原子分子动力学参数及其在天体物理、大气物理中的应用

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中国科学技术大学近代物理系

离子的动力学参数：辐射复合和双电子复合

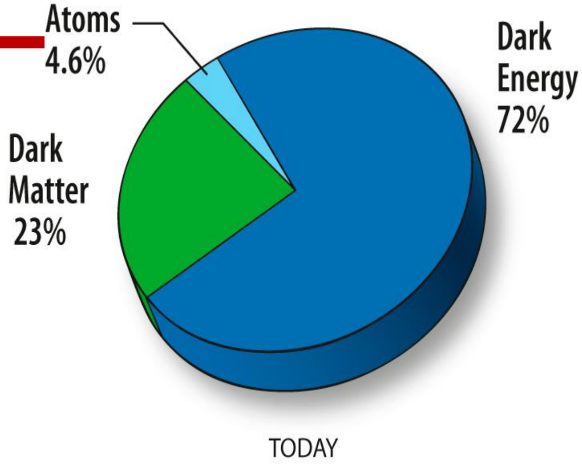
- 背景
- 研究方法
- 现状
- 展望

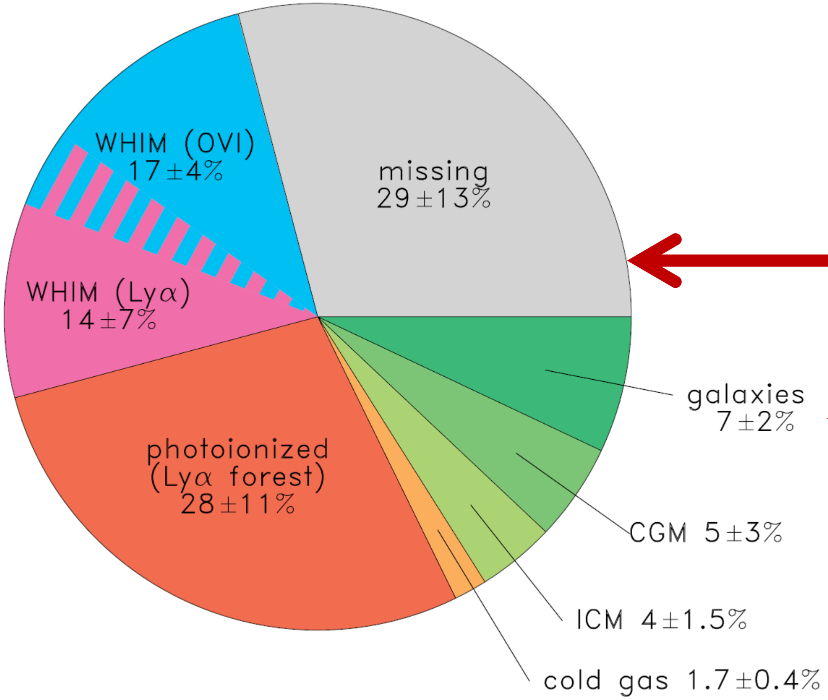
背景之一：天体物理的需求

宇宙中的可见物质：超过95%处于等离子体状态

重子物质的温度：10^5~10^8 K，绝大部分是等离子体

CGM：环星系介质
ICM：星系团内介质
WHIM：温热星系际介质





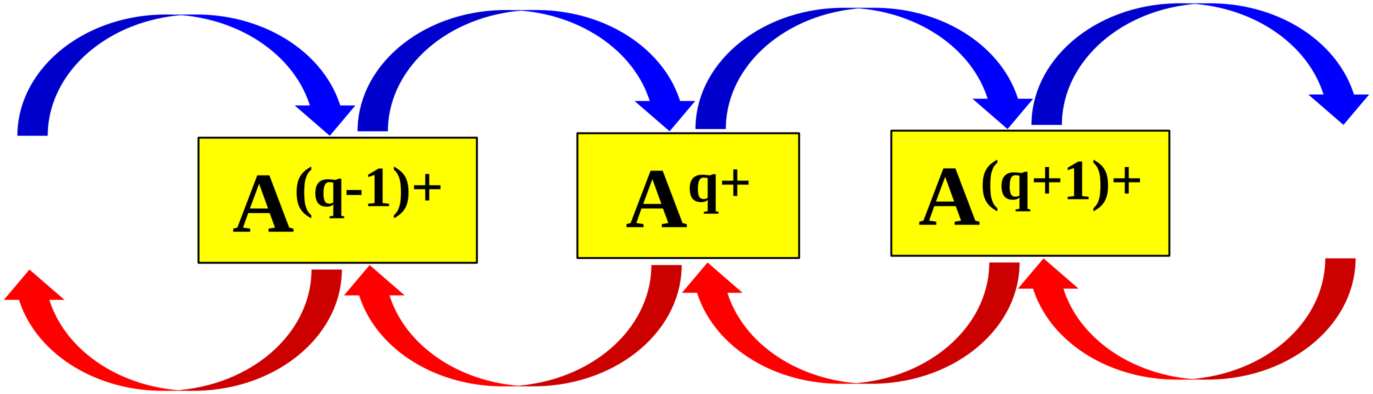
恒星（10%）
行星（0.01%）
星际气体（~90%）

Shull_2012_ApJ_759_23

背景之一：天体物理的需求

等离子体中的电离平衡

电离过程



$A^{(q-1)+}$ A^{q+} $A^{(q+1)+}$

复合过程

跃迁辐射源

- ➢ 诊断天体以及人造等离子体状态（温度，密度等）；
- ➢ 等离子体建模解释天文观测光谱的基本输入参数;

离子的动力学参数：辐射复合和双电子复合

天体等离子中的原子物理过程：电子，离子相互作用

电子碰撞电离
Electron impact ionization

$$^{A}X^{q+} + e \rightarrow {}^{A}X^{(q+1)+} + 2e$$

电子碰撞激发
Electron impact excitation

$$\rightarrow ({}^{A}X^{q+})^{*} + e$$

电子俘获
Resonance formation (capture)

$$^{A}X^{q+} + e \rightarrow ({}^{A}X^{(q-1)+})^{**}$$

$$\begin{tikzcd} & ({}^{A}X^{(q-1)+})^{**} \arrow[dl] \arrow[dr] & \\ {}^{A}X^{(q-1)+} + h\nu & & {}^{A}X^{(q+1)+} + 2e \end{tikzcd}$$

电子离子复合
Recombination
(“dielectronic”)

共振碰撞电离
Resonant impact ionization

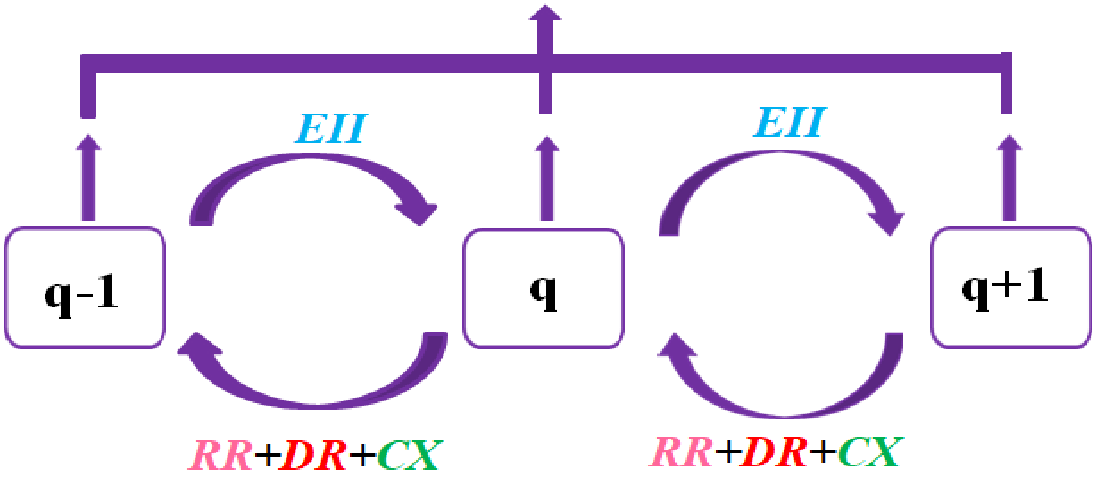
激发/自电离
Excitation / autoionization

$$\begin{tikzcd} {}^{A}X^{q+} + e \arrow[r] & ({}^{A}X^{q+})^{**} + e \arrow[d] \\ & {}^{A}X^{(q+1)+} + 2e \end{tikzcd}$$

天文观测谱的解释

光谱观测是认知宇宙的重要手段。在超新星遗迹、超大质量黑洞邻近区域、星际间介质等极端环境中，电子、离子、原子、分子和光子的相互作用、电荷交换等决定了等离子体的演化、辐射和吸收特征，体现在Saha方程：

$$\frac{dn_q}{dt}=\left[n_{q-1}(t)\alpha_{q-1}^{EII}+n_{q+1}(t)\left(\alpha_{q+1}^{DR}+\alpha_{q-1}^{RR}\right)-n_q(t)\left(\alpha_q^{EII}+\alpha_q^{DR}+\alpha_q^{RR}\right)\right]n_e f-\left[n_q(t)\alpha_q^{cx}-n_{q+1}(t)\alpha_{q-1}^{cx}\right]n_0-\frac{n_q(t)}{\tau_{exc}}$$



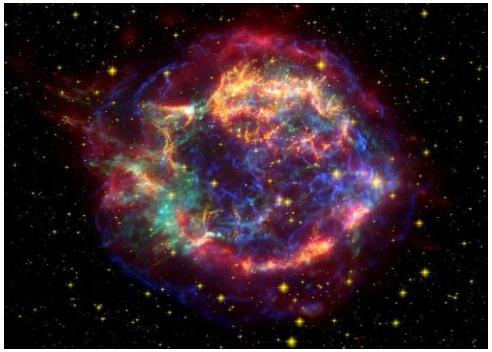
天文观测数据的解释极大地依赖于天文模型和原子数据。

但许多原子参数来自理论计算，观测与模型不符合，需要高精度定标实验数据。

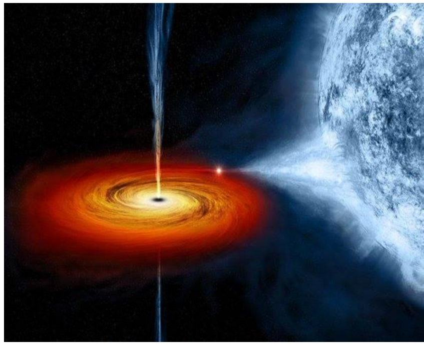
重离子加速器装置提供了最佳的实验平台

用高精度离子谱学数据揭秘天文观测


蝴蝶状星云


超新星爆发

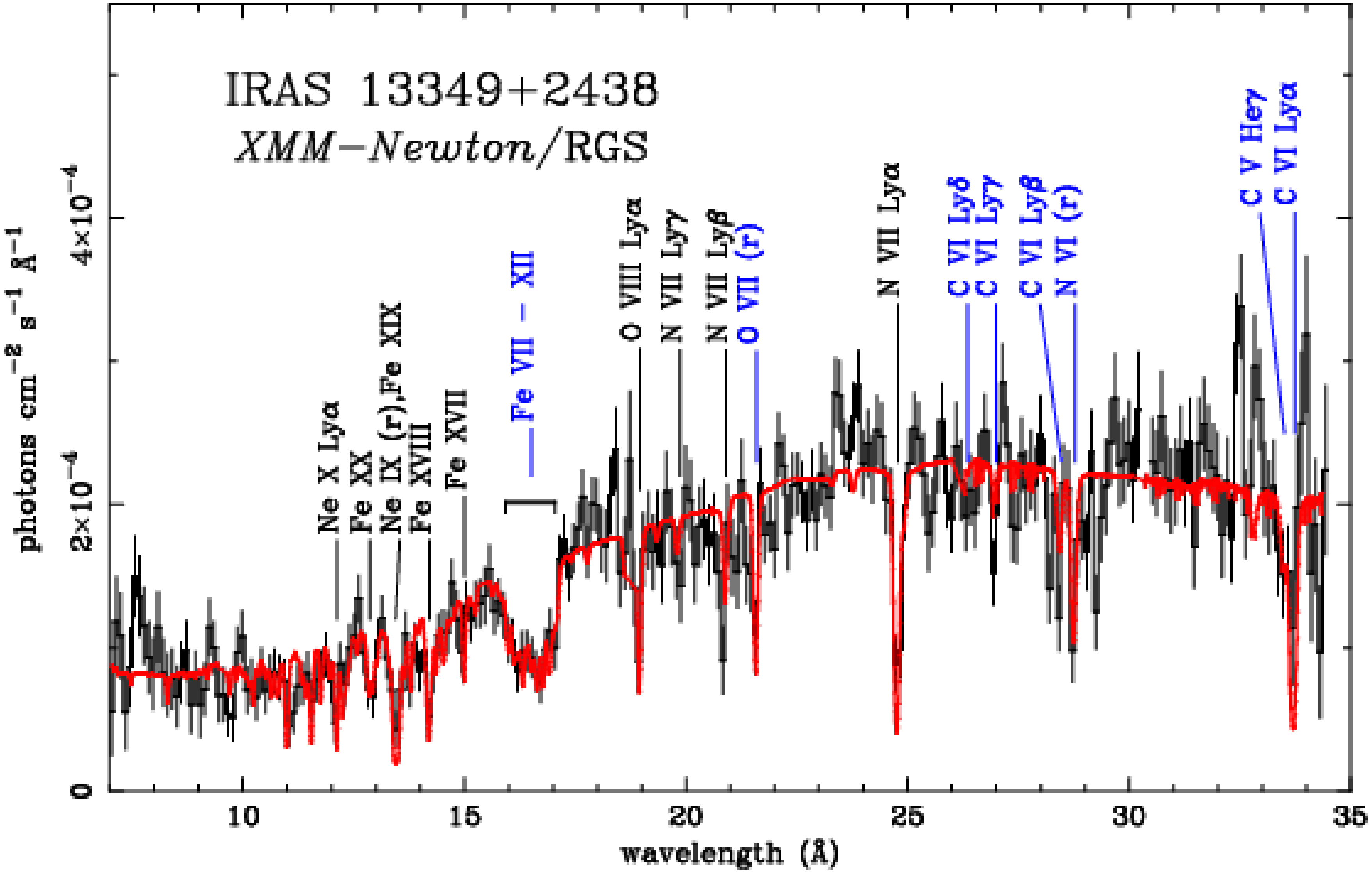

日冕


活动星系核


XMM-Newton: 0.1-12nm


Cassini: 56.3-191.2nm

XMM-Newton卫星天文台：AGN（Active Galactic Nuclei）



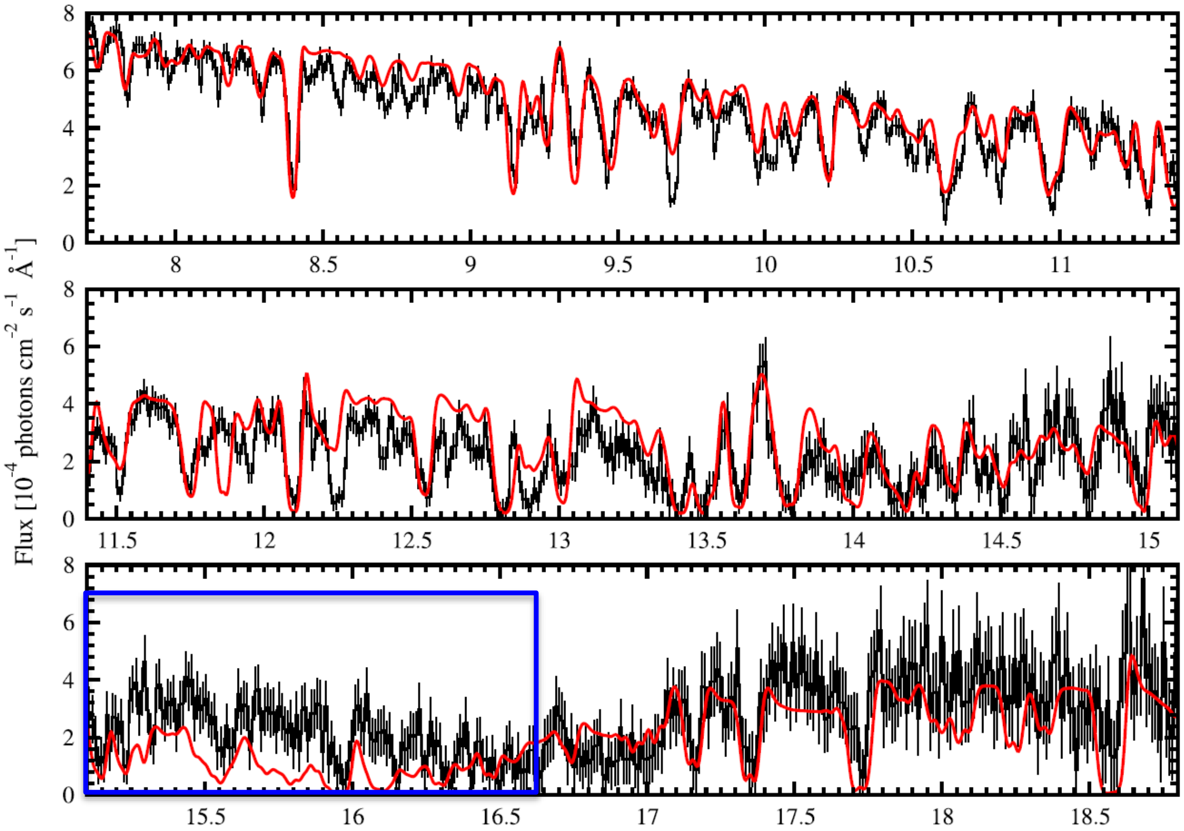
Sako et al. 2001, A&A, 365, L168

天文观测谱的解释

- 天体物理模型
- 原子分子谱学数据

  跃迁能量、谱线线型、跃迁概率、速率系数

Chandra卫星天文台观测结果：NGC 3783



蓝色方框中实验和理论模型不符是由于理论模型中使用的低能双电子复合截面太小，迫切需要精确的实验结果对理论模型进行刻度。

(Kraemeret al. 2004; Netzer 2004).

(Netzer et al. 2003, ApJ, 599, 933)

必须对DR速率系数做实验检验，储存环提供了最佳的实验平台

背景之一：天体物理的需求

宇宙元素丰度

- 宇宙元素丰度是研究元素起源的理论依据，是解释各类天体演化过程的基础
- 元素的宇宙丰度＝太阳系的元素丰度

  这里的丰度＝A/B的比值，一般B为Si
- 太阳系是由太阳、行星、行星物体(宇宙尘、彗星、小行星）组成的

  太阳的质量占太阳系总质量的99.8%，其他成员的总和仅为0.2%，所以太阳的成分是研究太阳系成分的关键。

测定方法

- **质谱分析：**天外陨石，地壳岩石，火星、月球等岩石样本；

  可以得到精度很高的元素丰度，但只能针对非挥发性的元素，挥发性元素在长时间的演化过程难以保存在岩石/陨石样本中。
- **光谱分析：**对太阳和其它星体的辐射光谱进行定性和定量分析；

