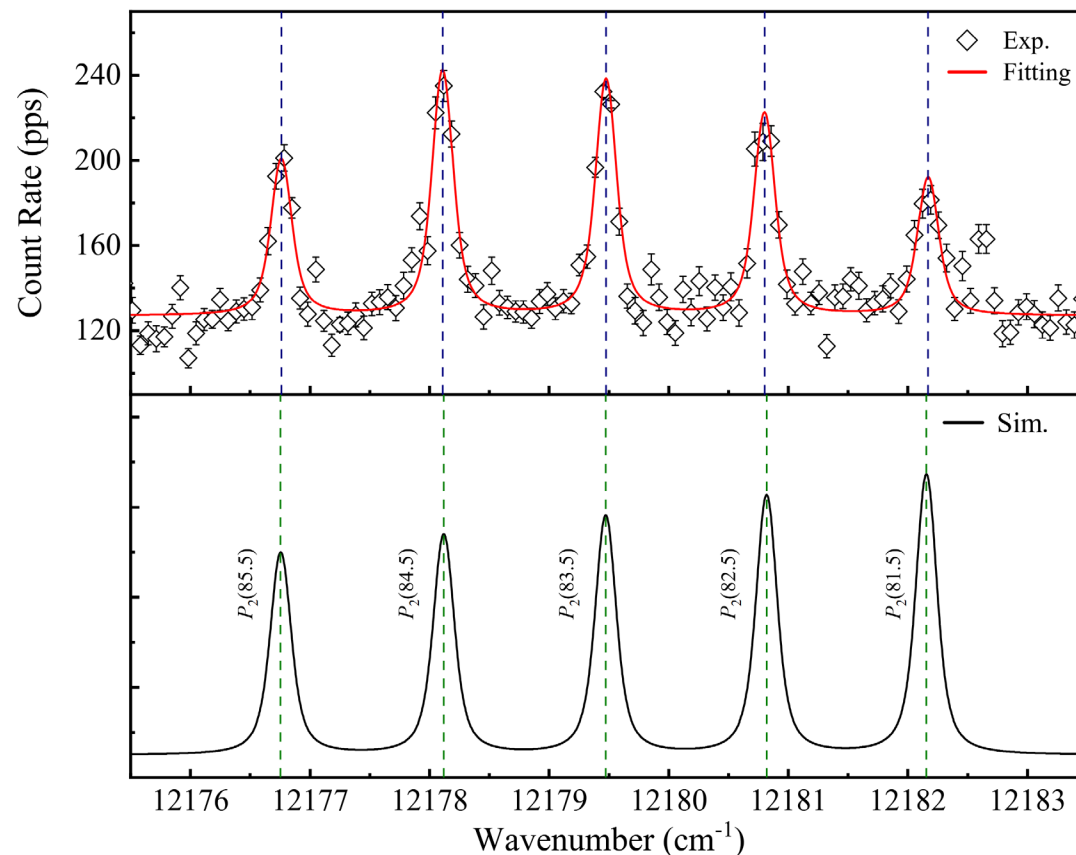
Reactive Gas	Element	Valence Electron	ΔH_1 (eV)	ΔH_2 (eV)	ΔH_3 (eV)	ΔH (eV)
CF ₄	Mg	3s ²	+0.82	7.65	7.68	+0.85
	Ca	4s ²	+0.14	6.11	5.83	-0.15
	Sr	5s ²	+0.04	5.69	5.36~5.62	-0.29~-0.03
	Ba	6s ²	-0.43	5.21	4.80	-0.84
	Ra	7s ²	-0.47	5.27	4.97	-0.78
	Yb	4f ¹⁴ 6s ²	+0.78	6.25	6.04	+0.57