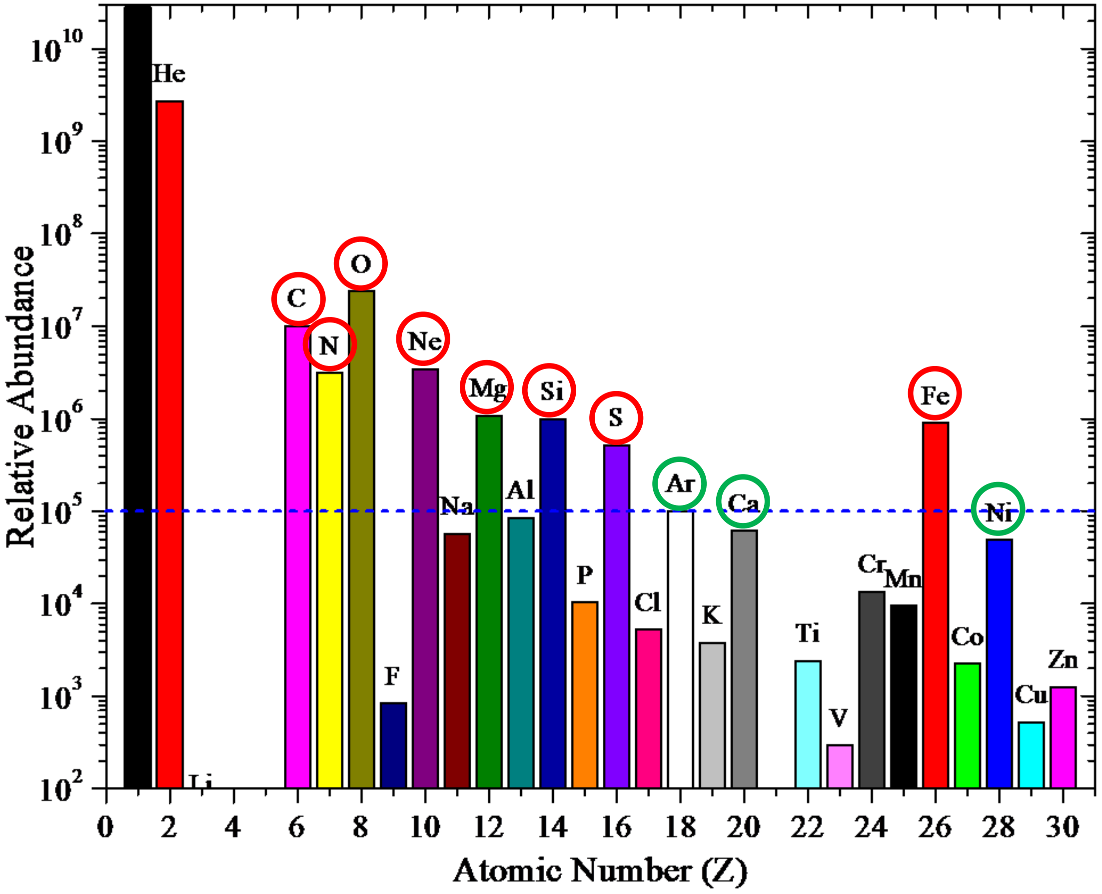
  精度往往受限于模型中所使用的原子分子数据，但可以测定几乎所有元素的丰度。

背景之一：天体物理的需求

Solar elements abundances

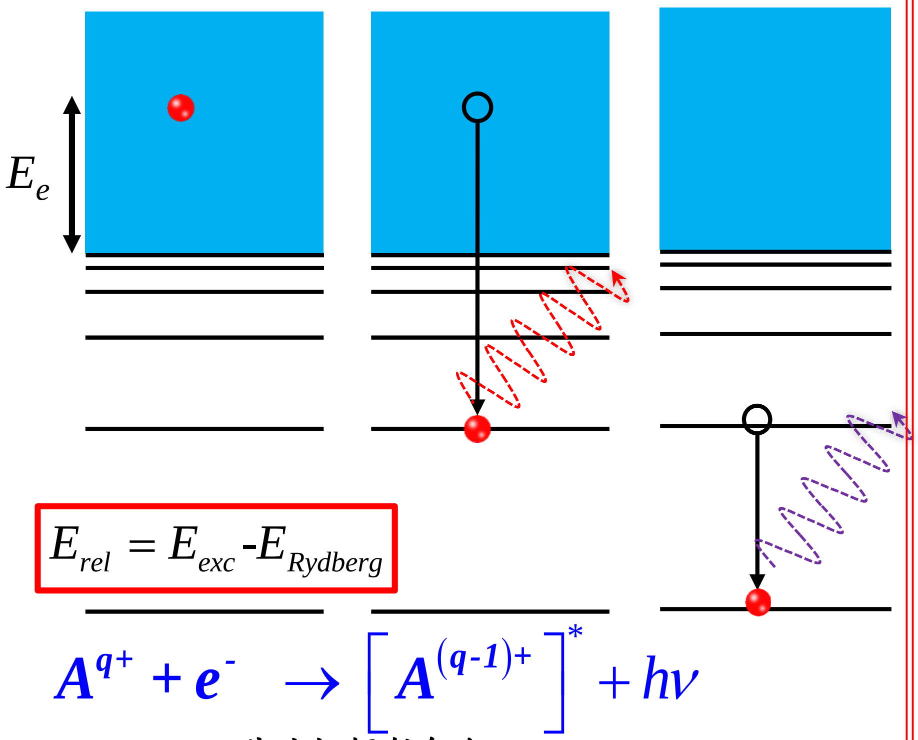
- Elements abundances in the solar system reflects the elements abundances in the whole universe;

Elements abundances in the Solar system.



E. Anders and N. Grevesse., Geochimica et Cosmochimica Acta, 53:197, (1989)

理论背景：什么是辐射复合和双电子复合？



$E_{rel} = E_{exc}$-$E_{Rydberg}$

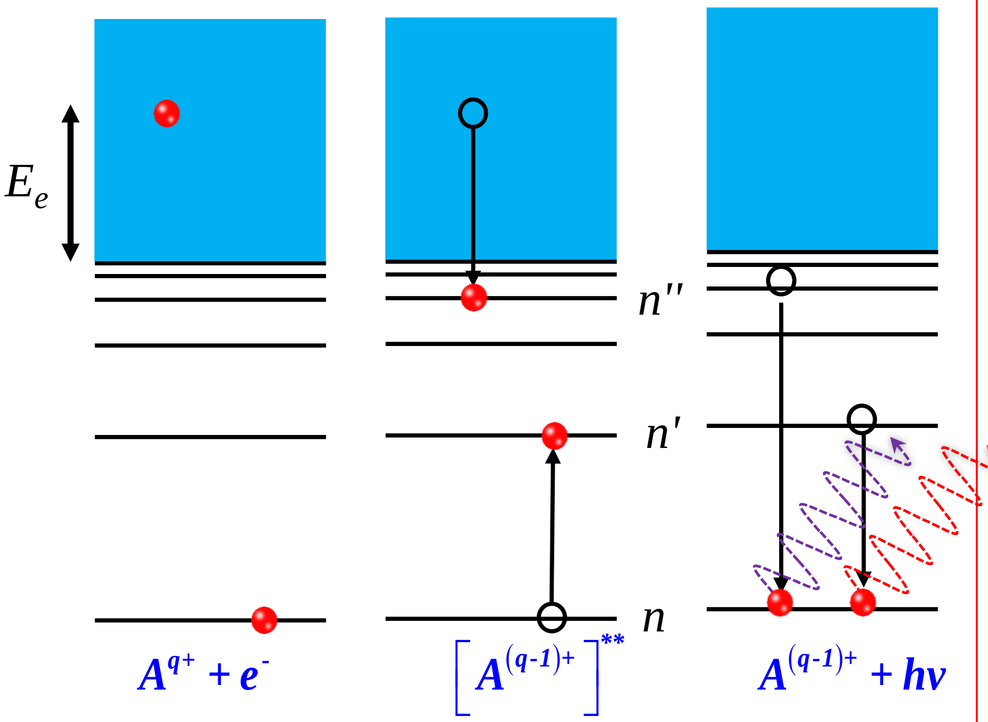
$A^{q+} + e^{-} \rightarrow \left[A^{(q-1)+}\right]^{*} + h\nu$

非共振辐射复合　　辐射稳定过程

(a) → (b) → (c)

辐射复合(RR)过程

$E_e + E_{n''} = \Delta E_{nn'}$



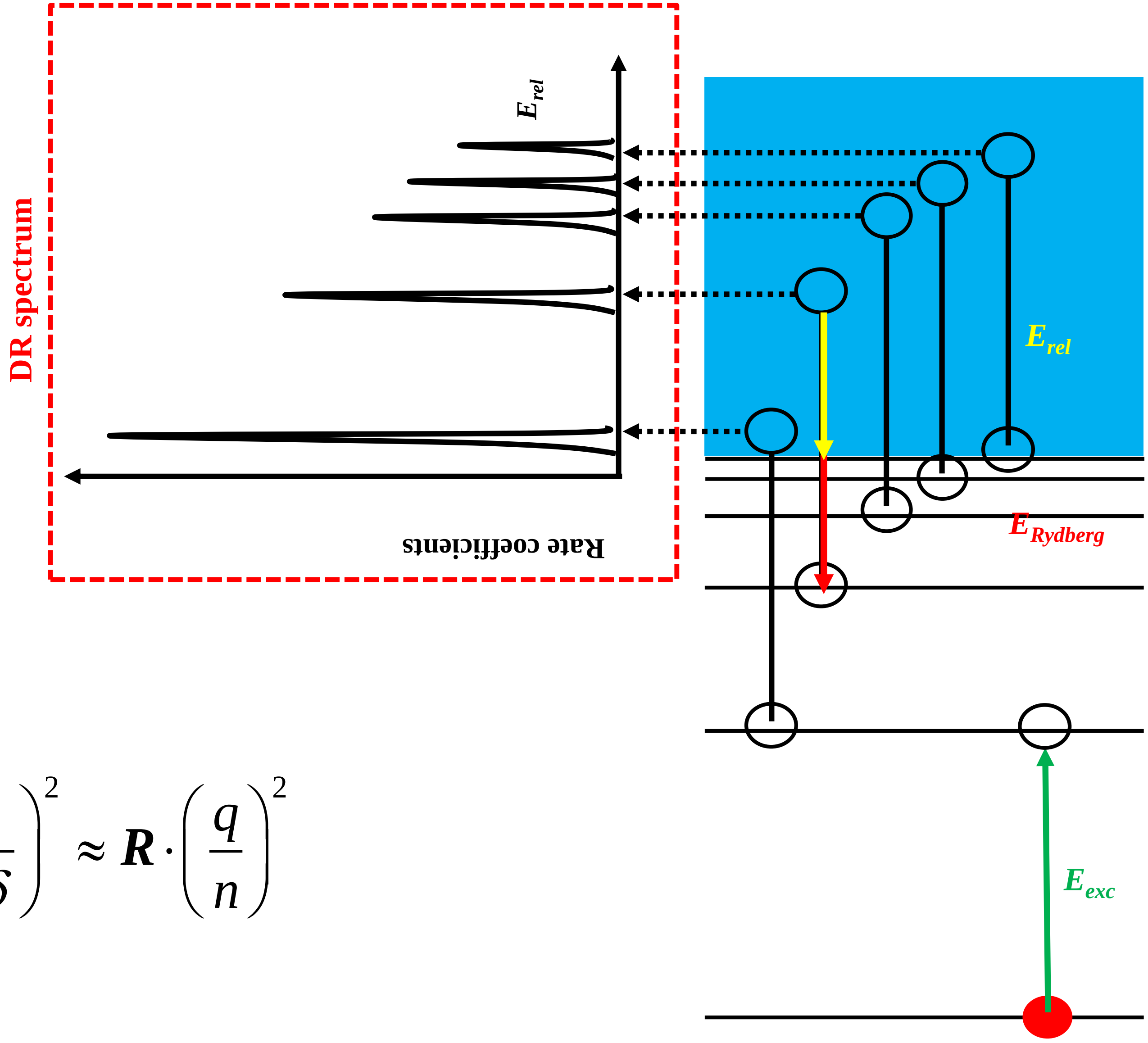
$A^{q+} + e^{-}$　　$\left[A^{(q-1)+}\right]^{**}$　　$A^{(q-1)+} + h\nu$

共振俘获过程　　辐射稳定过程

(a) → (b) → (c)

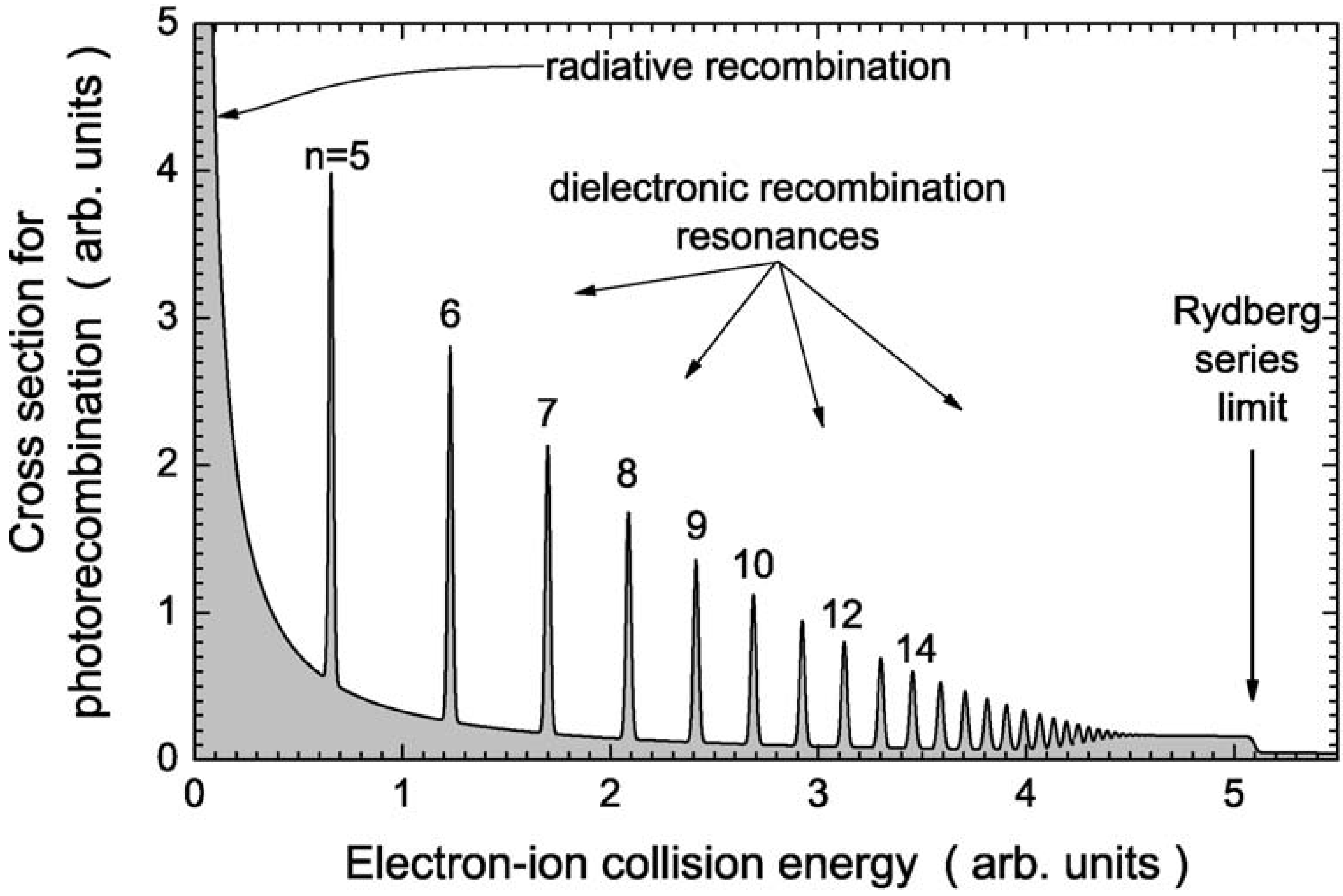
双电子复合（DR）过程

理论背景：什么是辐射复合和双电子复合？

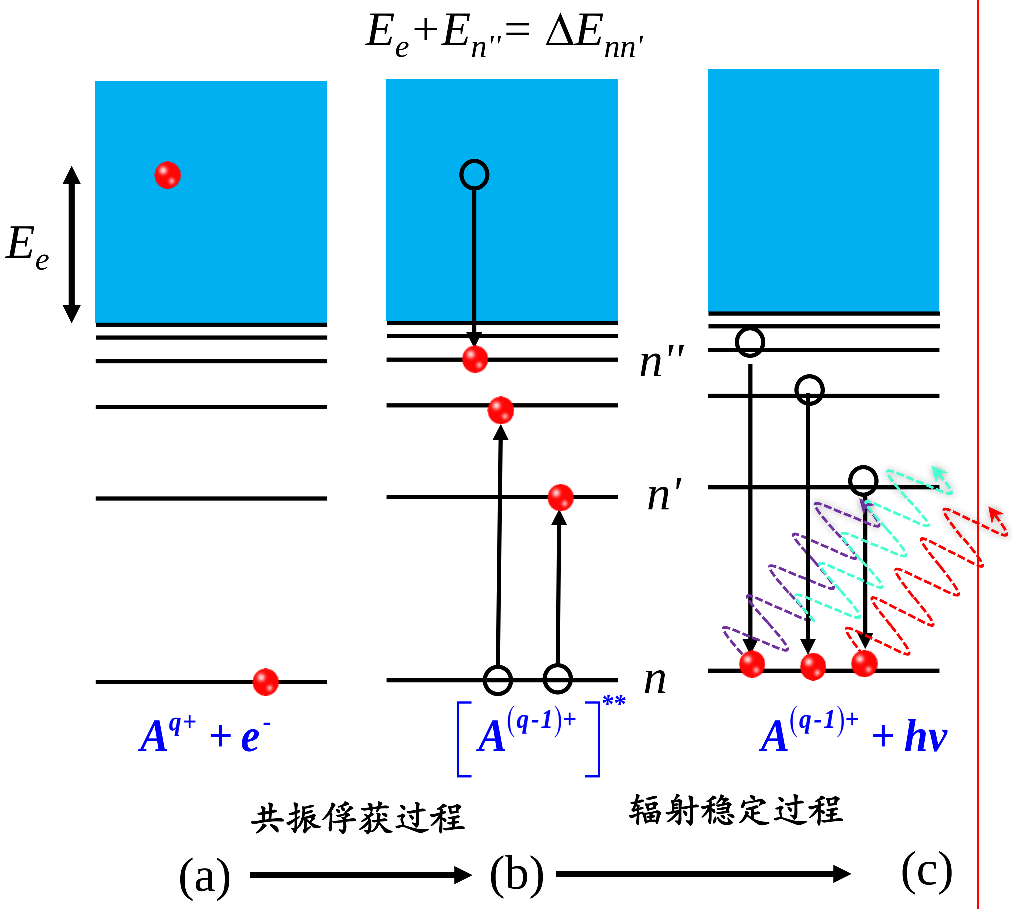


$$E_{Redberg} = \boldsymbol{R}\cdot\left(\frac{q}{n-\delta}\right)^2 \approx \boldsymbol{R}\cdot\left(\frac{q}{n}\right)^2$$

理论背景：什么是辐射复合和双电子复合？

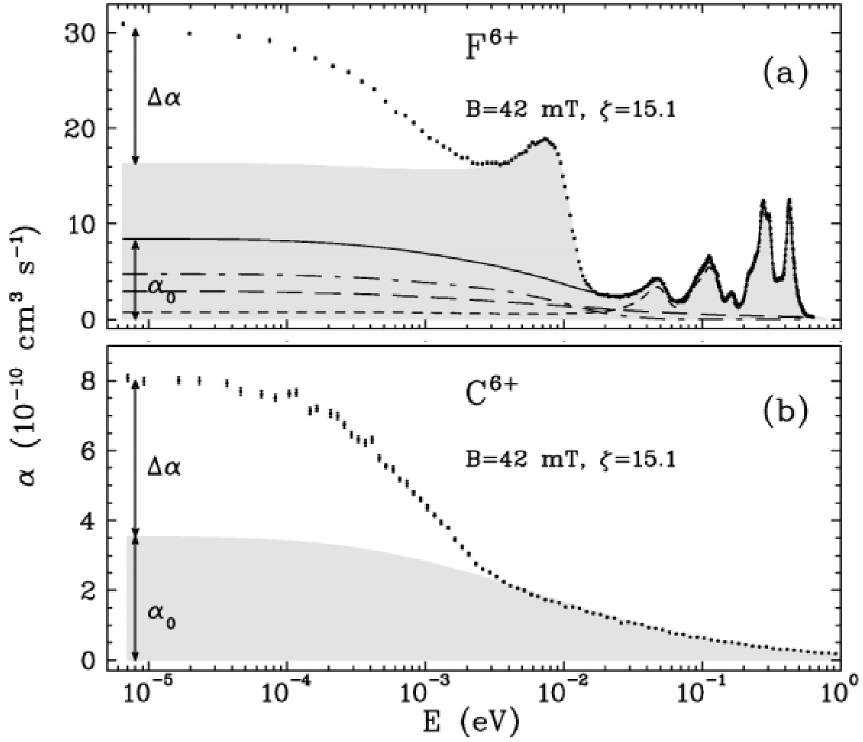


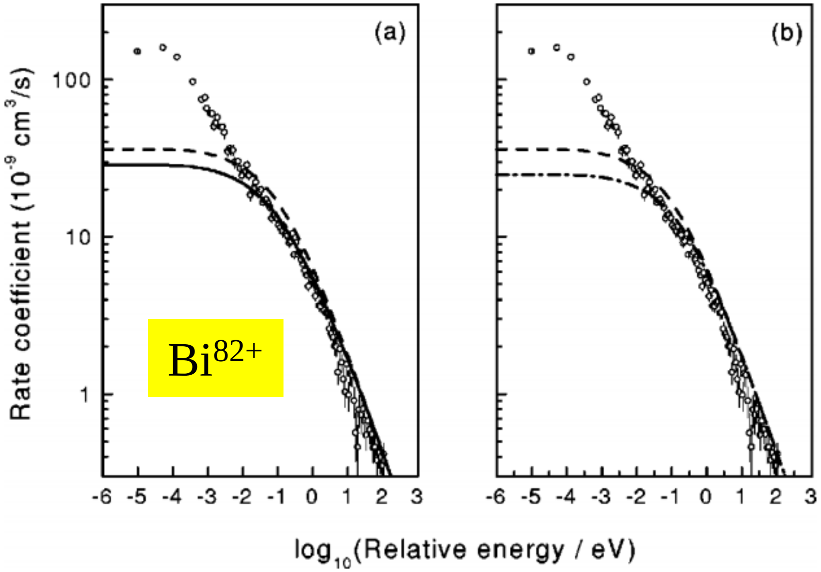
理论背景：三电子复合

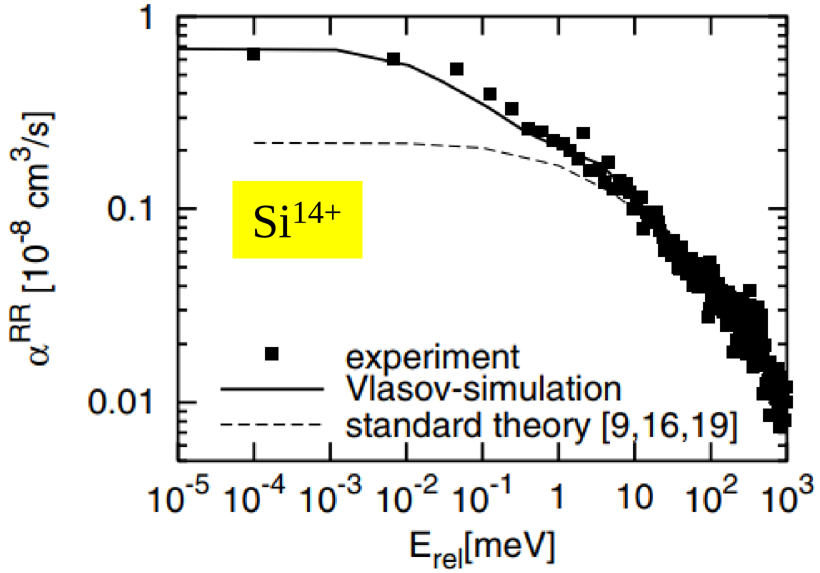


三电子复合（TR）过程

RR enhancement





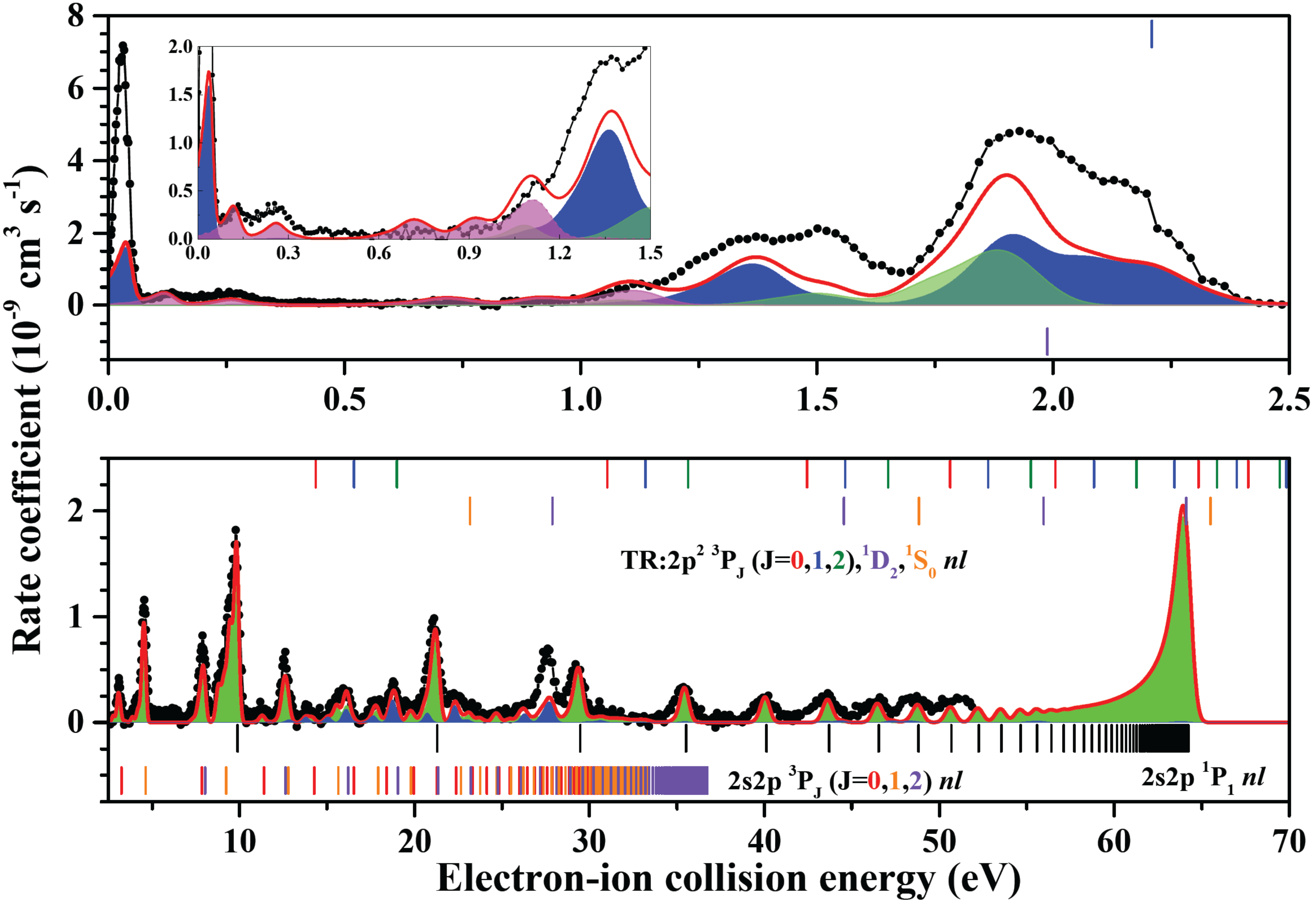


Phys. Rev. Lett. **84**, 4822 (2000)

Phys. Rev. A **63**, 012702 (2000)

Phys. Rev. Lett. **89**, 083202 (2002)

^{40}Ca^{16+}的DR精细谱学



S. X. Wang et al. Astrophys. J. 862, 134(2018)

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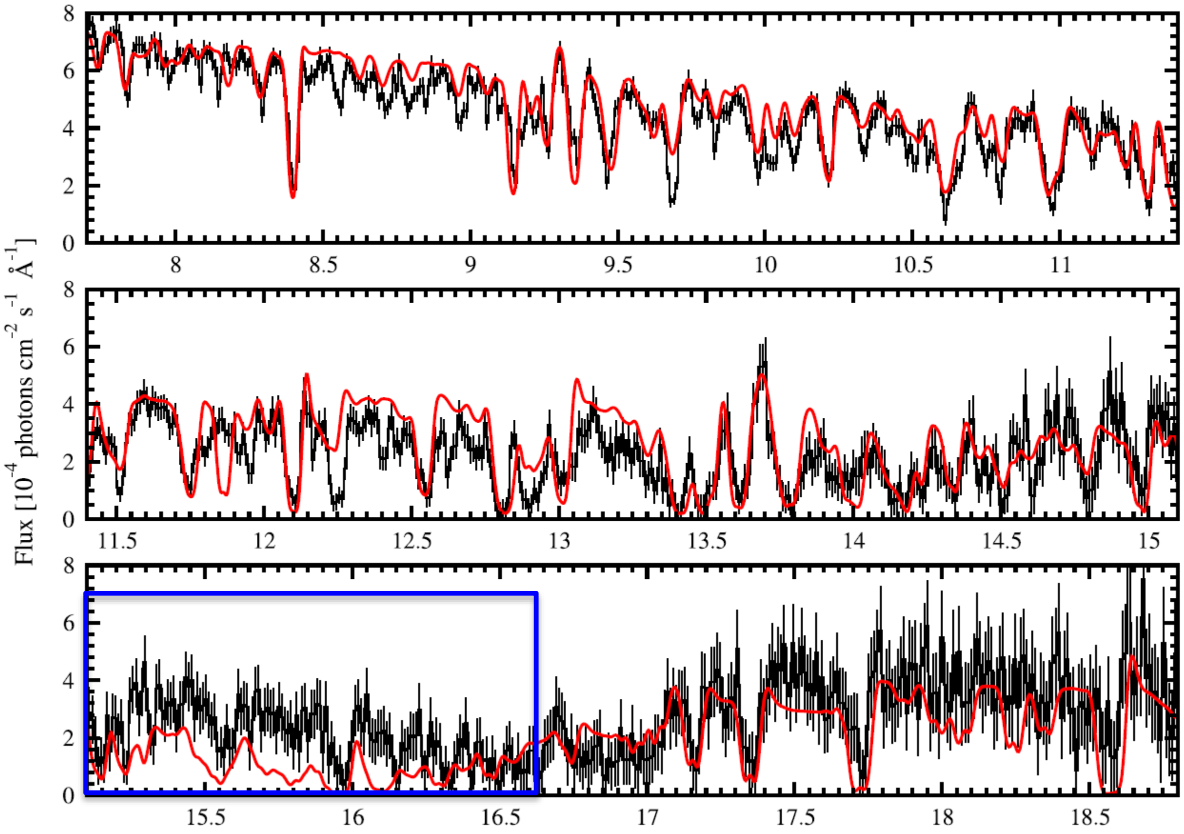

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必须对DR速率系数做实验检验，储存环提供了最佳的实验平台

天文观测谱的解释

Accurate experimental recombination rate coefficients are required to benchmark different theoretical approaches to provide more reliable recombination data for use in astrophysical modeling.

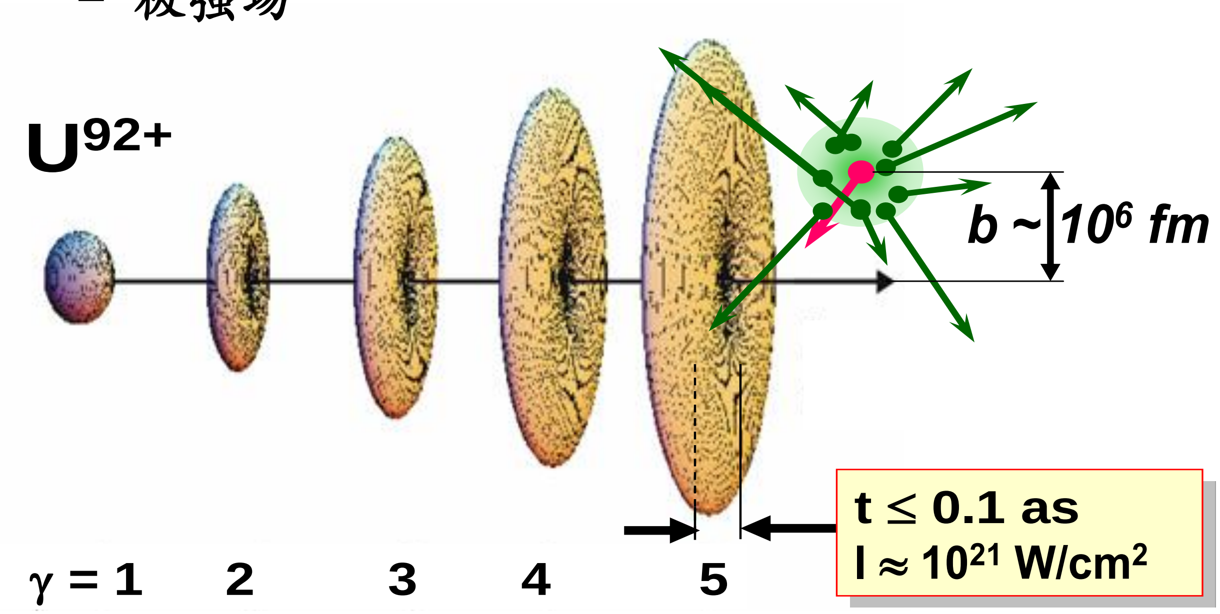
The aim of laboratory astrophysics is to reduce atomic physics uncertainties so that discrepancies between spectral observations and models tells us something about the properties of the observed sources and cannot be attributed to errors in the atomic data used in the models.

Daniel Wolf Savin (Columbia University)

背景之二：探索基本的原子分子物理特性

强场和QED物理

- 动态电磁场
  - 超快
  - 极强场



$t \leq 0.1$ as
$I \approx 10^{21}$ W/cm^2

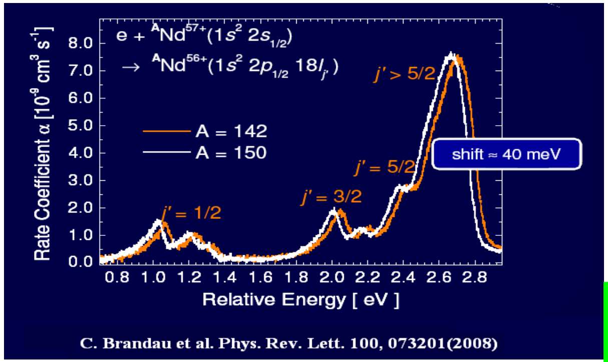
intense fields
ultra-short electromagnetic pulses
pair production

相对论重离子性质研究

A. Muller, Adv. Atom. Mol. Opt. Phys., 293, 55, 2008

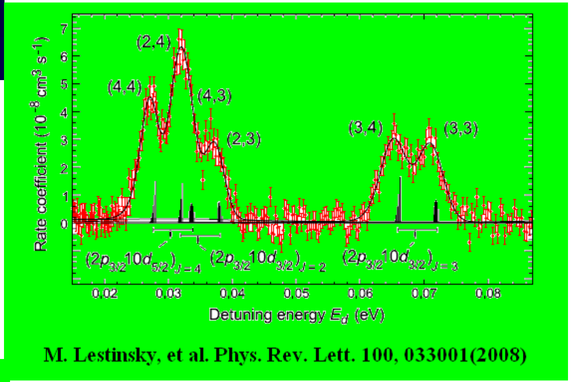
背景之二：探索基本的原子分子物理特性

- 少电子重离子体系相对论效应(Breit相互作用)，QED效应研究，比如Xe^{51+}, Au^{76+}, Pb^{79+}, Bi^{80+}, Bi^{83+}, U^{89+}, U^{90+}
- 稳定核素的同位素位移，超精细结构劈裂研究

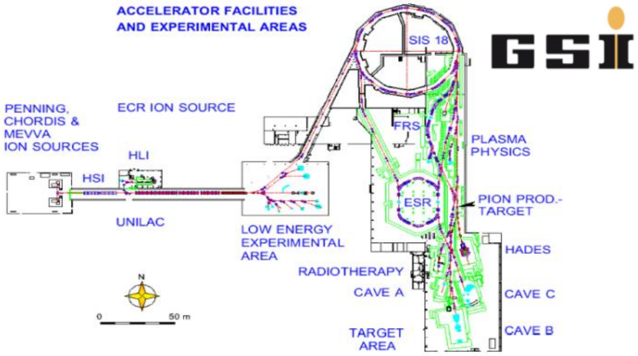


C. Brandau et al. Phys. Rev. Lett. 100, 073201(2008)

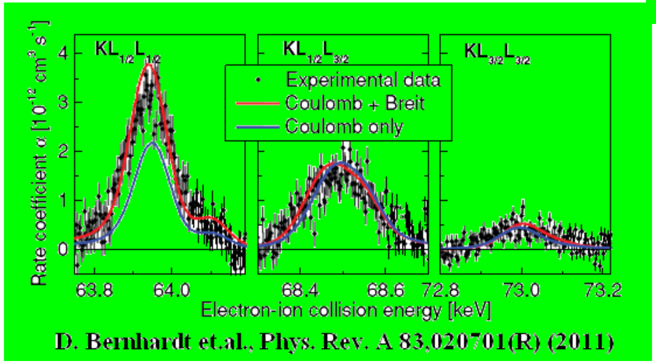
类锂钕离子DR中的同位素位移@GSI



M. Lestinsky, et al. Phys. Rev. Lett. 100, 033001(2008)

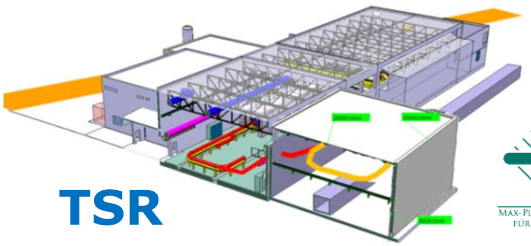


类锂钪离子DR中的超精细结构劈裂@TSR



D. Bernhardt et.al., Phys. Rev. A 83,020701(R) (2011)

类氢铀离子Breit相互作用@GSI



TSR

C. Brandau et al., Phys. Rev. Lett., 100, 073201 (2008)
M. Lestinsky et al., Phys. Rev. Lett., 100, 033001 (2008)
D. Bernhardt et al., Phys. Rev. A, 83, 020701(R) (2011)

离子的动力学参数：辐射复合和双电子复合

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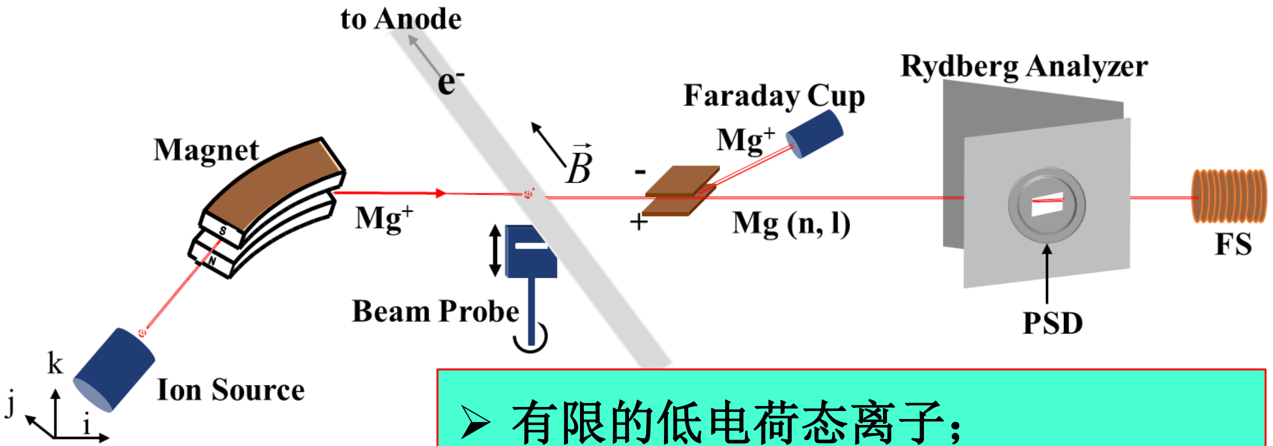
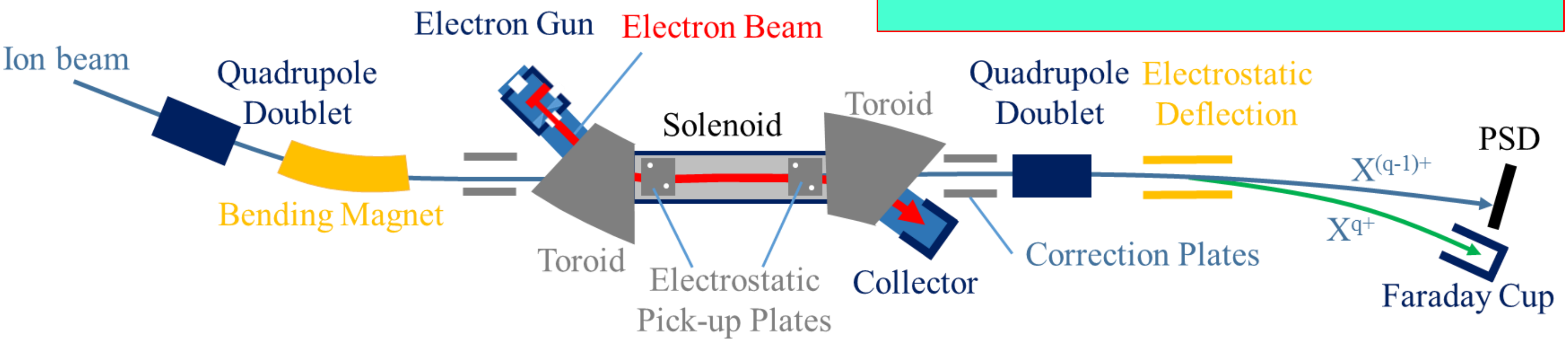
交叉束和合并束（融合束）

- ○ 等离子体技术（60年代）
- ○ 电子束离子阱（70年代）
- ○ 准自由电子（60年代）
- ○ 碰撞束技术
  - ◎交叉束（80年代）
  - ◎合并束（80年代）