冷却型RFQ分子制备+共线激光谱分子测量技术路线

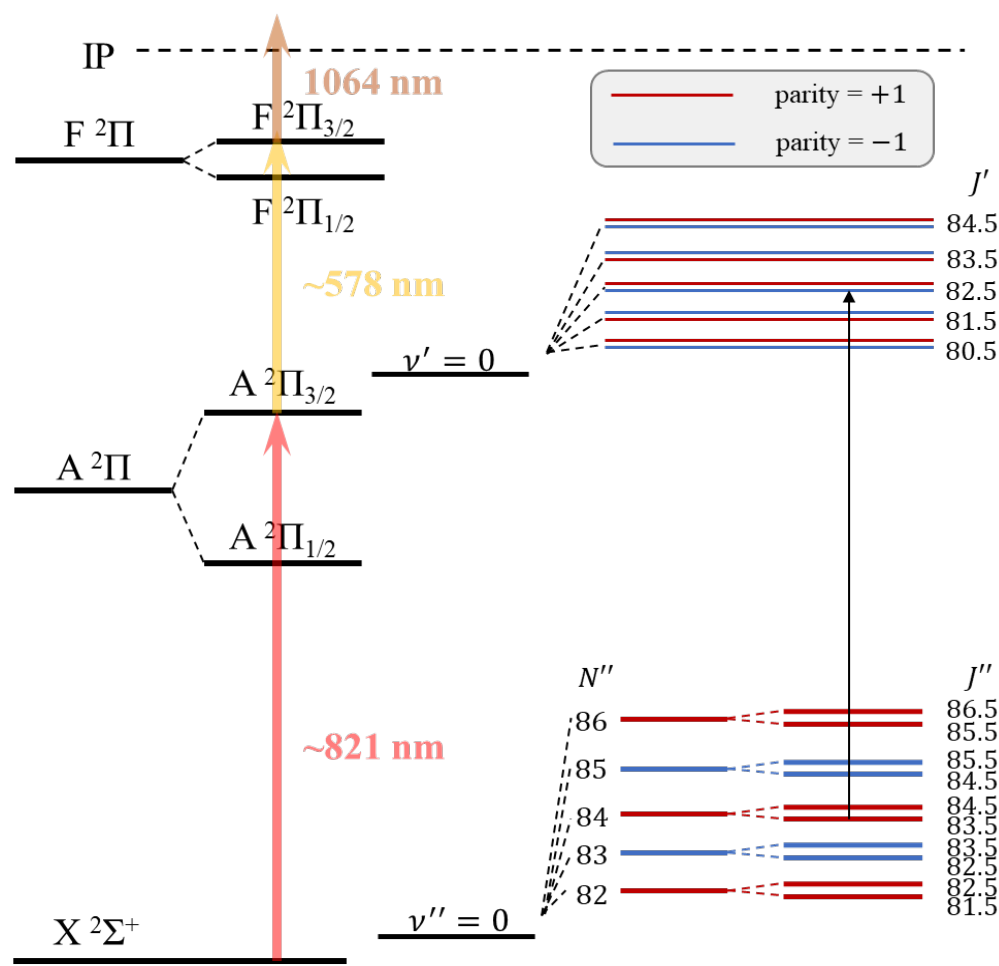
 ^{138}BaF 低分辨($\sim 6\text{GHz}$)振动能级谱

$$T_r = B_e J(J+1) - D_e J^2(J+1)^2$$

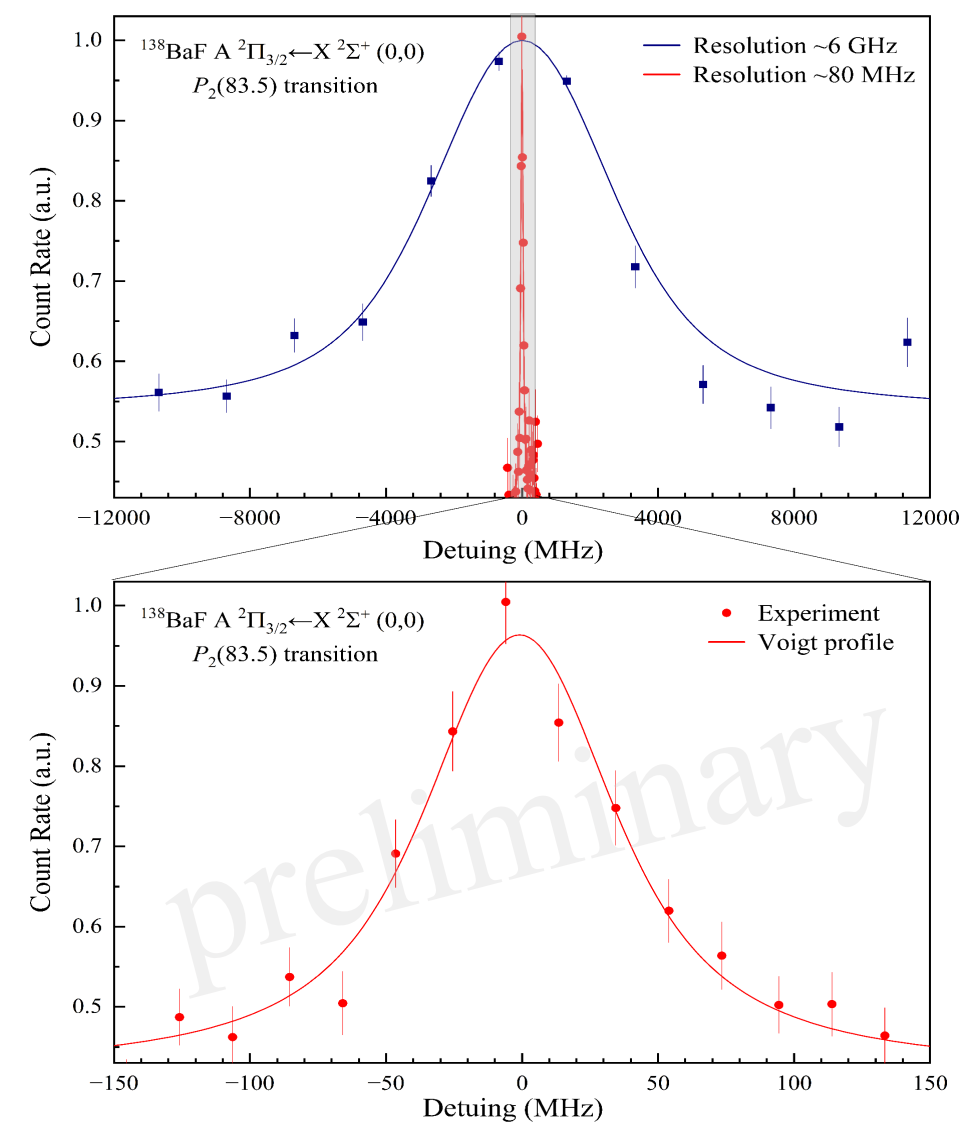


4. 国内放射性分子研究近期进展 离线技术路线验证@PKU

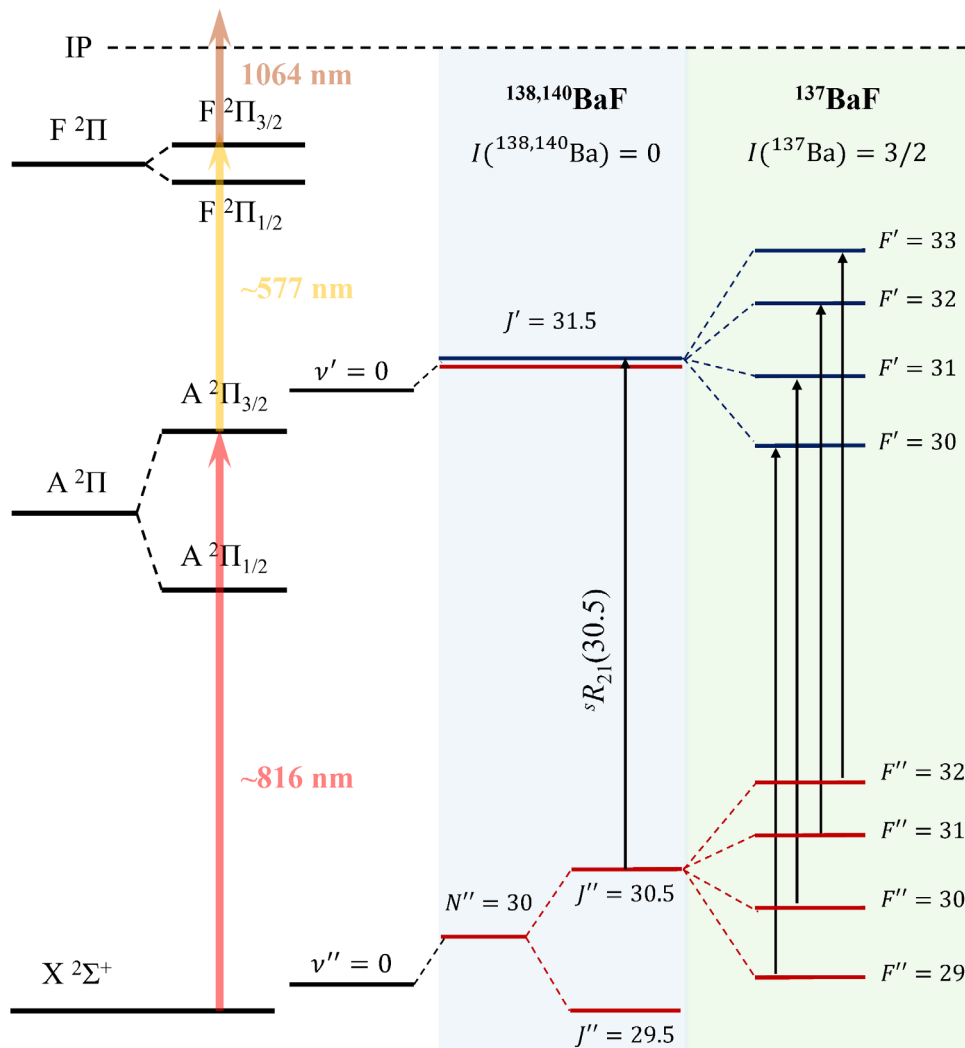