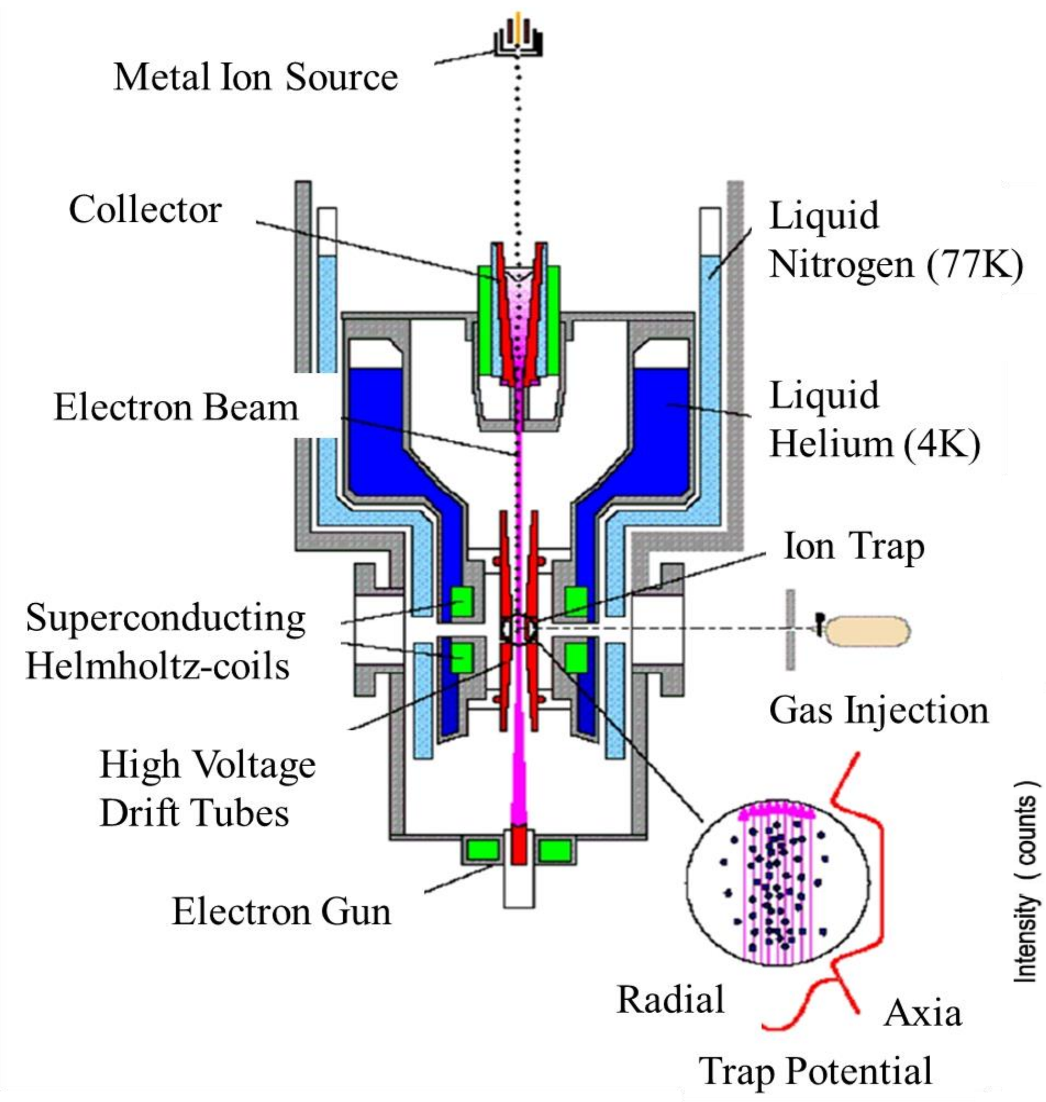
A. Müll

- ➢ 有限的低电荷态离子；
- ➢ 电子束和离子束的空间密度都很低；
- ➢ 电子束与离子束的作用体积非常小；
- ➢ 最低的E_{rel}近似为 $\frac{m_e}{2}(v_{ion}^2+v_e^2)$；



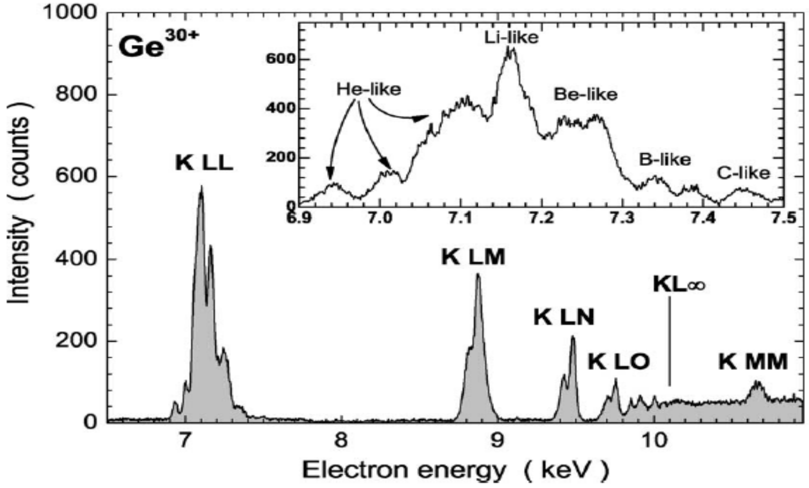
L.H. Andersen *et al.*, *Phys. Rev. Lett.* **63** 2656 (1989)

电子束离子阱（EBIT）



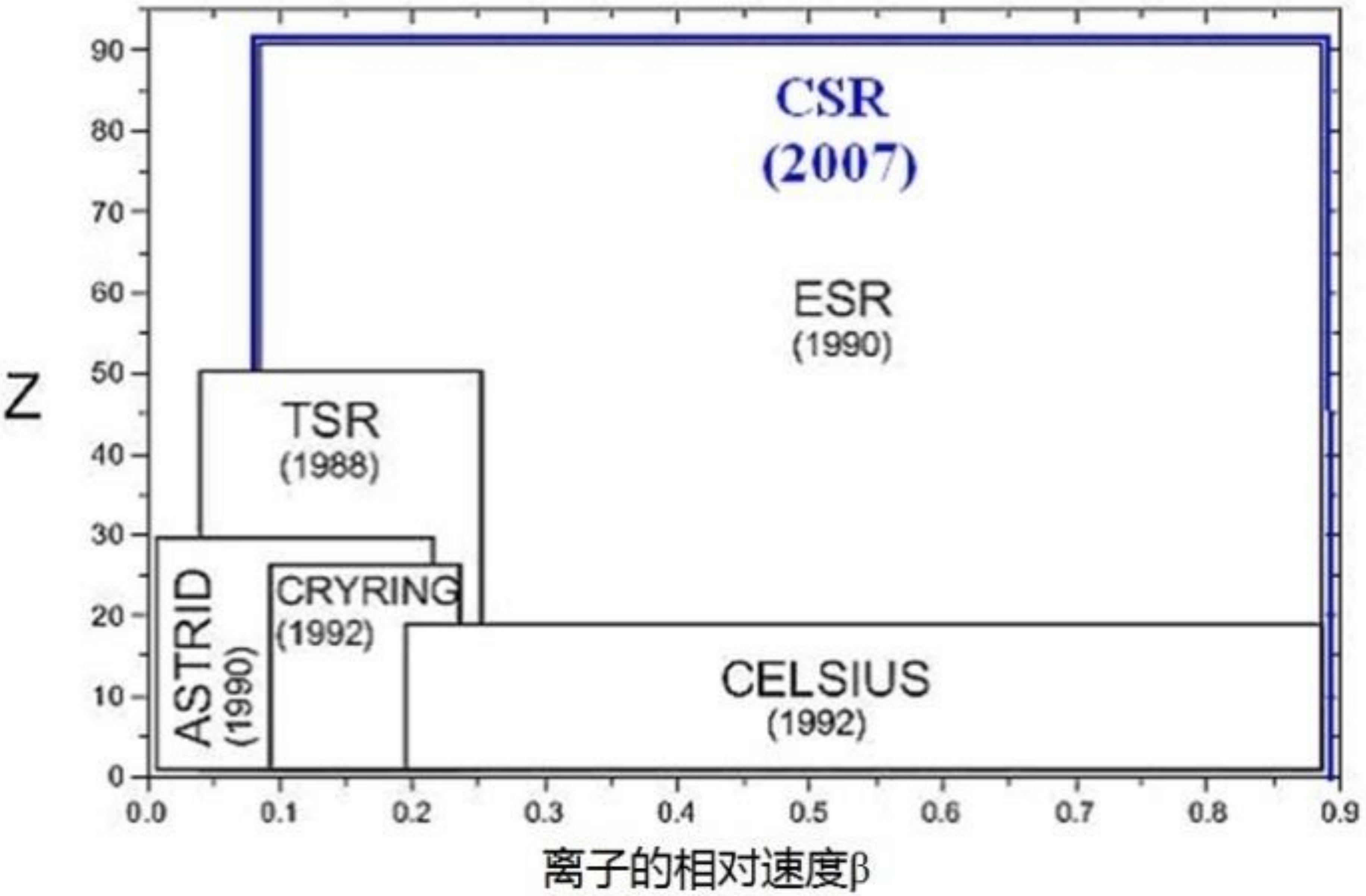
上海复旦大学EBIT实验装置示意图

- **EBIT的电子束能量约为50eV~100 keV**
- 电子束典型的能量分辨为**50 eV,**相对能量分散**ΔE/E** 可以做到10^{-3}
- 探测电子离子碰撞过程中发出的光子；
- 通过视窗对**x-ray**进行探测，无法直接获得绝对速率系数；
- 无法保证离子种类的纯净，所测得的结果需要结合理论进行分拆；
- 与交叉束类似，最低能达到的相对碰撞能量有限制；

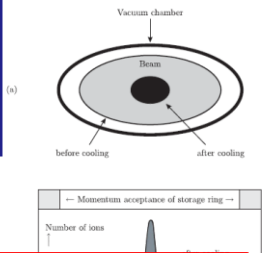


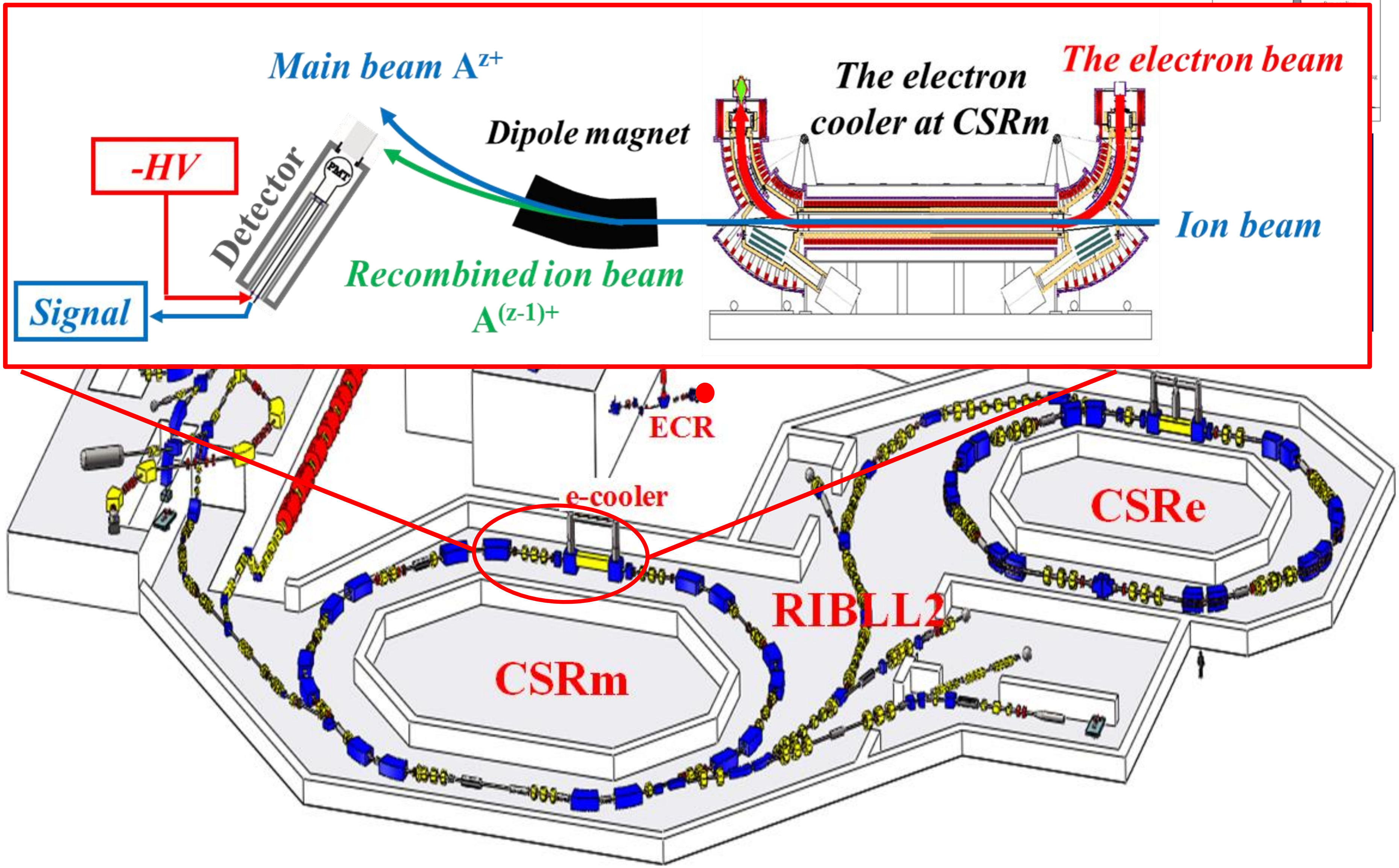
A. Muller, Adv. Atom. Mol. Opt. Phys., 293, 55, 2008
http://www.mpi-hd.mpg.de/ullrich/EBIT/

重离子冷却储存环


CSR
(2007)
ESR
(1990)
TSR
(1988)
ASTRID
(1990)
CRYRING
(1992)
CELSIUS
(1992)
Z
0
10
20
30
40
50
60
70
80
90
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
离子的相对速度β

实验装置

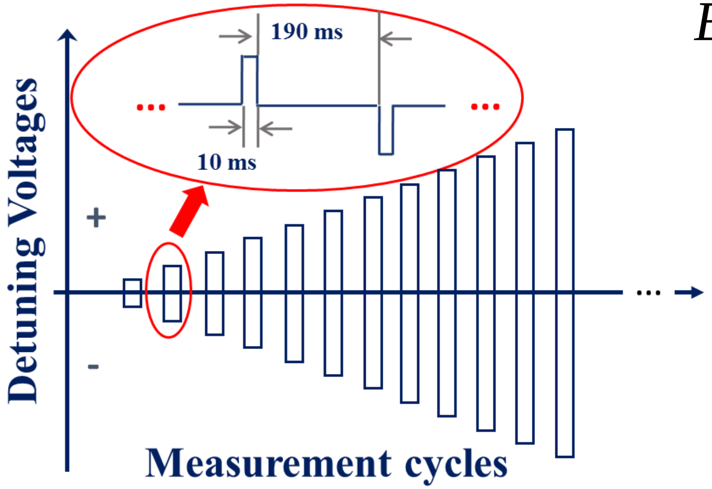

Vacuum chamber
Beam
(a)
before cooling
after cooling
← Momentum acceptance of storage ring →
Number of ions


Main beam A^{z+}
-HV
Detector
PMT
Signal
Dipole magnet
Recombined ion beam $A^{(z-1)+}$
The electron cooler at CSRm
The electron beam
Ion beam
ECR
e-cooler
CSRe
RIBLL2
CSRm

储存环双电子复合实验的优势

- 环内极高真空，保证了实验的低本底；
- 离子在环内高速运动与电子束多次作用保证了高效率；
- 可以在很大范围内精确调制碰撞能量；
- 电子束温度极低保证了实验的高分辨；
- 环内单一离子进行研究，保证所测谱的纯净；
- 可以对复合离子进行完全计数得到绝对速率系数；

实验方法



$$E_{rel} = \sqrt{m_e^2c^4 + m_{ion}^2c^4 + 2m_em_{ion}\gamma_e\gamma_{ion}c^4(1-\beta_e\beta_{ion}\cos\theta)} - m_ec^2 - m_{ion}c^2$$

Cooling

$$\gamma_e = \gamma_i$$

Detuning

$$\gamma_e = 1 + \frac{E_{e-0} + \Delta E_e}{m_ec^2} = \gamma_i + \frac{\Delta E_e}{m_ec^2}$$

Detuning+ modified term

$$\alpha(E_{rel}) = \frac{R}{N_in_e(1-\beta_e\beta_i)}\frac{C}{L}$$

$$= qe^2c^2\pi r_e^2 \cdot \frac{\beta_e\beta_i}{1-\beta_e\beta} \cdot \frac{RL}{I_{ion}I_e}$$

R : ***counts of recombined ions***

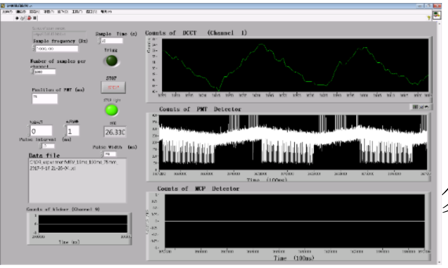
N_i : ***strored ions in storage ring***