冷却型RFQ分子制备+共线激光谱分子测量技术路线



^{138}BaF 高分辨($\sim 80\text{MHz}$)振动能级谱

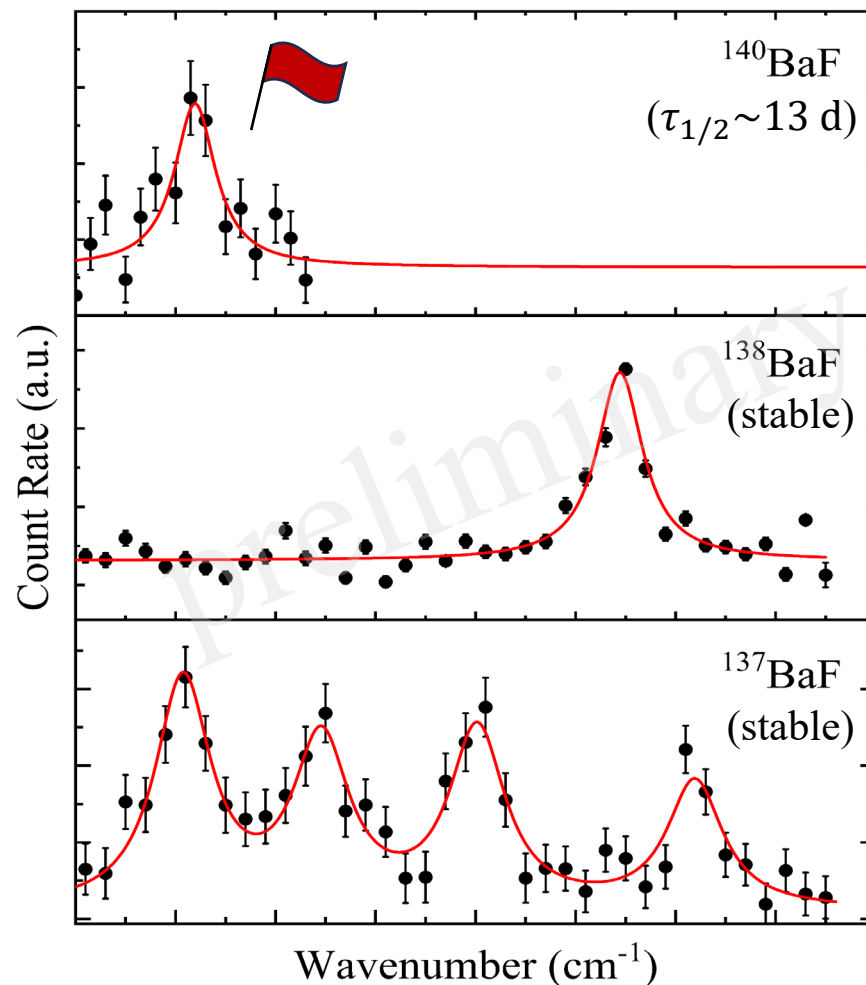


冷却型RFQ分子制备+共线激光谱分子测量技术路线



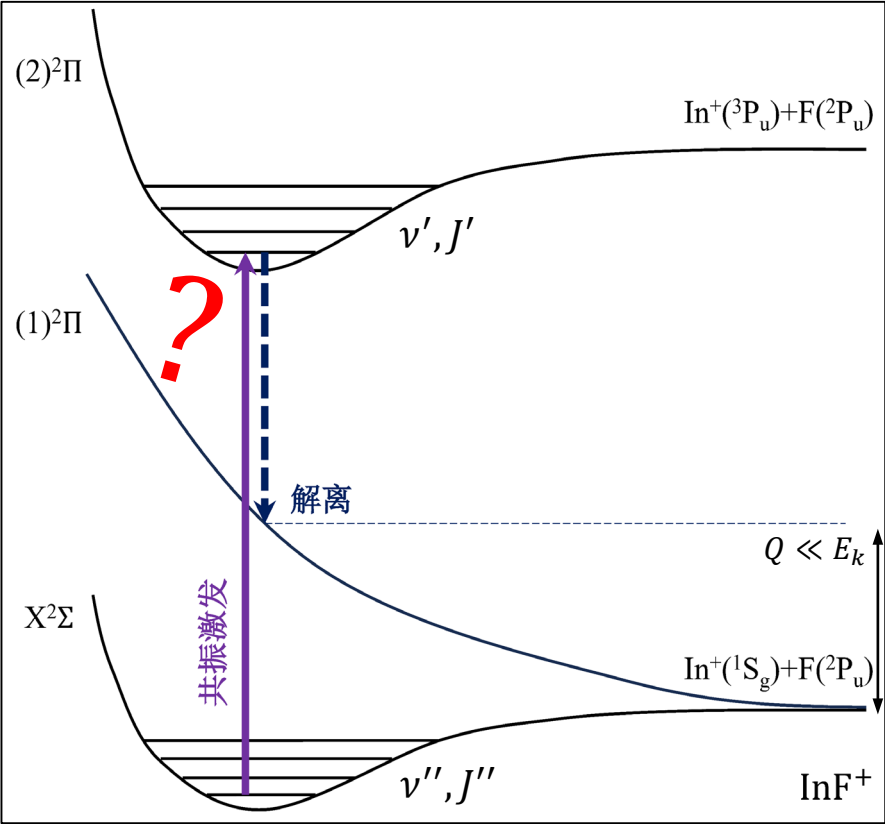
^{140}Ba : 产额: $\sim 10^6$ 离子/秒
寿命: ~ 12.75 天