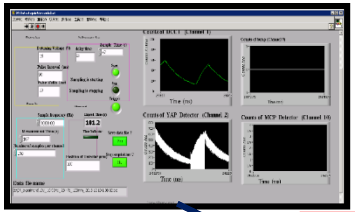
n_e : ***electron beam density***

L : ***effective interaction length***

C: ***the circumstance of CSRm***

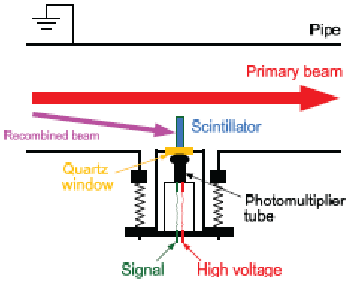
实验方法

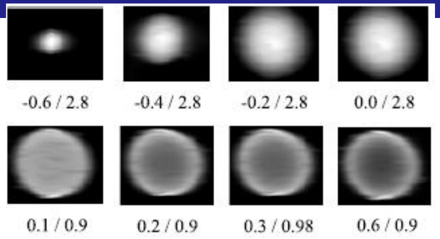




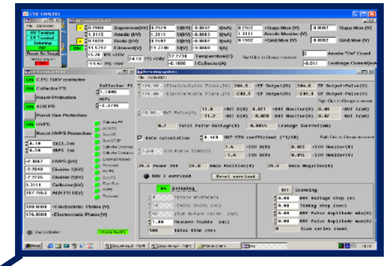
实验DAQ程序LabVIEW界面

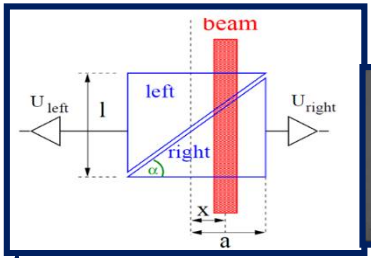
复合离子探测器



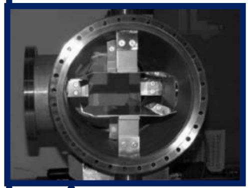


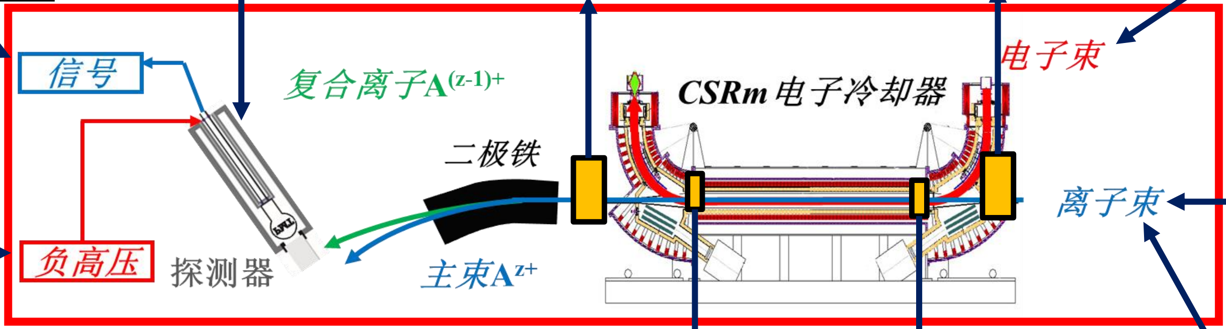
电子冷却与detuning系统





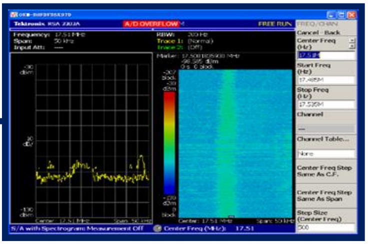
离子BPM



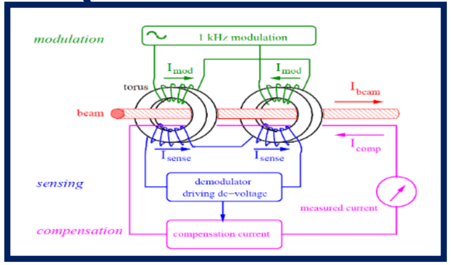


前端电子学系统

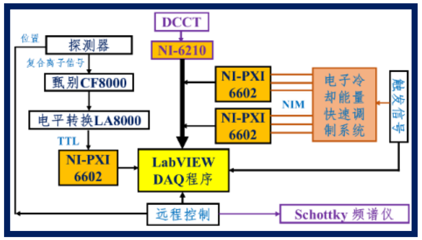
Schottky频谱系统



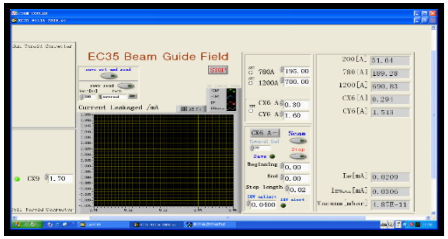
DCCT流强在线监测

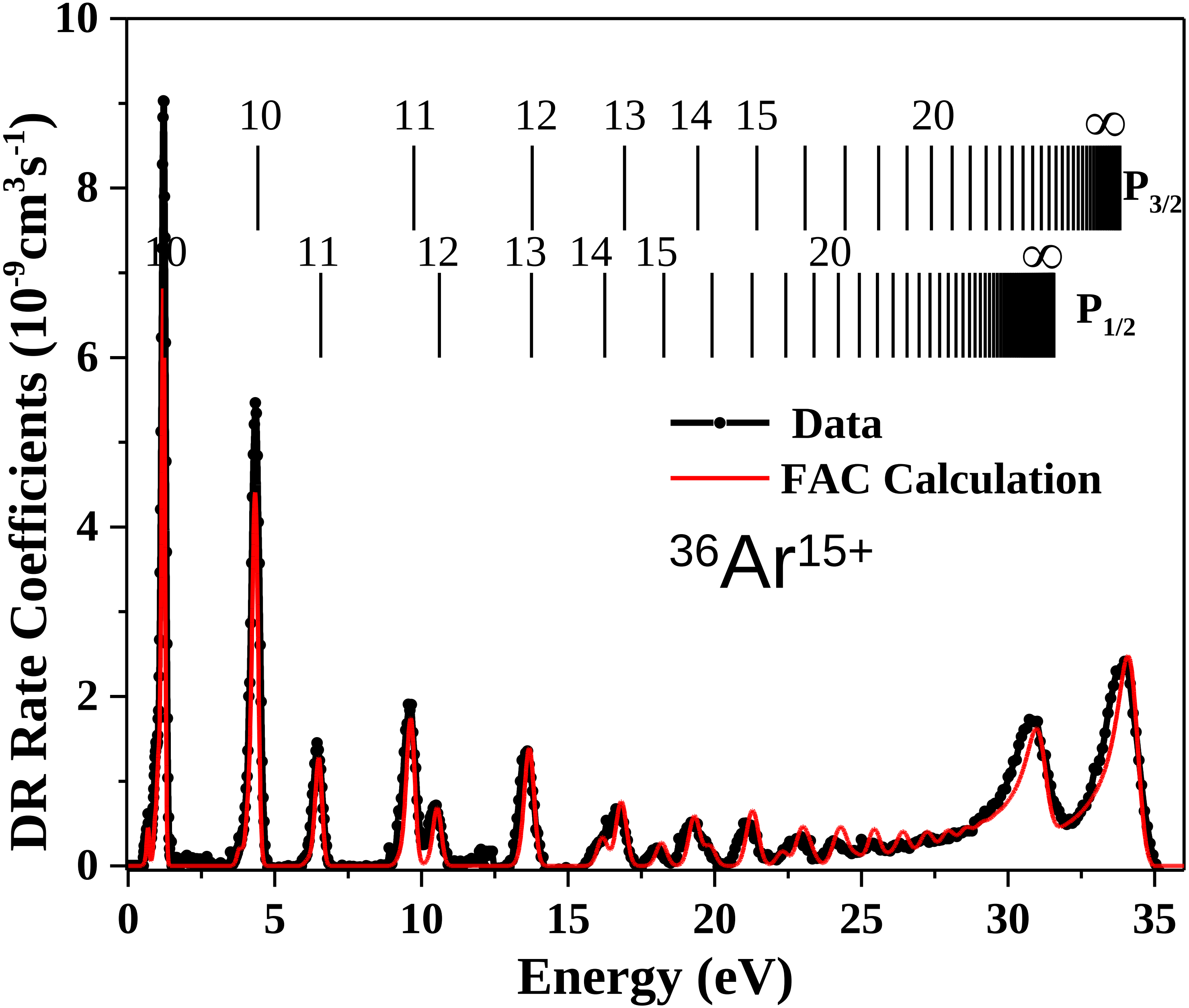


数据获取系统架构



电子BPM与磁场控制系统



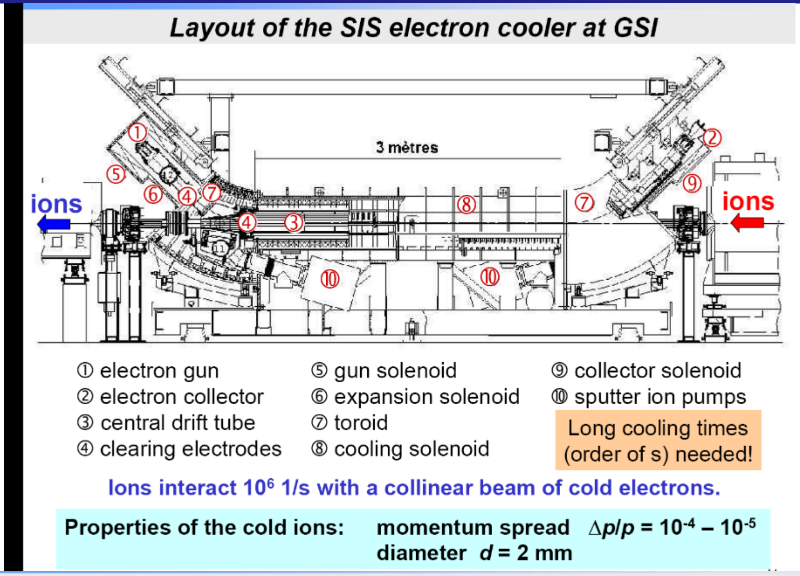


Z.K.Huang et al. Phys. Scr. T166 (2015) 014023

离子的动力学参数：辐射复合和双电子复合

- 背景
- 研究方法
- **现状**
- 展望

I、技术发展



Layout of the SIS electron cooler at GSI

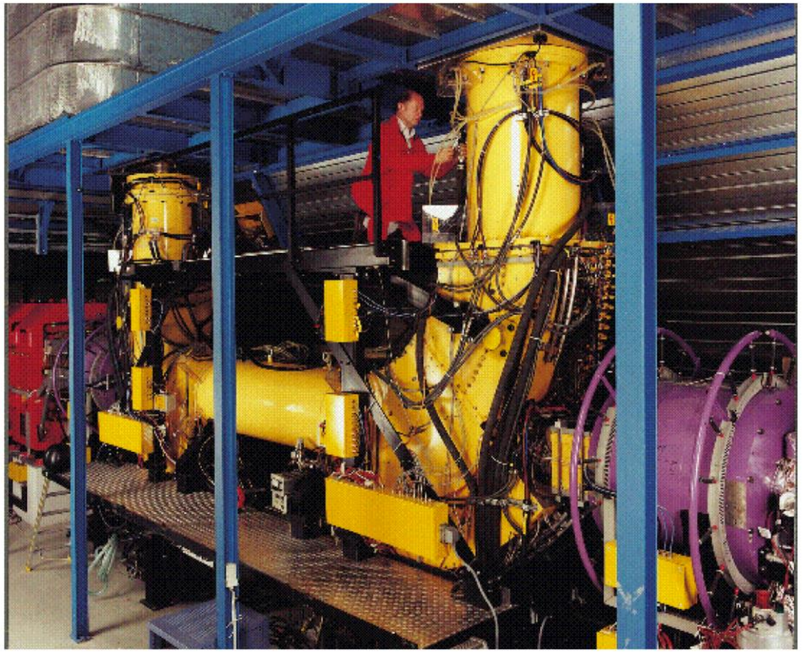
① electron gun
② electron collector
③ central drift tube
④ clearing electrodes
⑤ gun solenoid
⑥ expansion solenoid
⑦ toroid
⑧ cooling solenoid
⑨ collector solenoid
⑩ sputter ion pumps

Long cooling times (order of s) needed!

Ions interact 10^6 1/s with a collinear beam of cold electrons.

Properties of the cold ions: momentum spread $\Delta p/p = 10^{-4} - 10^{-5}$ diameter $d = 2$ mm

The SIS electron cooler at GSI



电子束冷却

- 电子束纵向加速冷却

  电子刚刚离开阴极时，其能量分散为**0.1eV**，其速度分散为**1.88×10⁵m/s**。加速到与冷却离子速度相同的电子能量为**5keV**，其速度分散减至**419m/s**。离子静止坐标下电子能量分散为**5×10^{-7}eV**，对应的电子纵向的温度为**5×10^{-4}meV/k**。

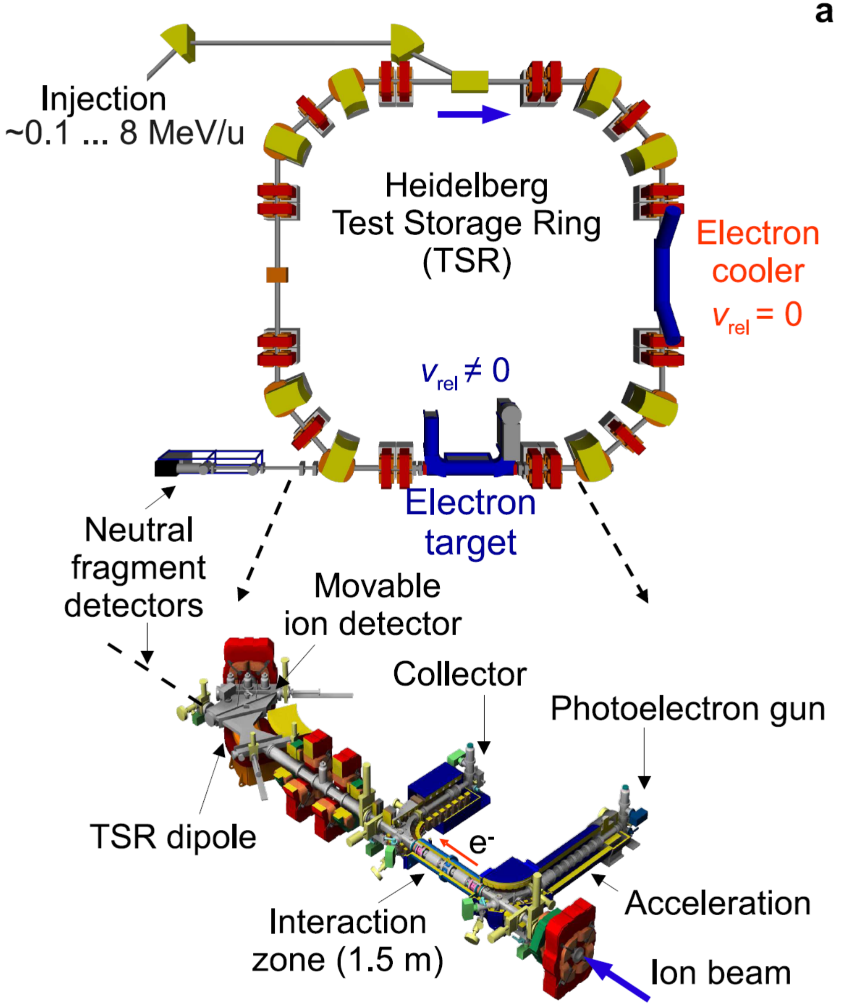
- 横向绝热膨胀冷却

  两维情况，电子束的温度降低和磁场的强度成反比

  在**CRYRING**离子冷却储存环上，其电子枪处的磁场强度为**0.3T**，但是其冷却段的磁场强度为**0.03T**，这样将放大**10**倍的面积，可以把电子束的横向温度**0.1eV**冷却到**0.01eV**。

- 目前的进展是把电子枪处的线圈用超导线圈代替，可以提高磁场的强度到**3T**，进而冷却电子束的横向温度到**0.001eV**。

I、技术发展

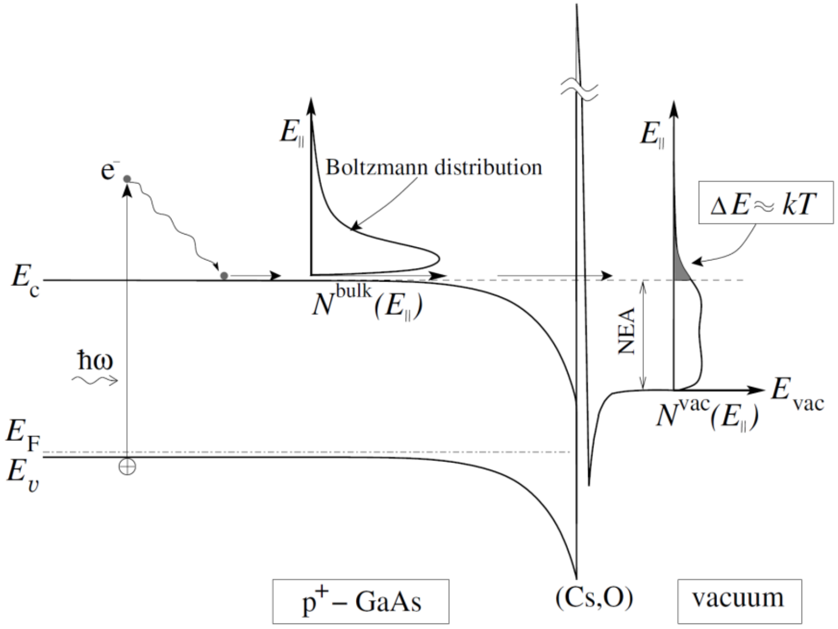


TSR的重离子冷却储存环及双电子冷却器

光阴极电子枪

- 双电子冷却器
- 光阴极电子枪

GaAs半导体作为阴极，表面覆盖了一层**Cs**和**O**，采用液氮冷却阴极材料。当用红外激光照射阴极时，电子通过**Cs**和**O**的偶极层向真空发射电子。电子纵向温度**22μeV**，横向温度**0.5meV**



II、物理成果：F-like ^{56}Fe^{17+}

D. W. Savin et al., Astrophys. J. 489,L115(1997)

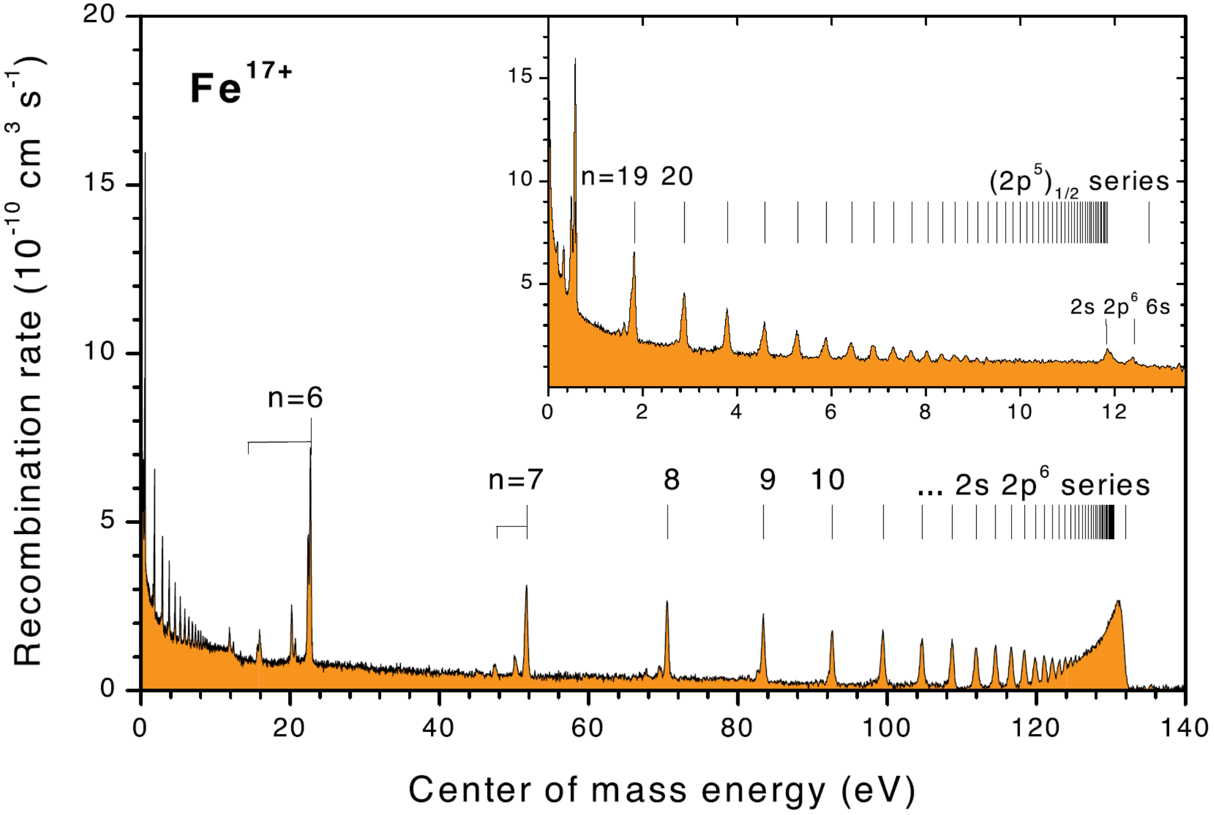


Figure 15. Recombination rate coefficients of Fe^{17+} ions measured [103] at the TSR in Heidelberg.

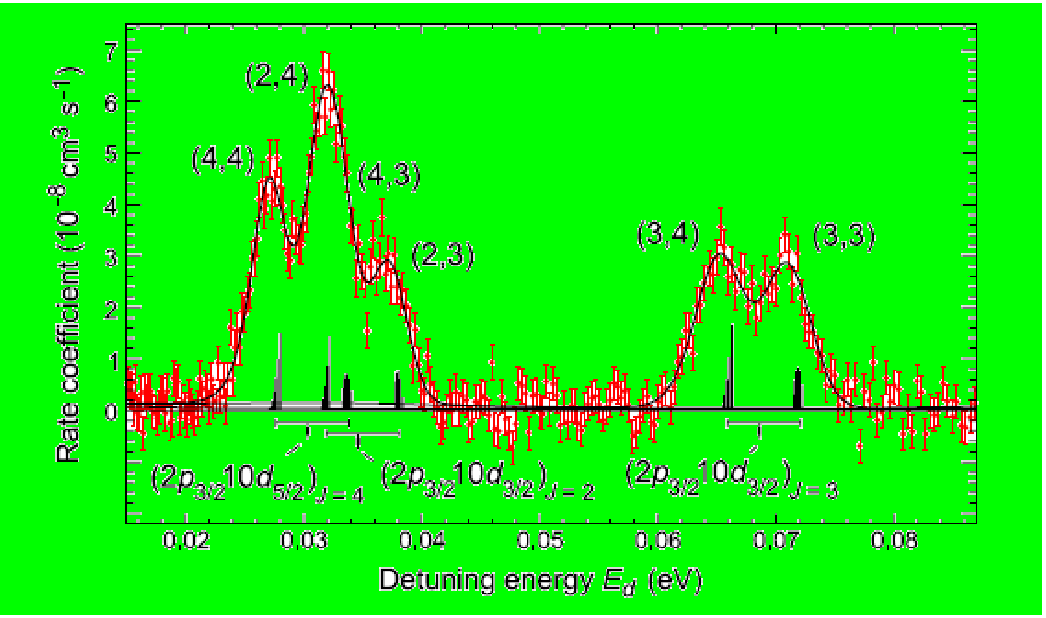
$$1s^2 2s^2 2p^5 (^2P_{3/2}) + e^- \rightarrow 1s^2 2s^2 2p^5 (^2P_{1/2}) nl$$

$$1s^2 2s^2 2p^5 (^2P_{3/2}) \rightarrow 1s^2 2s^2 2p^5 (^2P_{1/2})$$

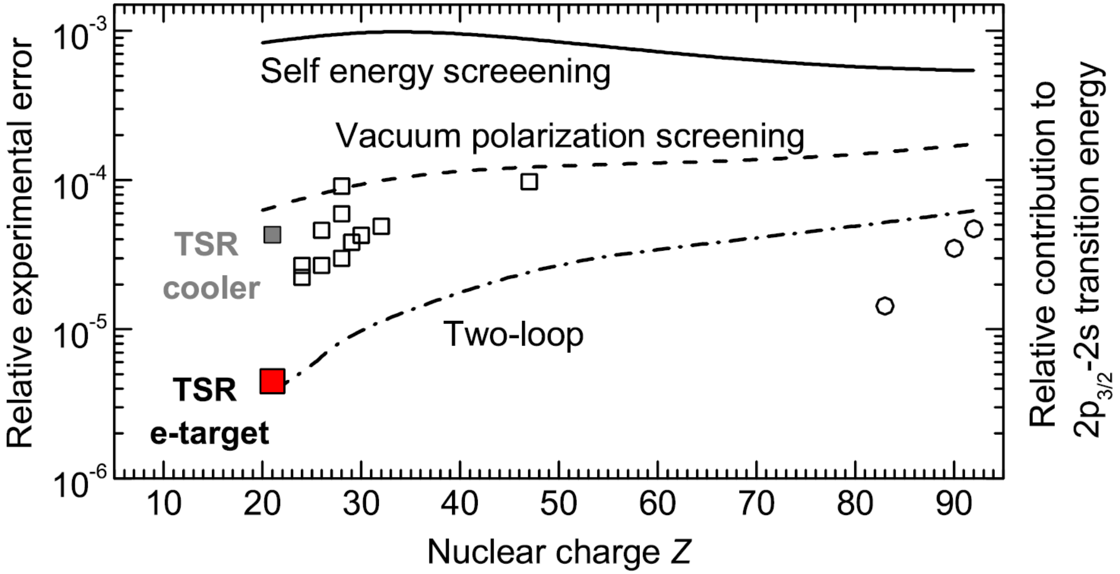
$$1s^2 2s^2 2p^5 (^2P_{3/2}) + e^- \rightarrow 1s^2 2s^1 2p^6 (^2S_{1/2}) nl$$