和 ^{225}Ra 相当

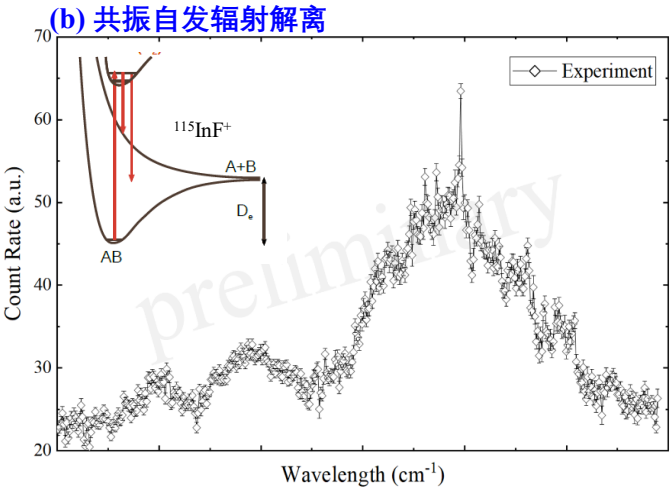
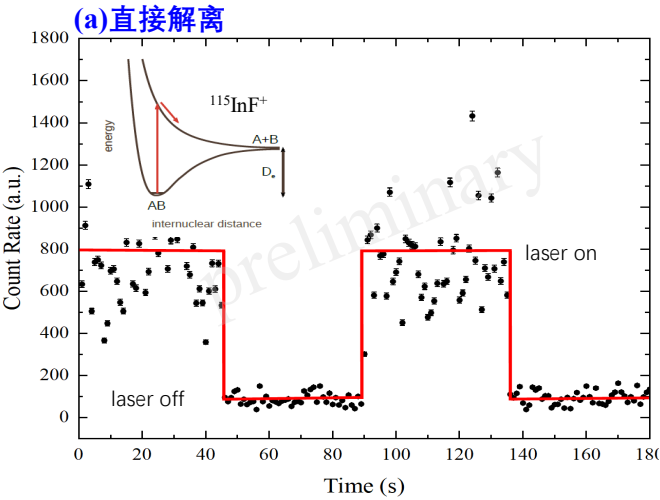
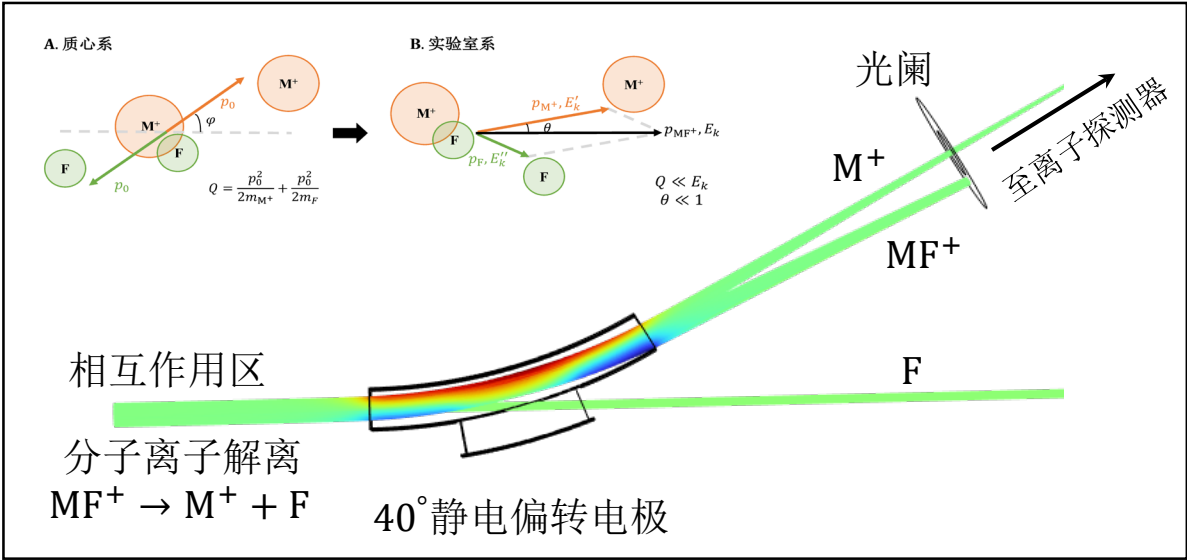


放射性分子制备+分子谱测量技术路线完整实现, 为下一步开展 RaF , RaOH^+ 分子谱学研究奠定了基础

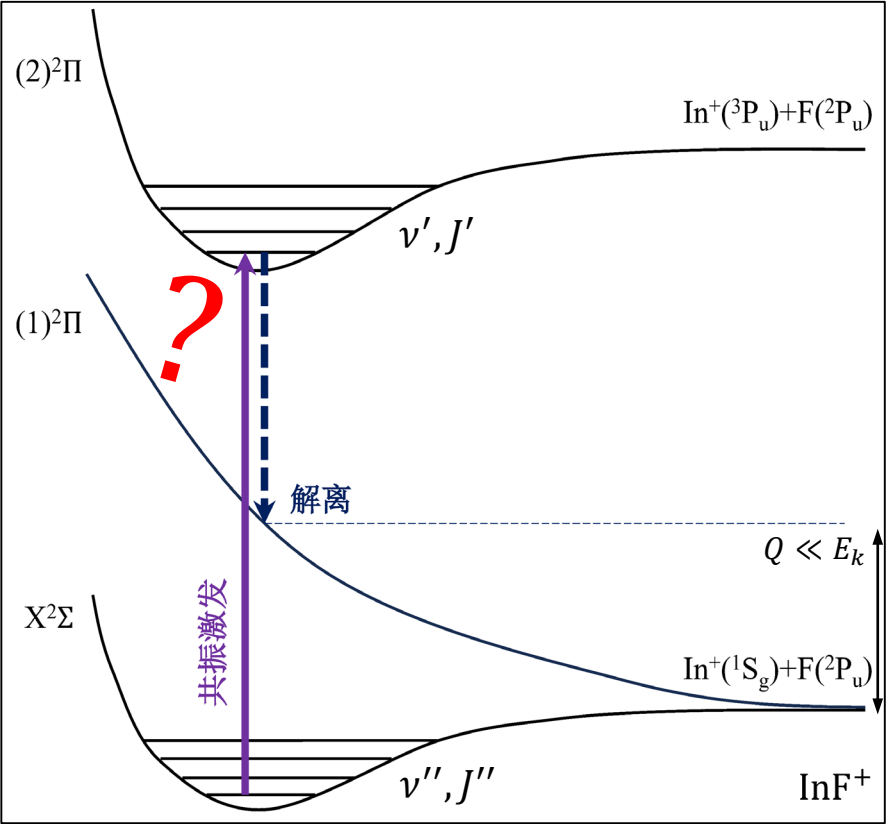
分子离子的共线共振解离光谱?



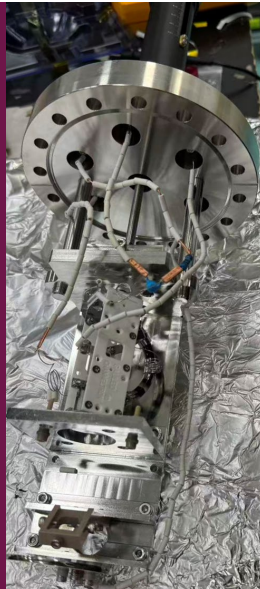
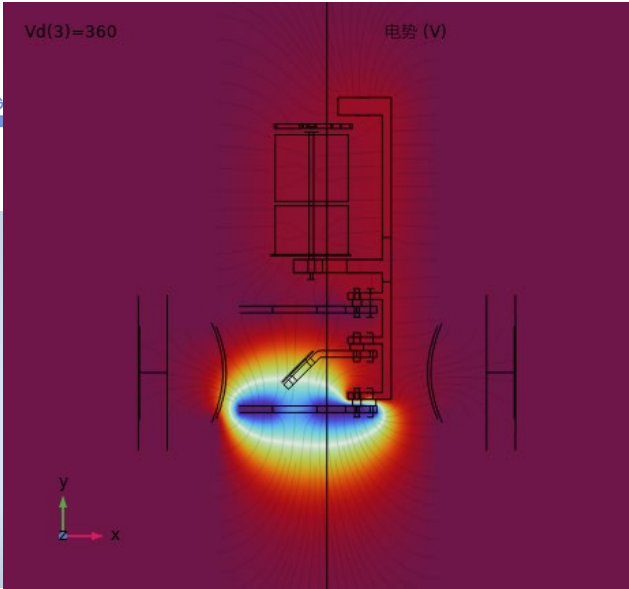
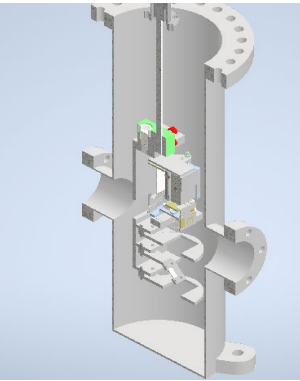
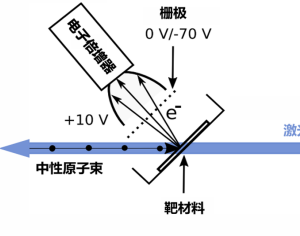
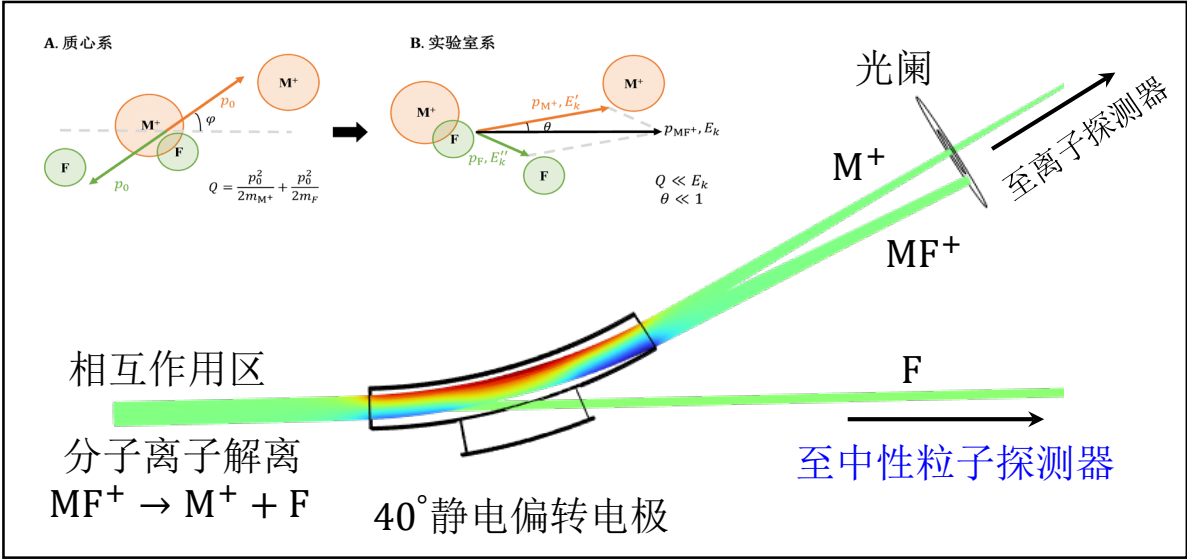
(根据合作者提供的分子理论计算初步结果重新绘制)