II、物理成果：超精细结构劈裂

M. Lestinsky et al., Phys. Rev. Lett. 100,033001(2008)



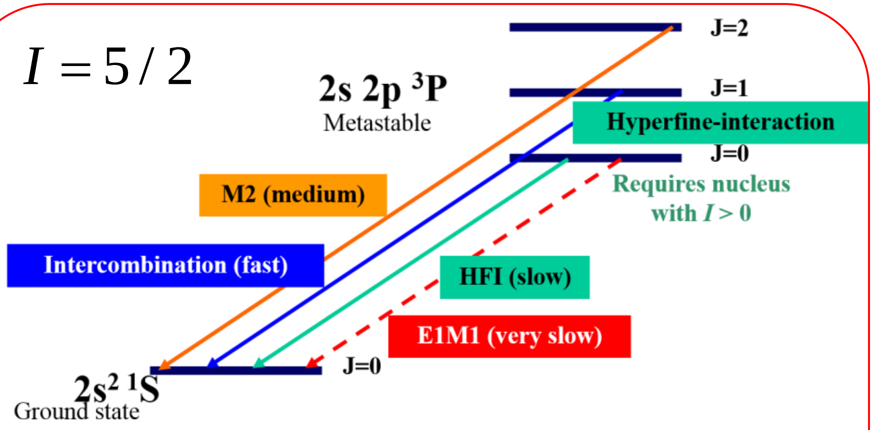
类锂钪离子DR中的超精细结构劈裂@TSR



II、物理成果：超精细诱导自发辐射

S. Schippers et al., Phys. Rev. Lett. 98, 033001(2007)

$I = 5/2$

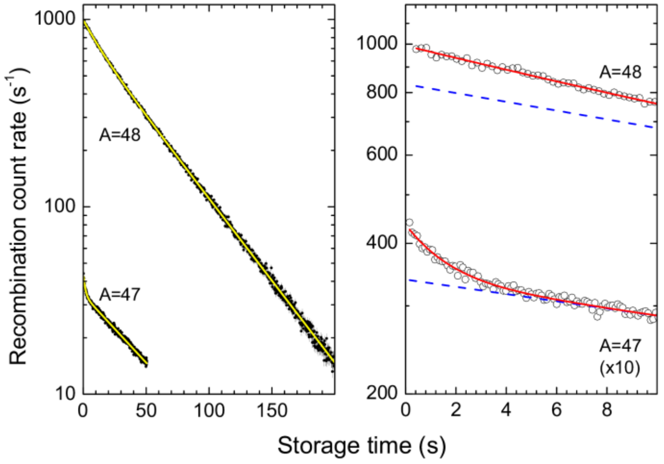


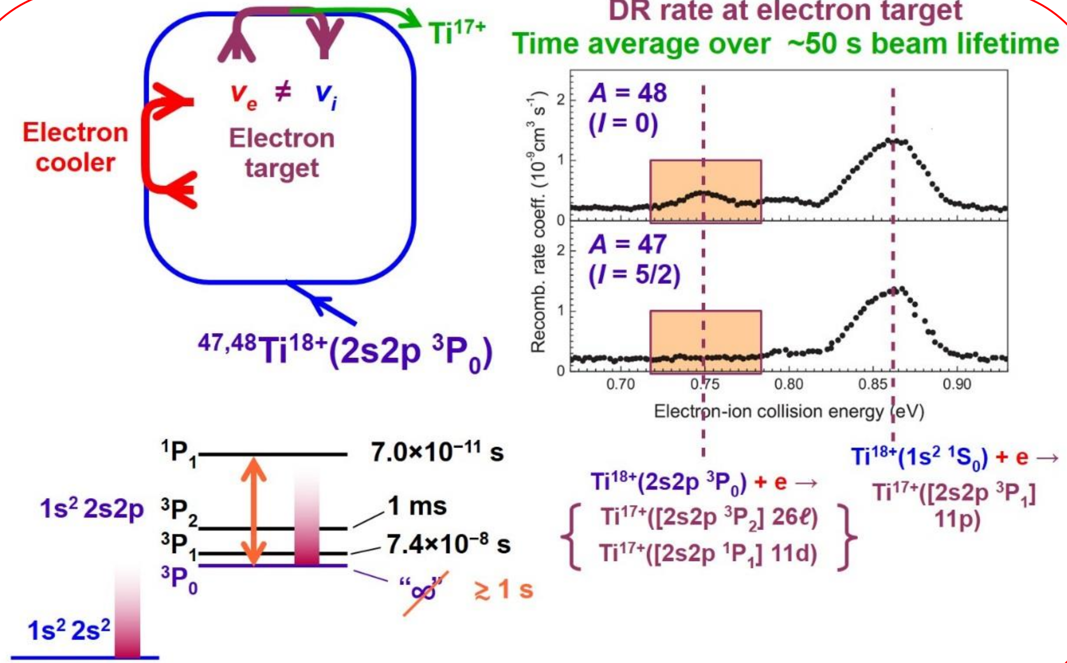
$^{47}\mathrm{Ti}^{18+}$: $A_{HFI} = 0.56(3)\ \mathrm{s}^{-1}$

超精细诱导自发辐射系数@TSR

$$A_{HFI}^{\mathrm{exp}} = 0.56(3) s^{-1}$$

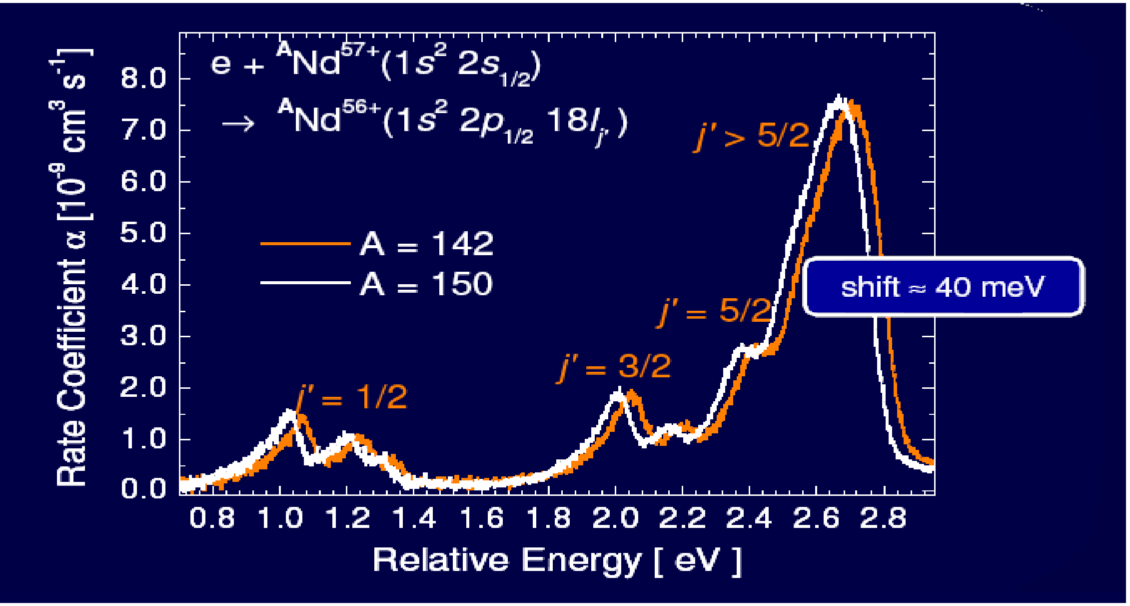
$$A_{HFI}^{\mathrm{theo}} = 0.3556 s^{-1}$$





II、物理成果：同位素位移

C. Brandau et al., Phys. Rev. Lett. 100, 073201(2008)



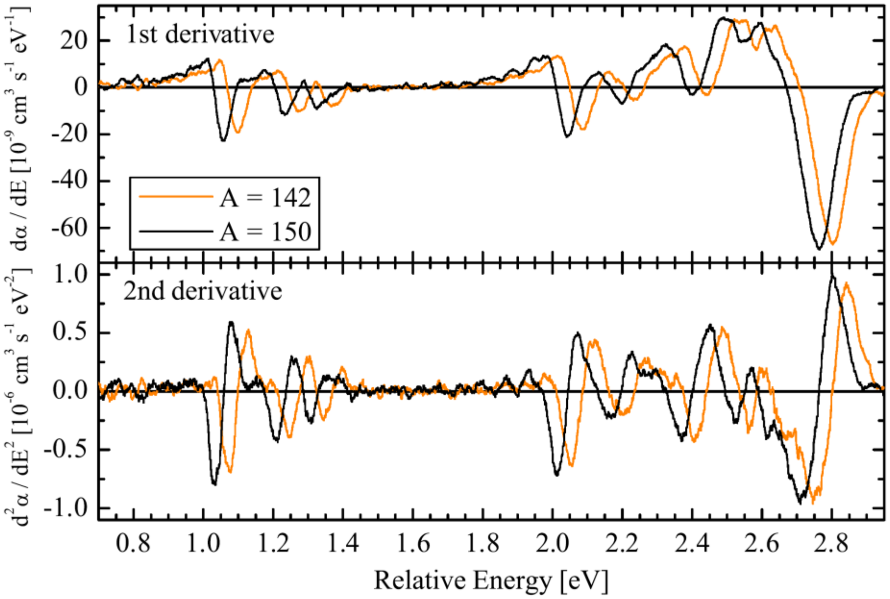
类锂钕离子DR中的**同位素位移@GSI**

$$\delta E^{142-150}\left(2s-2p_{1/2}\right)=40.2(3)(6)\,\mathrm{meV}$$

$$\delta E^{142-150}\left(2s-2p_{3/2}\right)=42.3(12)(20)\,\mathrm{meV}$$

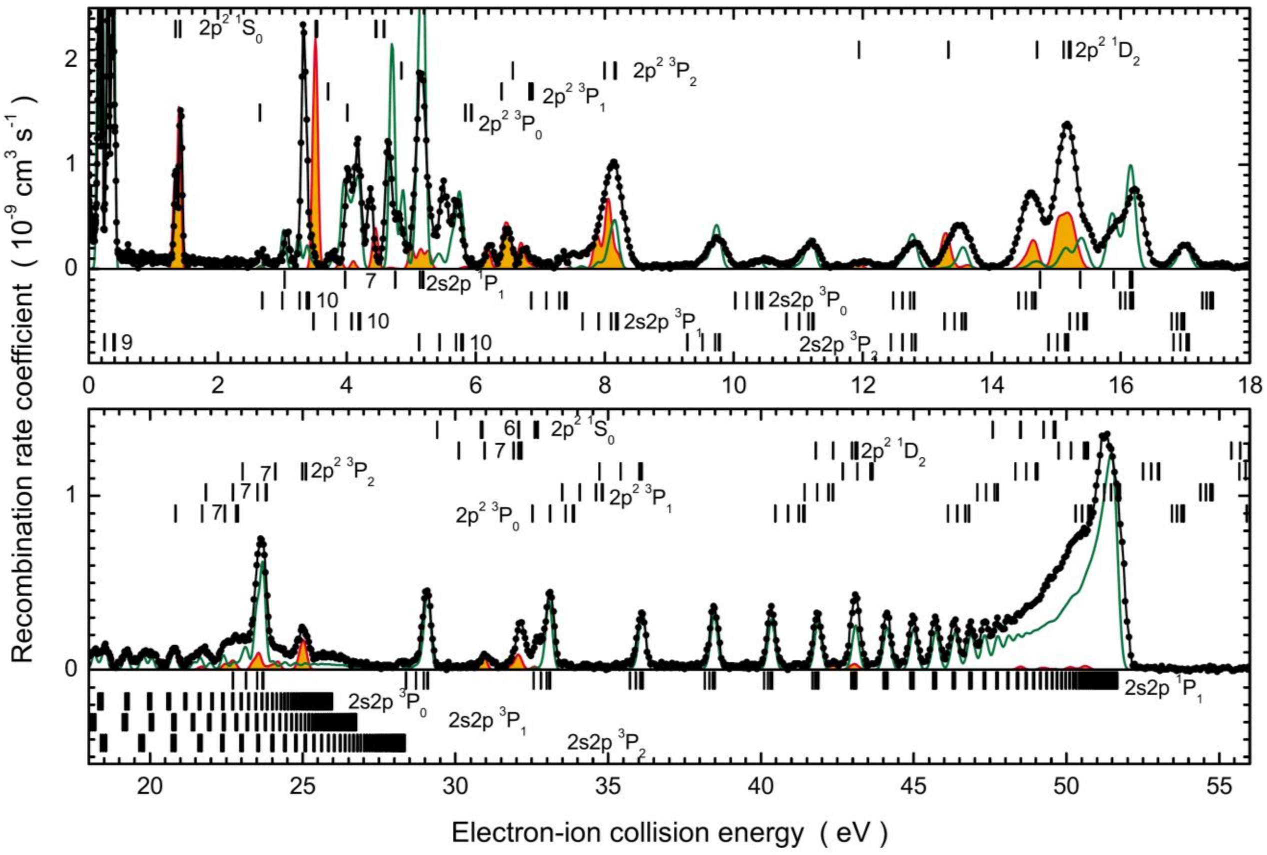
均方电荷半径变化：

$$^{142-150}\delta\left\langle r^{2}\right\rangle=-1.36(1)(3)\,fm^{2}$$

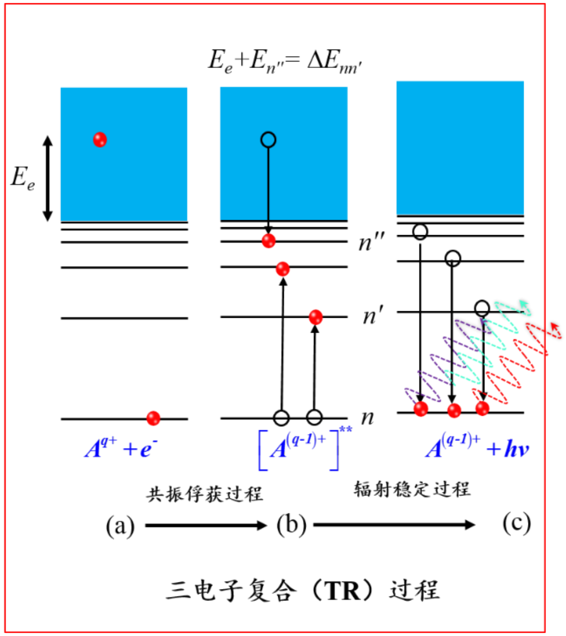


II、物理成果：三电子复合

M. Schnell et al., Phys. Rev. Lett.91(2003) 043001



Be-like Cl^{13+}



三电子复合（TR）过程

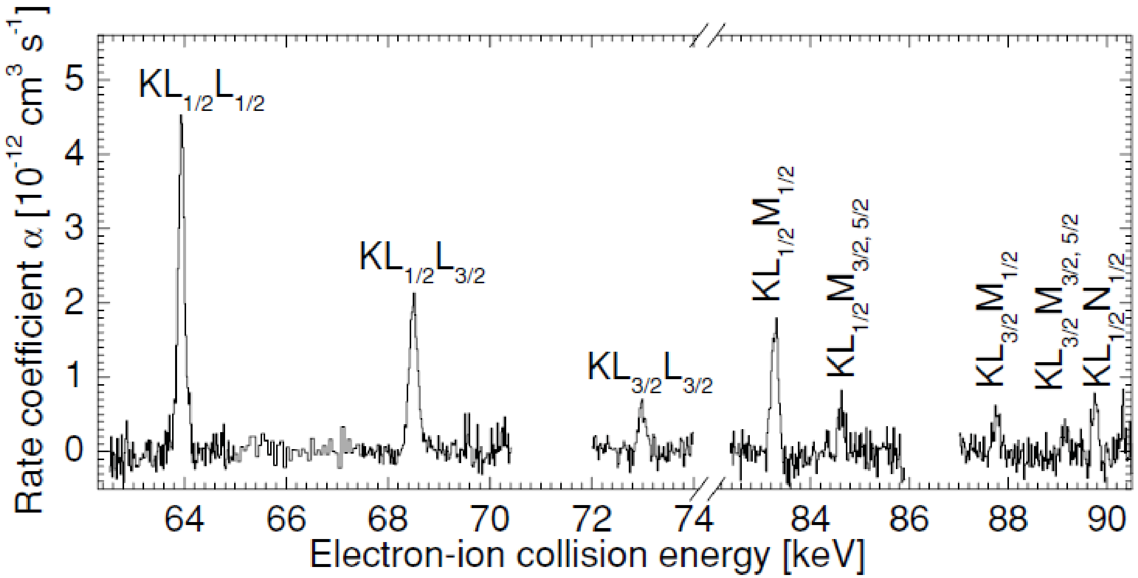
$$\Delta N = 0$$

Dielectronic recombination: $(2s^2 \rightarrow 2s2p)$

Trielectronic recombination: $(2s^2 \rightarrow 2p^2)$

II、物理成果：Breit相互作用

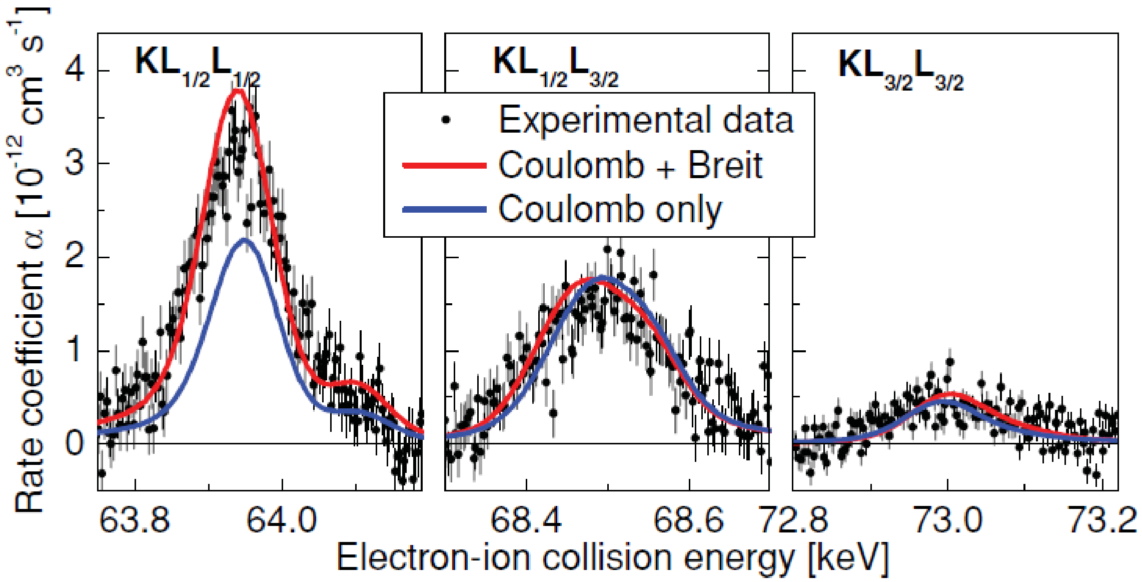
D. Bernhardt et al./Physical Review A ***83****, 020701(R) (2011)*



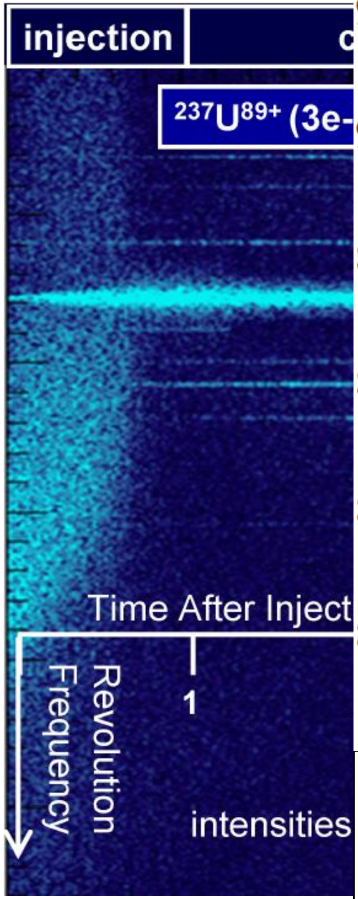
H-like U^{91+}

Resonance group	Experiment E_{res} (eV)	Experiment S (kb eV)	MCDF C + B E_{res} (eV)	MCDF C + B S (kb eV)	MCDF C E_{res} (eV)	MCDF C S (kb eV)
$KL_{1/2}L_{1/2}$	63 954(1)	58.7(11)	63 961	61.7	63 966	34.5
$KL_{1/2}L_{3/2}$	68 513(16)	33.1(11)	68 488	35.5	68 495	34.2
$KL_{3/2}L_{3/2}$	73 019(29)	9.1(14)	73 005	8.69	72 998	7.27
$KL_{1/2}M_{1/2}$	83 284(8)	18.9(9)	83 284	21.4	83 288	11.9
$KL_{1/2}M_{3/2}$	84 628(21)	8.0(4)	84 596	8.46	84 591	7.91
$KL_{1/2}M_{5/2}$			84 944	1.17	84 947	0.90
$KL_{3/2}M_{1/2}$	87 792(24)	5.6(16)	87 782	5.41	87 783	5.29
$KL_{3/2}M_{3/2}$	89 162(23)	4.0(6)	89 146	4.62	89 144	3.95
$KL_{3/2}M_{5/2}$			89 482	0.77	89 481	0.66

TABLE I. Measured and calculated (C + B = Coulomb + Breit, C = Coulomb only) U^{91+} *KLL*, and *KLM*-DR resonance energies E_{res} and strengths *S*. The experimental uncertainties (in parentheses) comprise statistical errors only. Systematic errors are 0.05% for E_{res} and 13% for *S*. The MCDF theoretical resonance energies in this table are given as weighted averages for a given group.