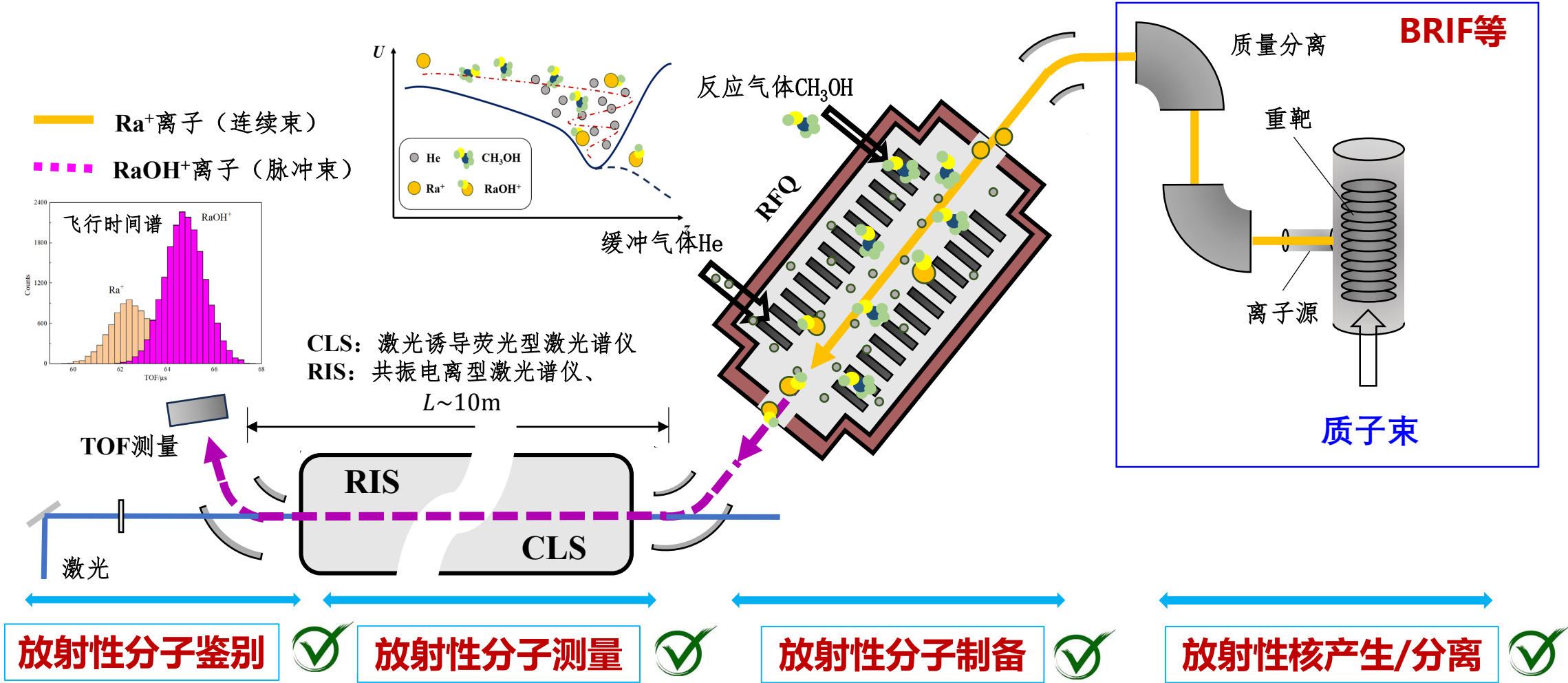
分子离子的共线共振解离光谱?



(根据合作者提供的分子理论计算初步结果重新绘制)



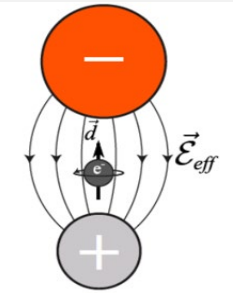
4. 国内放射性分子研究初步进展



报告内容

1. P,T 破缺 (研究背景)
2. 重核(放射性)分子的优势
3. 国际放射性分子研究现状
4. 国内放射性分子研究近期发展
5. 总结及展望

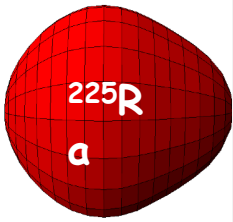
八极形变重核分子(²²⁵RaX)的优势: 灵敏度~7个量级提升, 有望覆盖全部未知区域

$$\mathcal{H} = -\mu \cdot B - d \cdot E$$


极性分子内
强有效电场

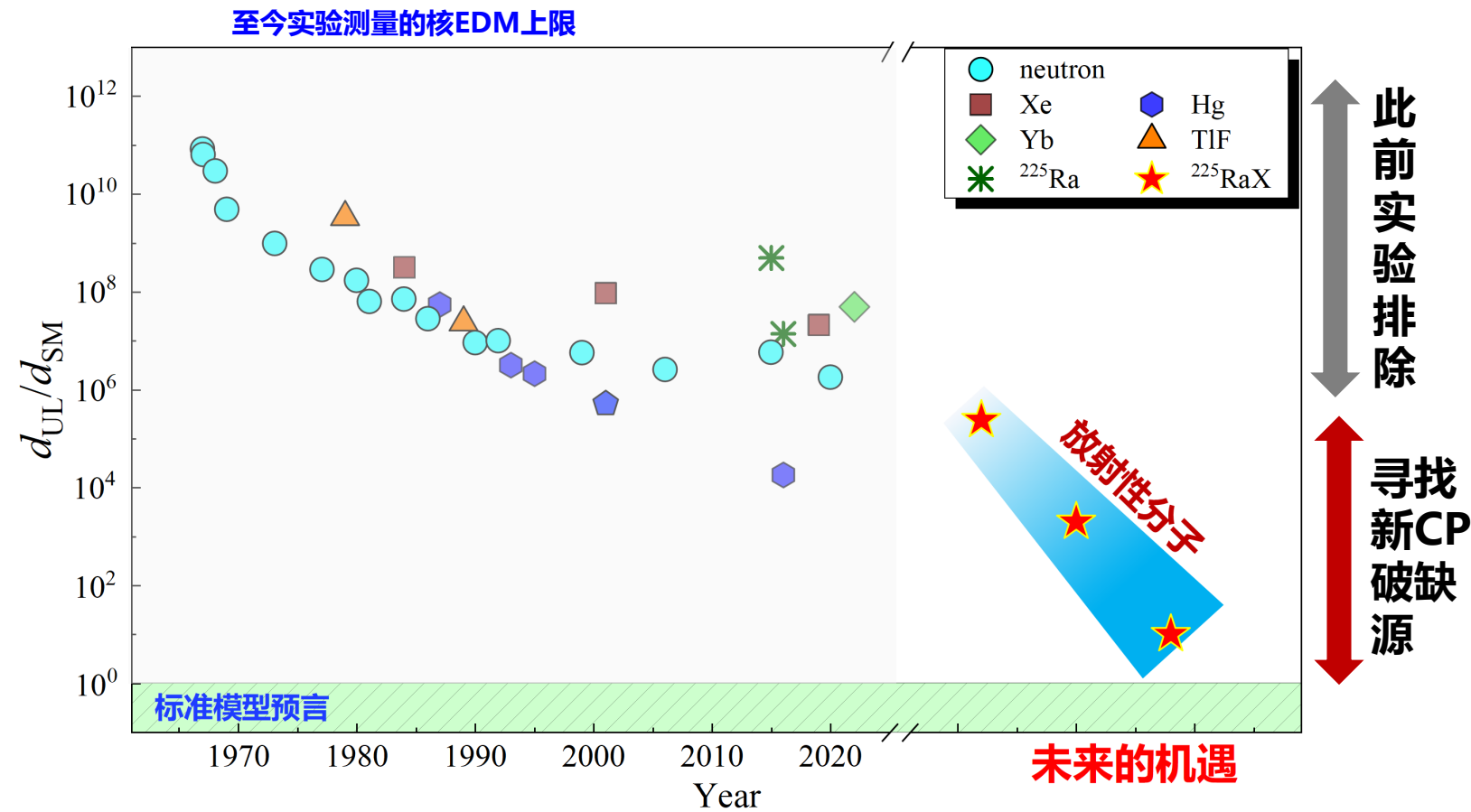
E 提升 10^4

+



八极形变重核
强EDM效应

d 提升 10^3



Report on the Progress in Physics, 87, 084301(2024) 《寻找原子核中的CP破缺：放射性分子的新机遇》 DOI: 10.1360/CSB-2025-5440 (2025)

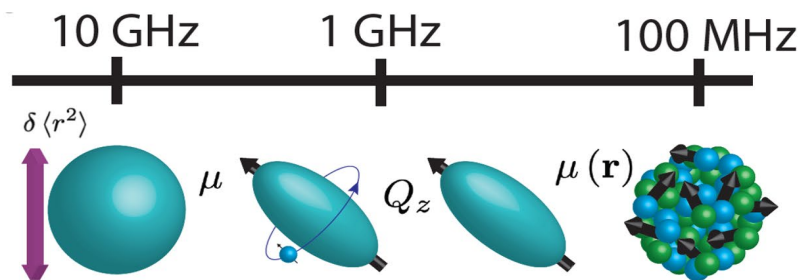
基于放射性分子开展EDM测量，需要亚Hz的精度，对应于AMO领域的精密测量技术

基于放射性原子/分子的原子核性质研究

基于放射性分子的基本对称性研究

$$H_{\text{MOL}} = H_{\text{EL}} + H_{\text{VIB}} + H_{\text{ROT}} + H_{\text{HFS}} + \dots$$

$$+ H_{\text{PV}} + H_{\text{PTV}}$$

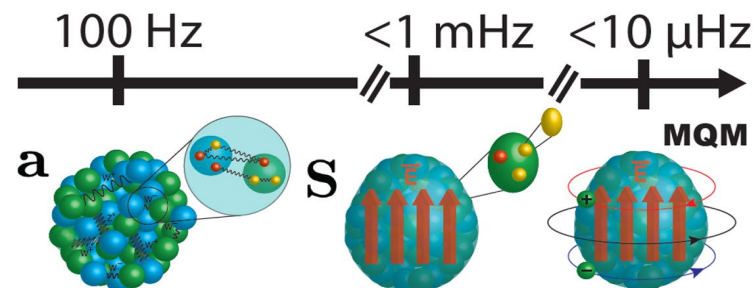


半径 磁矩 电四极矩 磁分布

核物理领域成熟技术



4K低温离子阱
正在建设中



Anapole矩 席夫矩 磁四极矩

AMO领域成熟技术

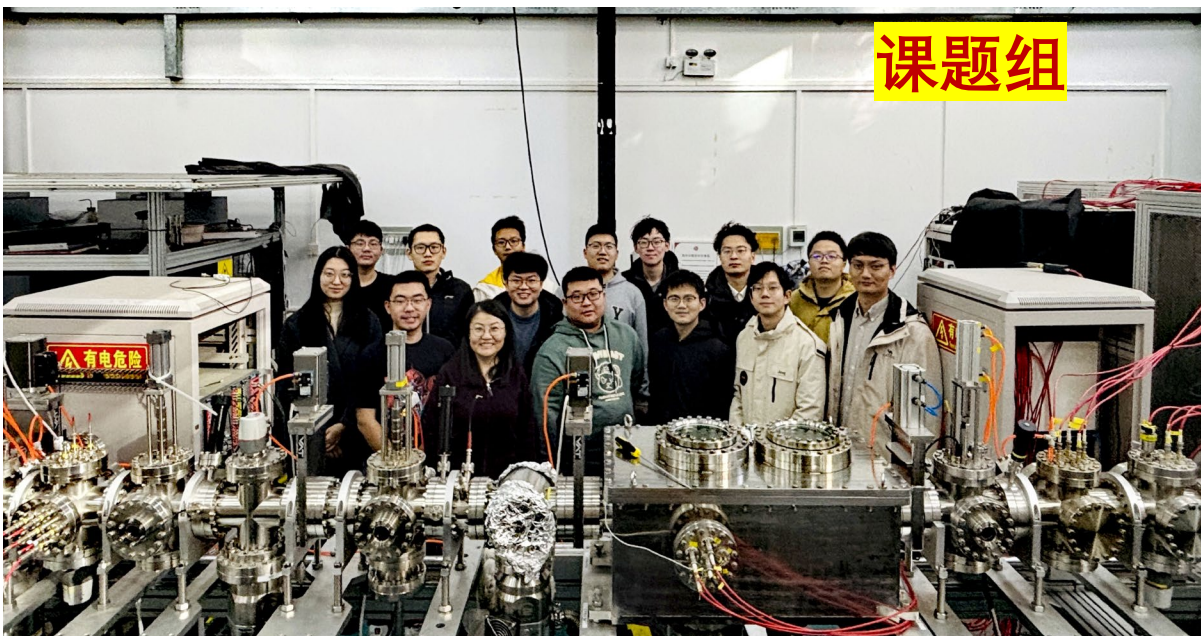


KU LEUVEN

MANCHESTER
1824



Thanks for your attention!