II、物理成果：核反应



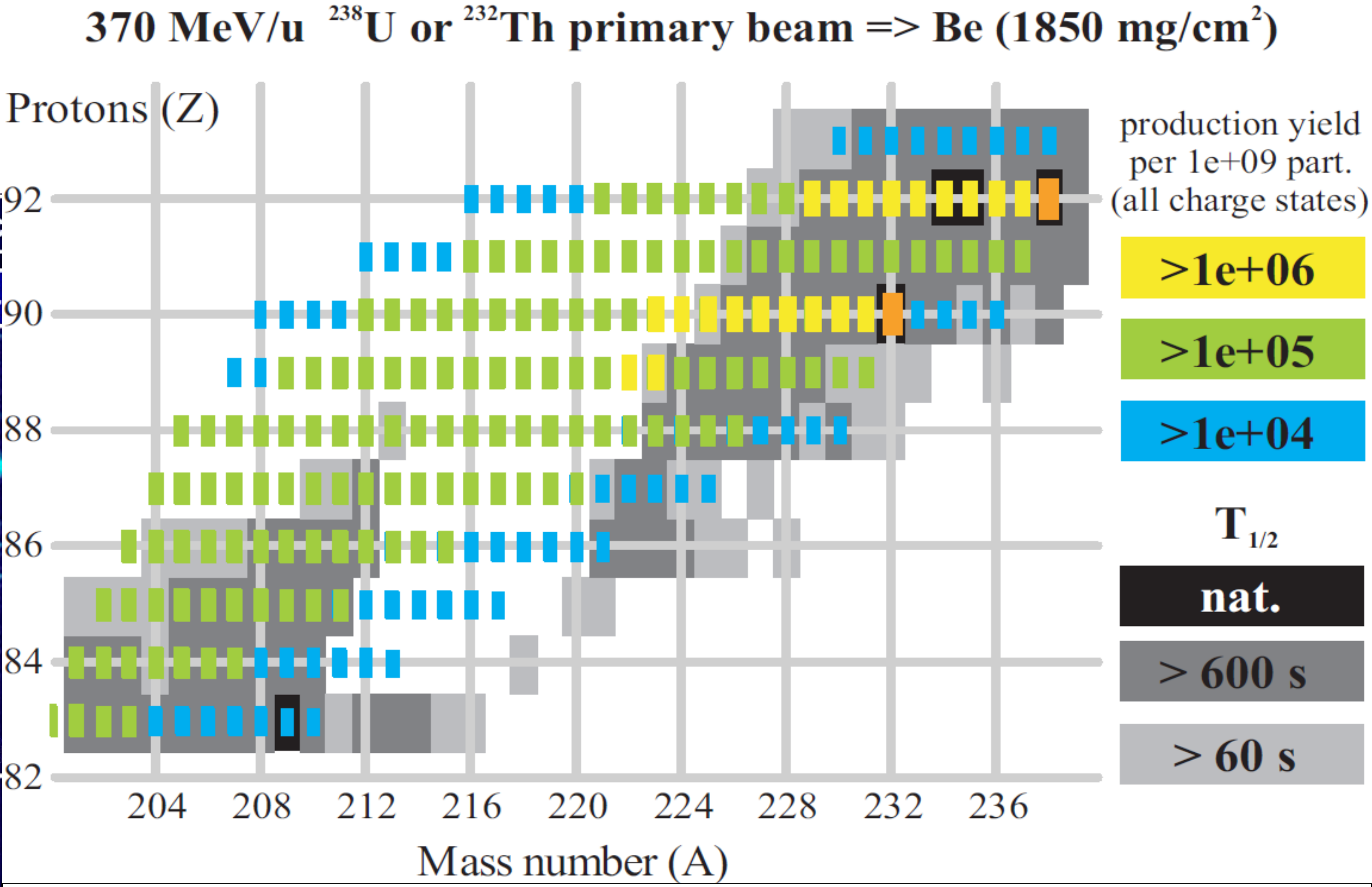
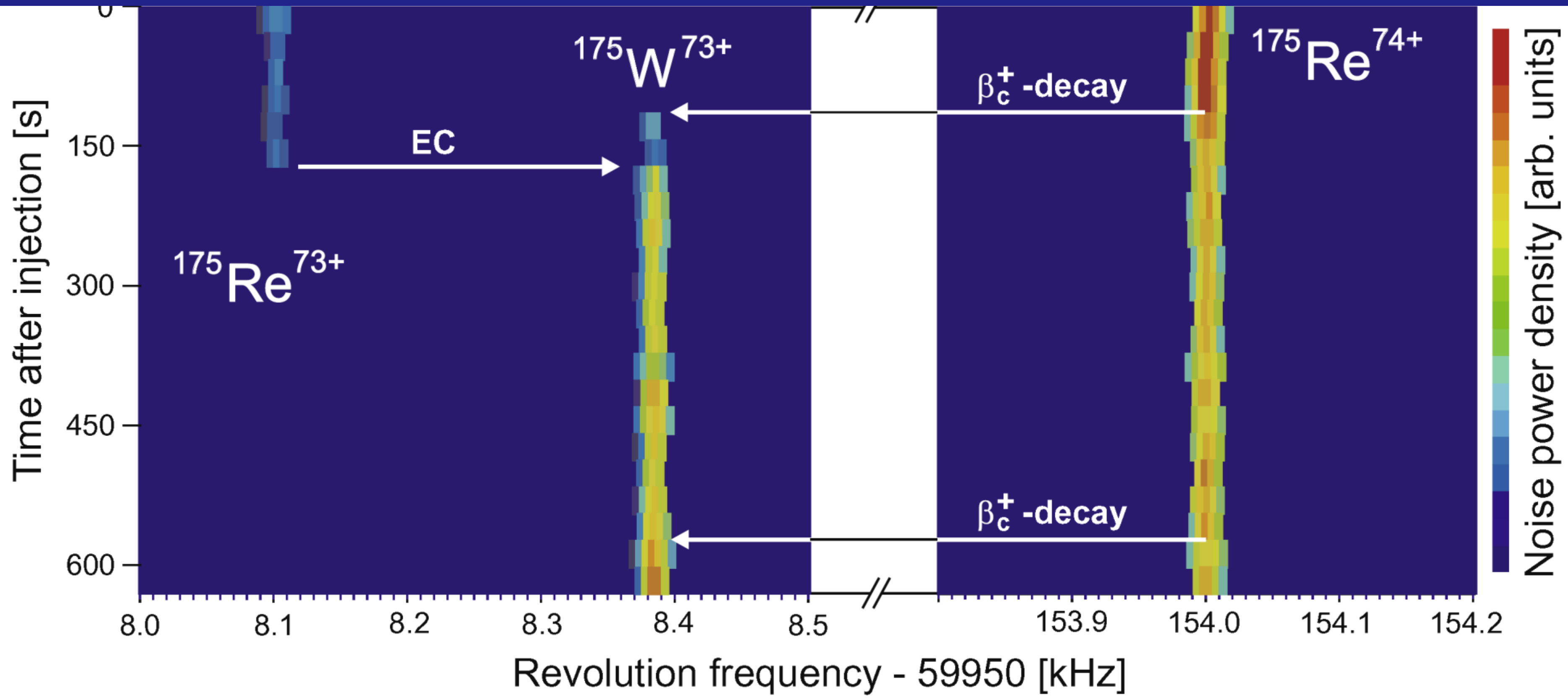

370 MeV/u ^{238}U or ^{232}Th primary beam => Be (1850 mg/cm^2)

Fig. Calculated production yields of in-fight produced isotopes per 10^9 primary beam ions of either 370 MeV/u ^{238}U or ^{232}Th impinging on a 1 cm Be target. Half-lives of the produced isotopes > 1 min and > 10 min are indicated as well.

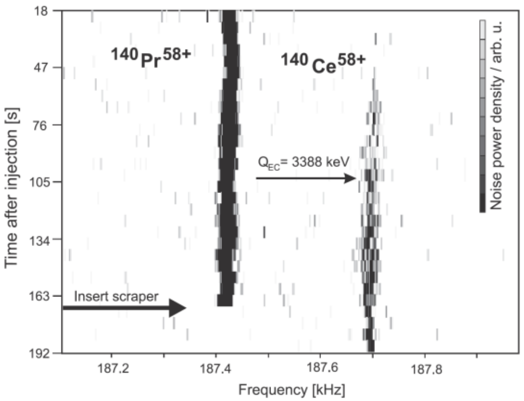
C.Brandau et al./Journal of Physics: Conference Series **194** (2009) 012023
Yu. A. Litvinoc et al., Nucl. Instrum. Meth. B 317, 603(2013)

II、物理成果：核反应



C.Brandau et al./Journal of Physics: Conference Series **194** (2009) 012023

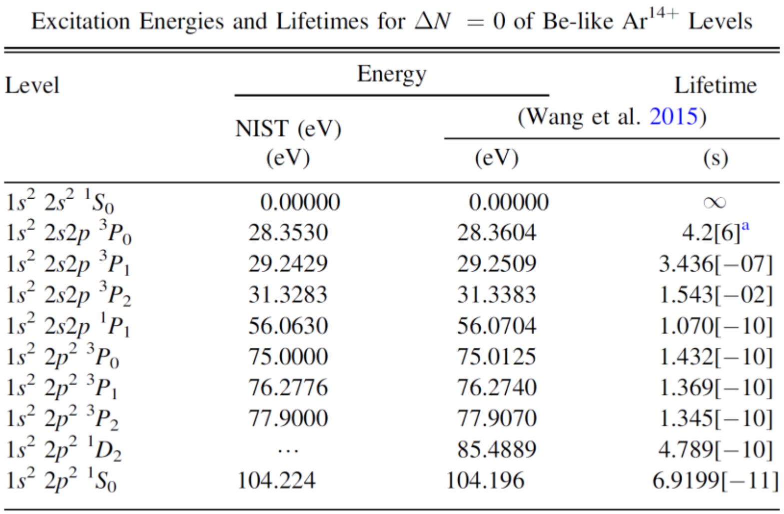
Yu. A. Litvinoc et al., Nucl. Instrum. Meth. B 317, 603(2013)



II、物理成果：Be-like $^{40}Ar^{14+}$

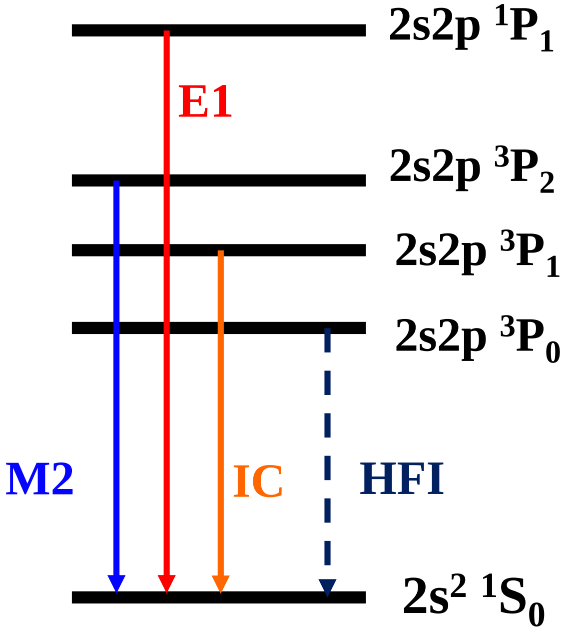
双电子和三电子复合过程：

$$\mathrm{Ar}^{14+}(2s^2\ {}^1S_0) + e^- \rightarrow \begin{cases} \mathrm{Ar}^{13+}[2s^2nl],\ \mathrm{RR}; \\ \mathrm{Ar}^{13+}[2s2p({}^3P_{0,1,2})nl],\ n \geqslant 10,\ \mathrm{DR}; \\ \mathrm{Ar}^{13+}[2s2p({}^1P_1)nl],\ n \geqslant 7,\ \mathrm{DR}; \\ \mathrm{Ar}^{13+}[2p^2({}^3P_{0,1,2};\ {}^1D_2;\ {}^1S_0)nl],\ n \geqslant 6,\ \mathrm{TR} \end{cases}$$

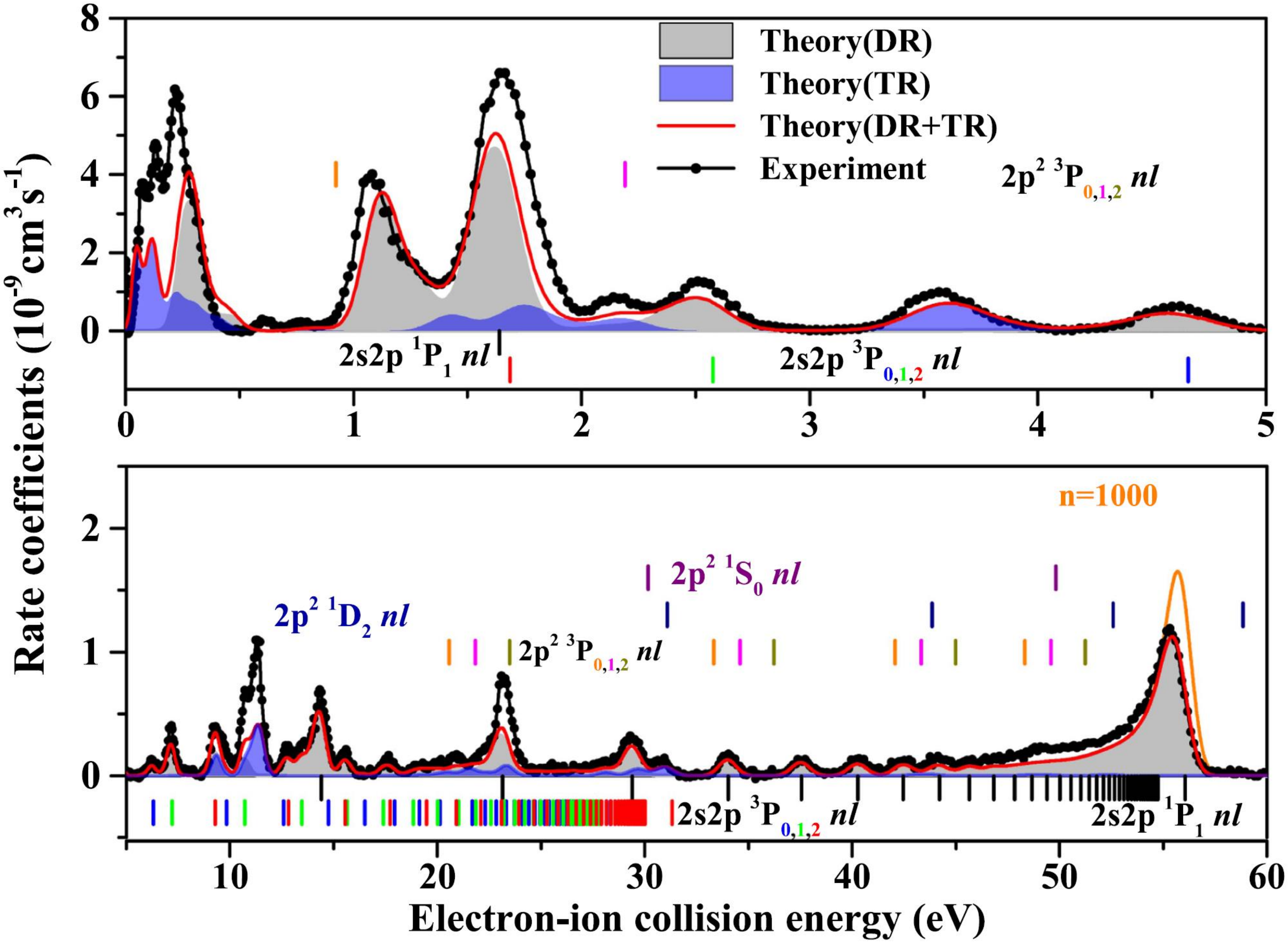


Excitation Energies and Lifetimes for $\Delta N = 0$ of Be-like Ar^{14+} Levels

Level	Energy		Lifetime
	NIST (eV)	(Wang et al. 2015)	
	(eV)	(eV)	(s)
$1s^2\ 2s^2\ {}^1S_0$	0.00000	0.00000	∞
$1s^2\ 2s2p\ {}^3P_0$	28.3530	28.3604	4.2[6][a]
$1s^2\ 2s2p\ {}^3P_1$	29.2429	29.2509	3.436[−07]
$1s^2\ 2s2p\ {}^3P_2$	31.3283	31.3383	1.543[−02]
$1s^2\ 2s2p\ {}^1P_1$	56.0630	56.0704	1.070[−10]
$1s^2\ 2p^2\ {}^3P_0$	75.0000	75.0125	1.432[−10]
$1s^2\ 2p^2\ {}^3P_1$	76.2776	76.2740	1.369[−10]
$1s^2\ 2p^2\ {}^3P_2$	77.9000	77.9070	1.345[−10]
$1s^2\ 2p^2\ {}^1D_2$	…	85.4889	4.789[−10]
$1s^2\ 2p^2\ {}^1S_0$	104.224	104.196	6.9199[−11]



II、物理成果：Be-like $^{40}Ar^{14+}$



Z.K.Huang et al. Astrophys. J. Suppl. 235: 2(2018)

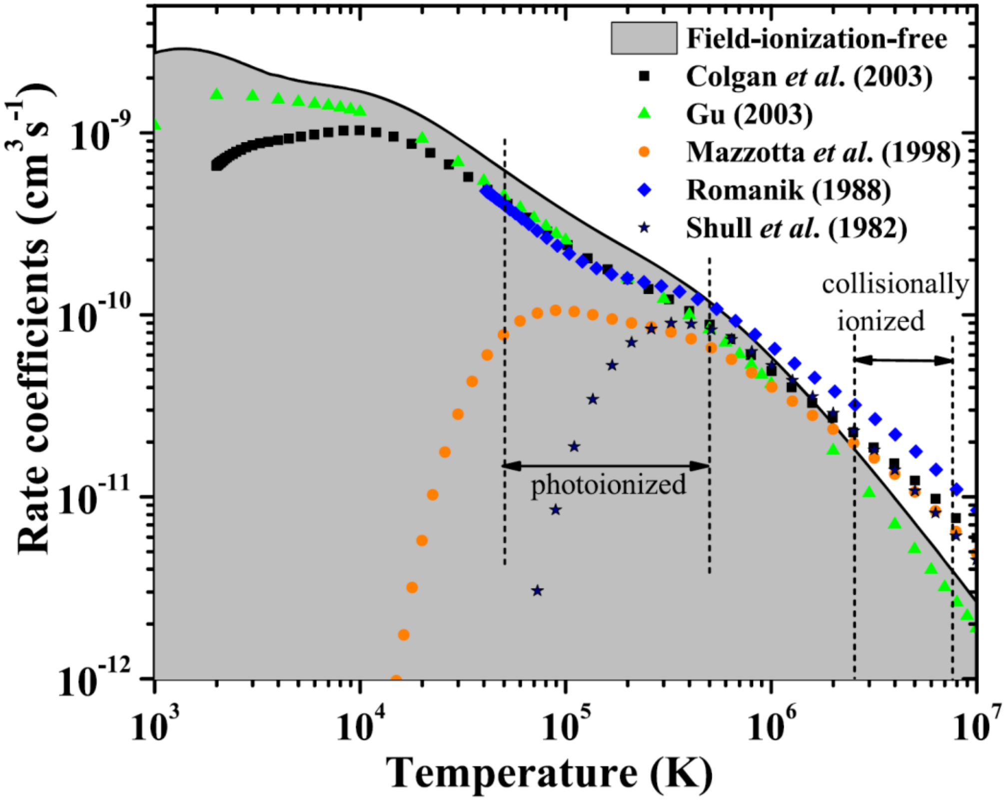
II、物理成果：Be-like ^{40}Ar^{14+}→等离子体速率系数

$$\alpha\left(T_e\right)=\int\alpha\left(E\right)f\left(E,T_e\right)dE$$

电子–离子复合速率系数

$$f\left(E,T_e\right)=\frac{2E^{1/2}}{\pi^{1/2}\left(k_BT_e\right)^{3/2}}\exp\left(-\frac{E}{k_BT_e}\right)$$

$$\alpha(T_e)=T_e^{-3/2}\sum_i c_i\times\exp\left(-\frac{E_i}{kT_e}\right).$$



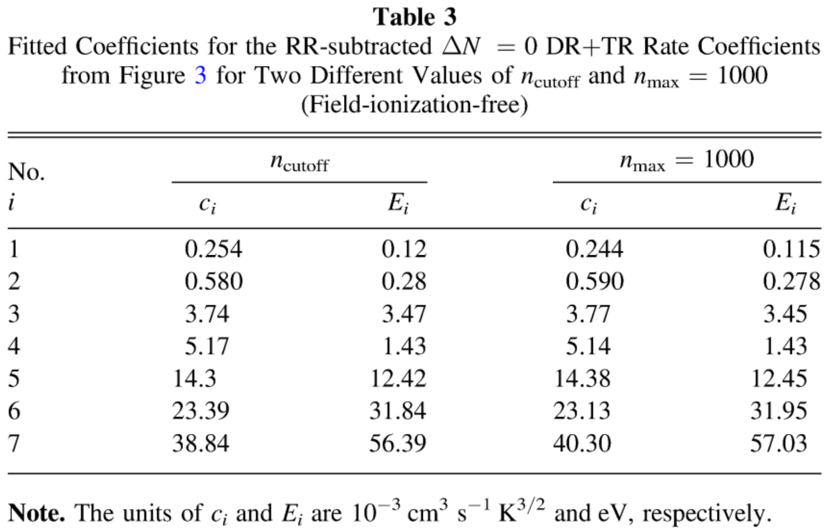


Table 3
Fitted Coefficients for the RR-subtracted $\Delta N=0$ DR+TR Rate Coefficients from Figure 3 for Two Different Values of $n_{\rm cutoff}$ and $n_{\max}=1000$ (Field-ionization-free)

No.	$n_{\rm cutoff}$		$n_{\max}=1000$	
i	c_i	E_i	c_i	E_i
1	0.254	0.12	0.244	0.115
2	0.580	0.28	0.590	0.278
3	3.74	3.47	3.77	3.45
4	5.17	1.43	5.14	1.43
5	14.3	12.42	14.38	12.45
6	23.39	31.84	23.13	31.95
7	38.84	56.39	40.30	57.03

Note. The units of c_i and E_i are 10^{-3} cm^3 s^{-1} K$^{3/2}$ and eV, respectively.