https://faculty.pku.edu.cn/yangxiaofei/zh_CN/index.htm



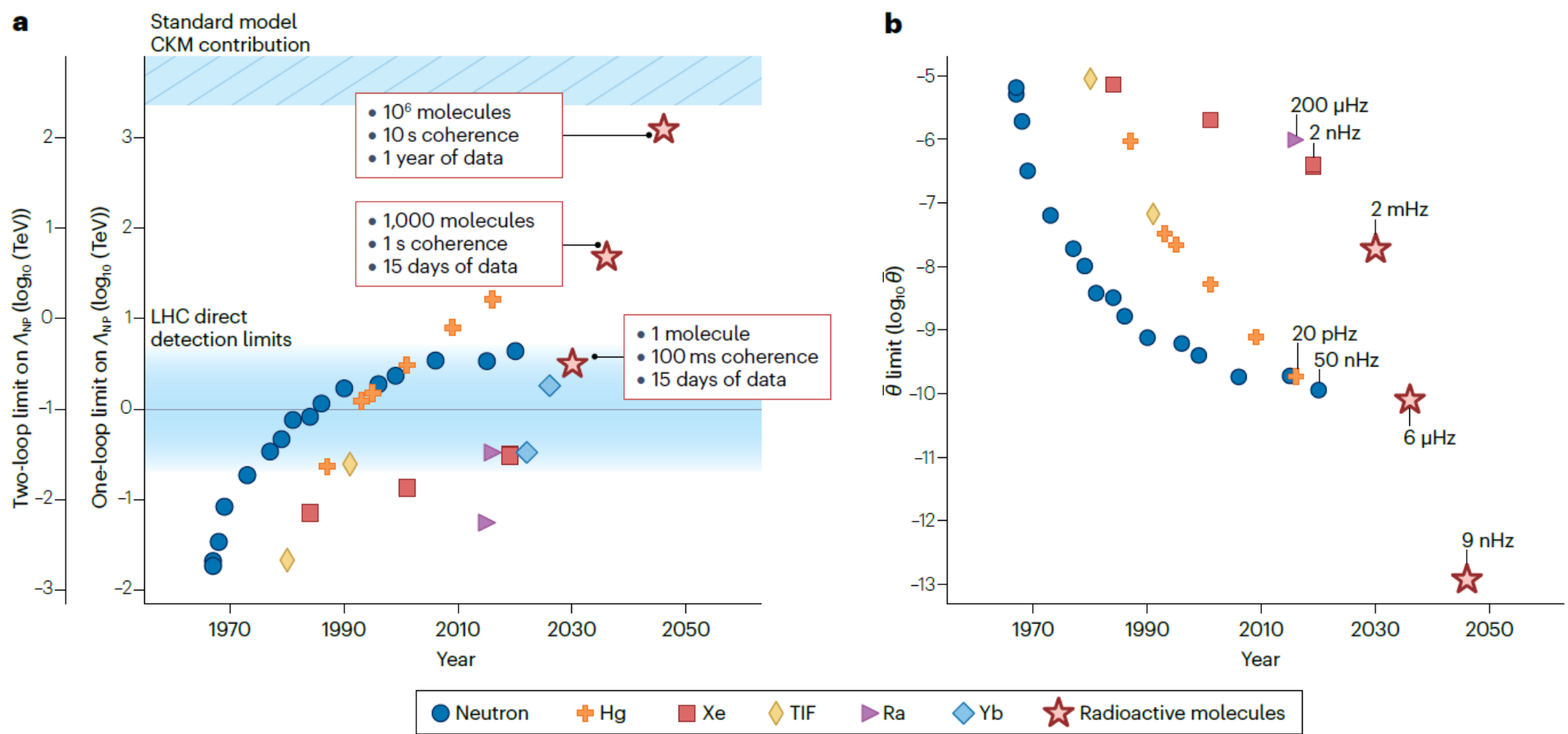


Fig. 3 | Hadronic electric dipole moment limits. Prospects for probing new physics with radioactive molecules (pink stars), in comparison to current Large Hadron Collider (LHC) limits (horizontal faded band) and previous hadronic electric dipole moment measurements. Hadronic enhancement factors from equation (2) in the Supplementary information are estimated by geometric means of the values in ref. 48. **a**, One-loop and two-loop limits on the new physics energy scale, Λ_{NP} , obtained from a single-source approximation of $\bar{g}_0$ from an isovector quark chromoelectric-EDM (CEDM) $\bar{d}_1$. See ref. 17 for more details. LHC constraints taken from refs. 143–145. The equivalent signal from the

standard model Cabibbo–Kobayashi–Maskawa (CKM) contribution is shown with the hatched region. **b**, Limits on $\bar{\theta}$ from a single-source approximation considering only CPV pion exchange $\bar{g}_0$. The best limits from ^{225}Ra , ^{129}Xe , ^{199}Hg , ^{171}Yb , and the neutron, as well as radioactive molecule projections, are labelled with their frequency precision, contextualizing differences in sensitivity. For $\bar{\theta}$, both the expected standard model CKM contribution^{5,19} at $\bar{\theta} \sim 10^{-16}$ and the quantum chromodynamics axion oscillation scale²⁶ at $\bar{\theta}_{\text{rms}} \sim 4 \times 10^{-19}$ lie outside the plotted range. All calculations assume 1 s experimental cycle dead-time. Compiled measurements and constraints are available at ref. 146.