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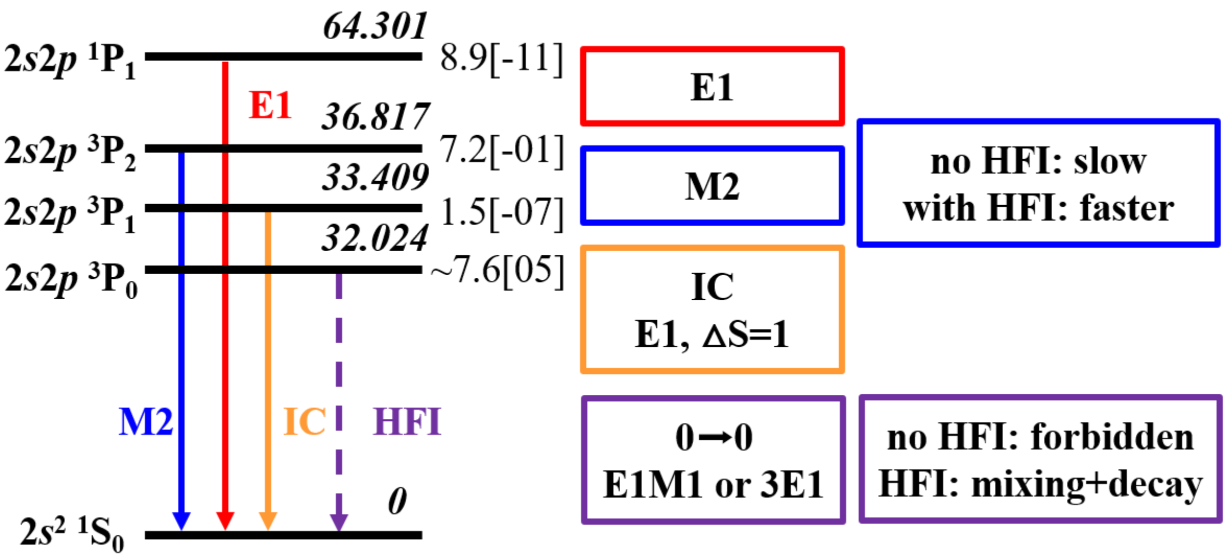
II、物理成果：Be-like $^{40}Ca^{16+}$

三电子复合过程：强电子关联效应；**2s2p $^3P_0$**亚稳态：能级、寿命；

$$Ca^{16+}(1s^22s^2[^1S_0]) + e^- \to \begin{cases} Ca^{15+}(1s^22s2p[^3P_{0,1,2},{}^1P_1]nl)^{**}, \boldsymbol{DR} \\ Ca^{15+}(1s^22p^2[^3P_{0,1,2},{}^1D_2,{}^1S_0]nl)^{***}, \boldsymbol{TR} \end{cases}$$

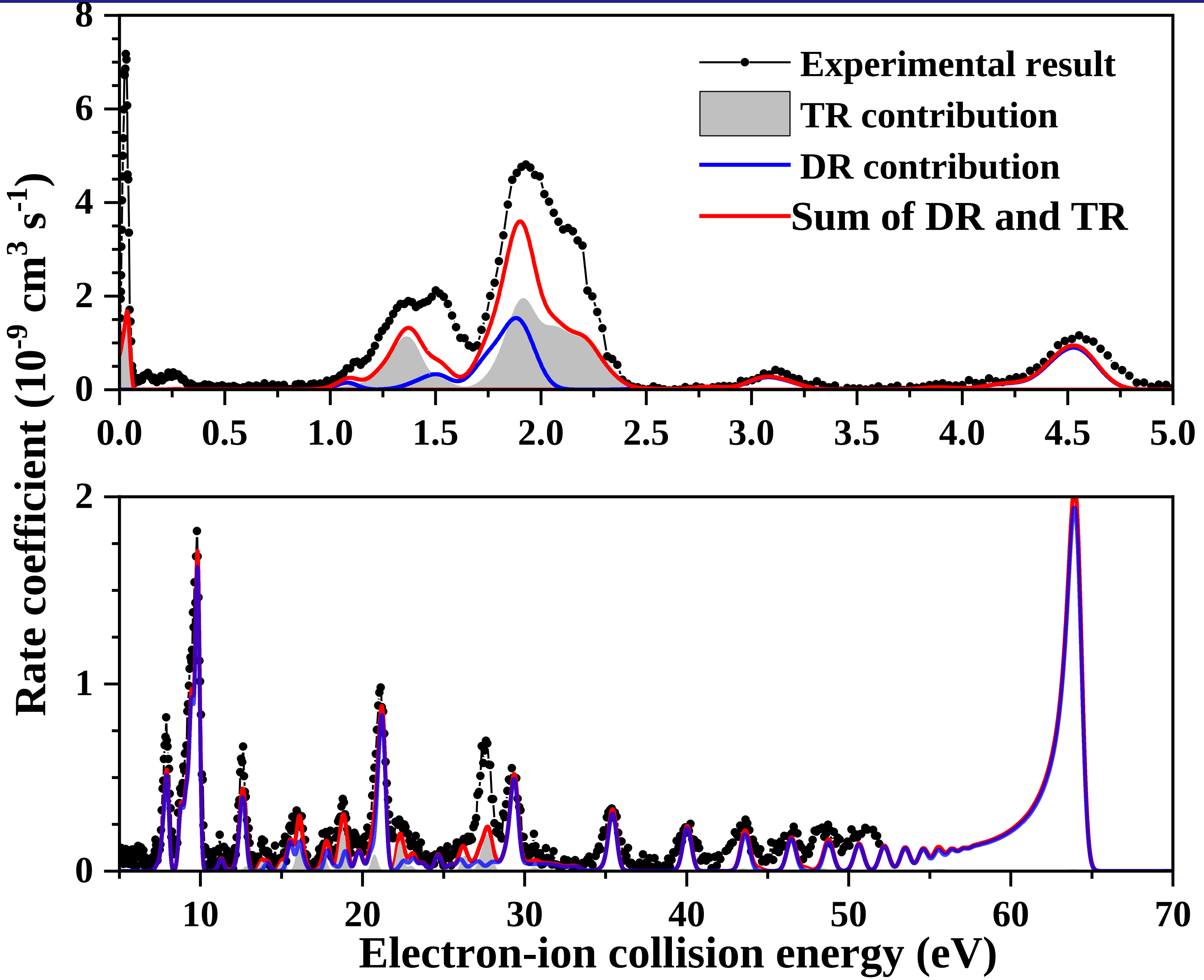
$$Ca^{16+}(1s^22s2p[^3P_0]) + e^- \to Ca^{15+}(1s^22p^2nl)^{***}$$

Configuration	Term	J	Level (eV)
$1s^22s^2$	^1S	0	0.00
$1s^22s2p$	^3P	0	32.024
		1	33.409
		2	36.817
	^1P	1	64.301
$1s^22p^2$	^3P	0	85.435
		1	87.617
		2	90.068
	^1D	2	98.956
	^1S	0	119.914



类铍钙离子的能级结构以及相应跃迁。

II、物理成果：Be-like $^{40}Ca^{16+}$



S. X. Wang et al. Astrophys. J. 862, 134(2018)

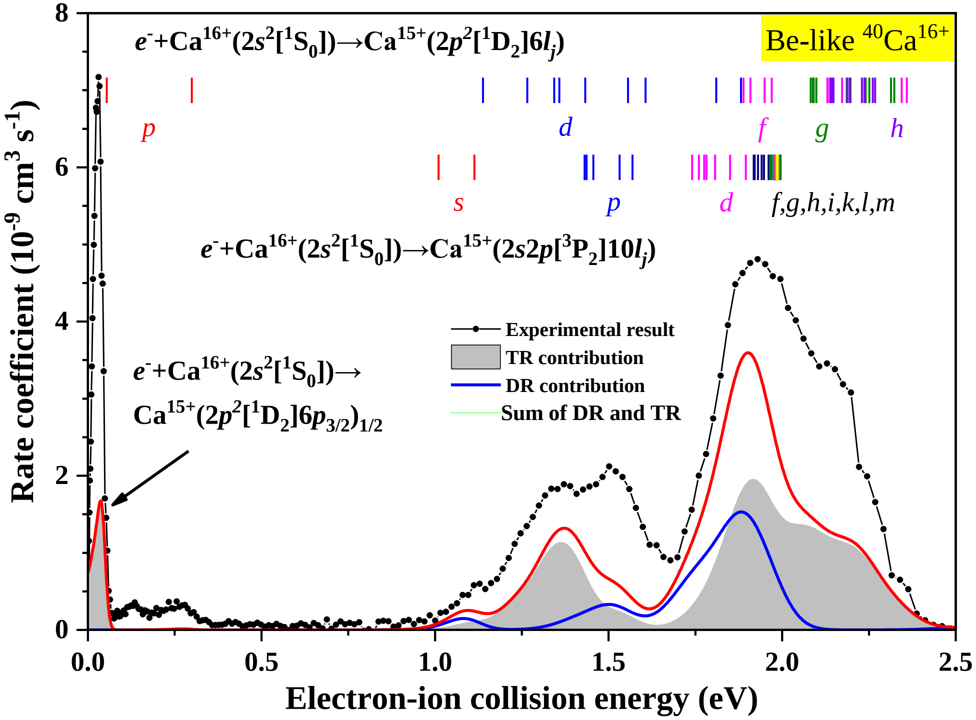
II、物理成果：Be-like $^{40}Ca^{16+}$

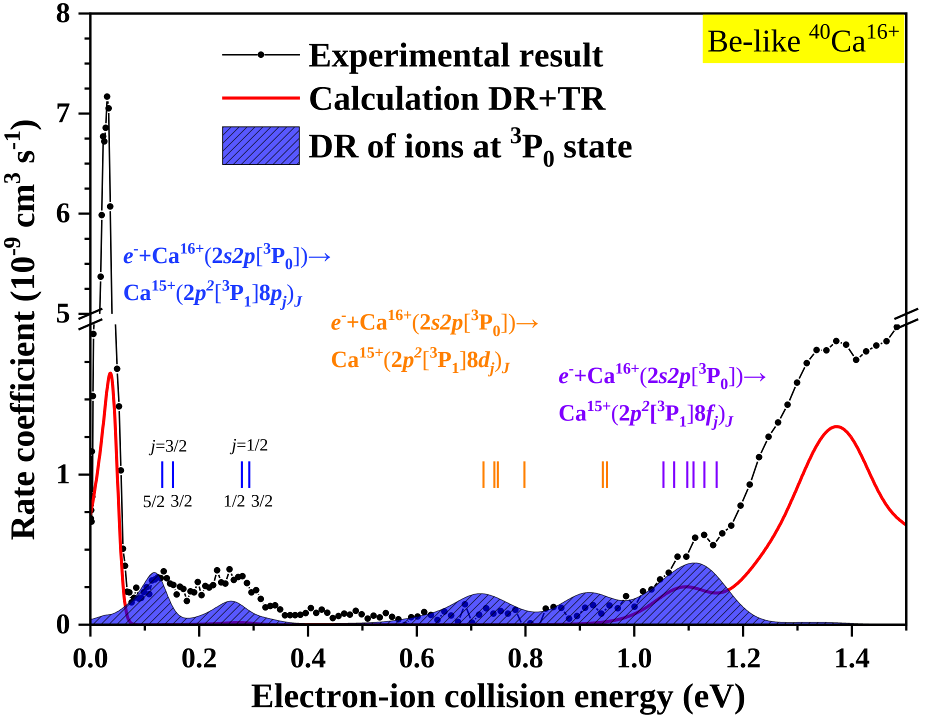
- 双电子复合过程的理论计算位置和强度上都与实验符合很好；
- 三电子复合理论计算和实验在强度上仍然存在较大的差异；
- 亚稳态离子对于双电子复合的贡献在低能端有明显的贡献；

$$e^- + Ca^{16+}(1s^2 2s^2[^1S_0]) \rightarrow Ca^{15+}\left(1s^2 2p^2[^1D_2]6l_j\right)_J^{**}$$

$$e^- + Ca^{16+}(1s^2 2s^2[^1S_0]) \rightarrow Ca^{15+}\left(1s^2 2s2p[^3P_2]10l_j\right)_J^{**}$$

$$e^- + Ca^{16+}(1s^2 2s2p[^3P_0]) \rightarrow Ca^{15+}\left(1s^2 2p^2[^3P_1]8l_j\right)_J^{**}$$





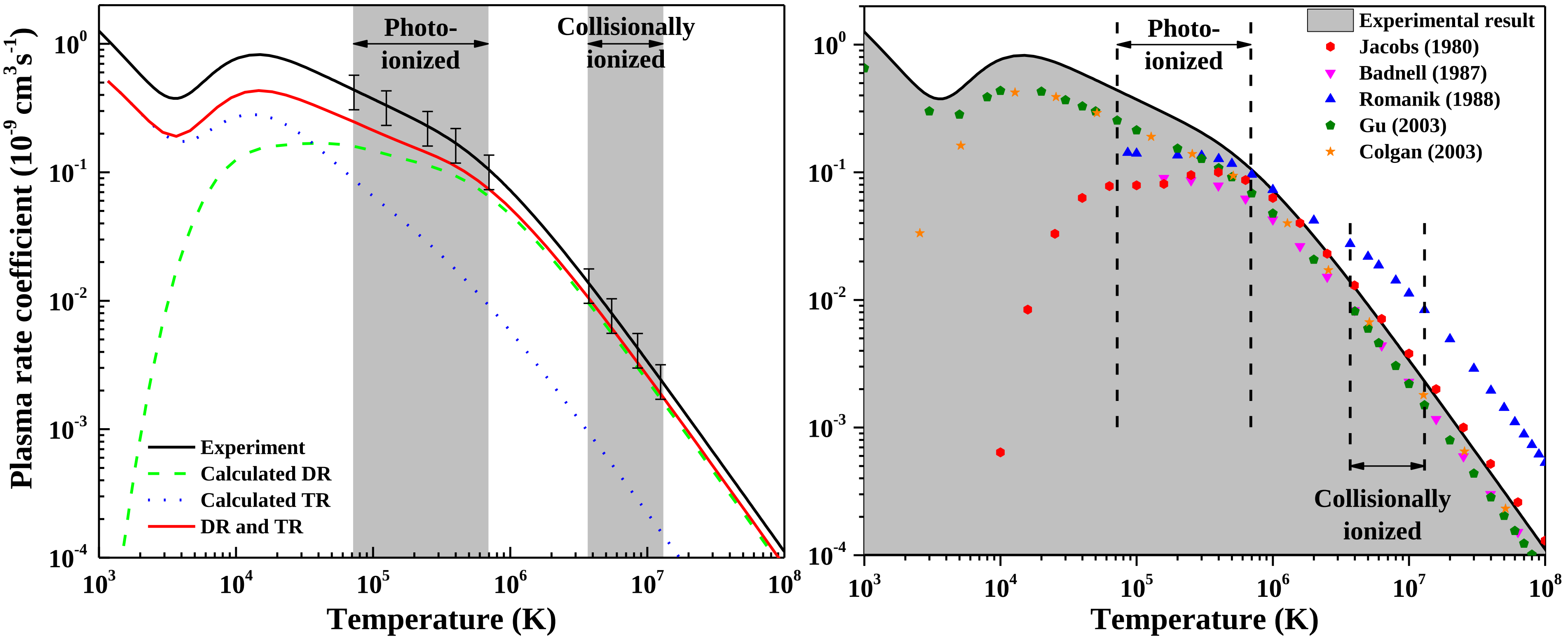
S. X. Wang et al. Astrophys. J. 862, 134(2018)

II、物理成果：Be-like $^{40}Ca^{16+}$

$$\alpha(T_e)=\int\alpha(E)f(E,T_e)dE$$

电子-离子复合速率系数

$$f(E,T_e)=\frac{2E^{1/2}}{\pi^{1/2}(k_BT_e)^{3/2}}\exp\left(-\frac{E}{k_BT_e}\right)$$



S. X. Wang et al. Astrophys. J. 862, 134(2018)

II、物理成果：F-like $^{58}Ni^{19+}$

类氟^{58}Ni^{19+}离子双电子复合通道：

$$e^- + {}^{58}Ni^{19+}\left(2s^2 2p^5\left[{}^2P_{3/2}\right]\right) \rightarrow \begin{cases} {}^{58}Ni^{18+}\left(2s^2 2p^5\left[{}^2P_{1/2}\right]nl\right)^{**}, n \geq 17 \\ {}^{58}Ni^{18+}\left(2s 2p^6\left[{}^2S_{1/2}\right]nl\right)^{**}, n \geq 6 \end{cases}$$

Configuration	**Term**	**J**	**Level (eV)**[a]
$2s^22p^5$	^{2}P	3/2	0.00
		1/2	17.8486
$2s2p^6$	^{2}S	1/2	149.054

[a] NIST atomic spectra data base.

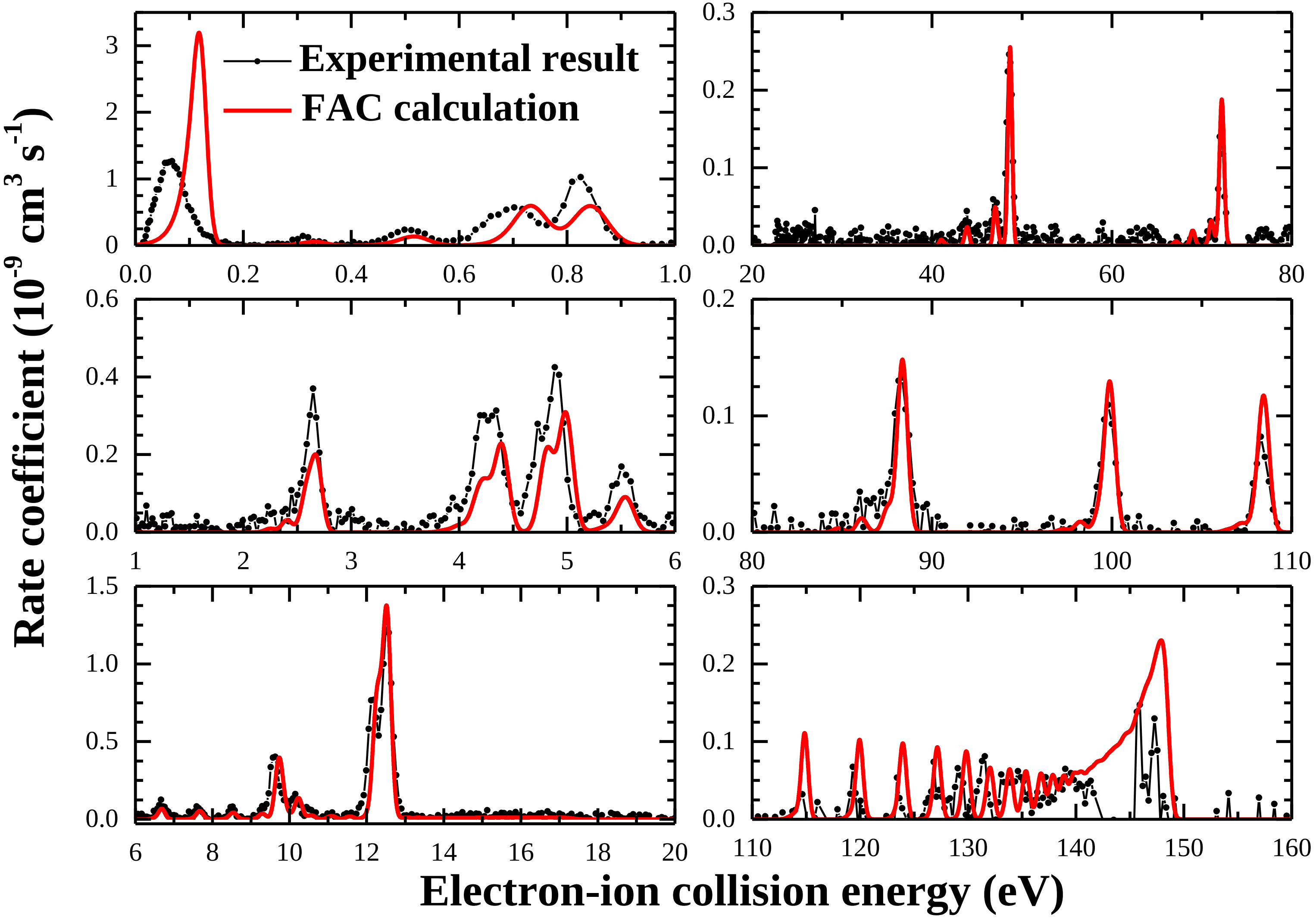
新的电子冷却电源：稳定性能更好；电子温度更低；实验分辨更高。

$$kT_{\parallel} = 0.8meV, kT_{\perp} = 40meV; \rightarrow kT_{\parallel} = 0.41meV, kT_{\perp} = 21meV$$

S. X. Wang et al. Astrophys. J. (to be submitted)

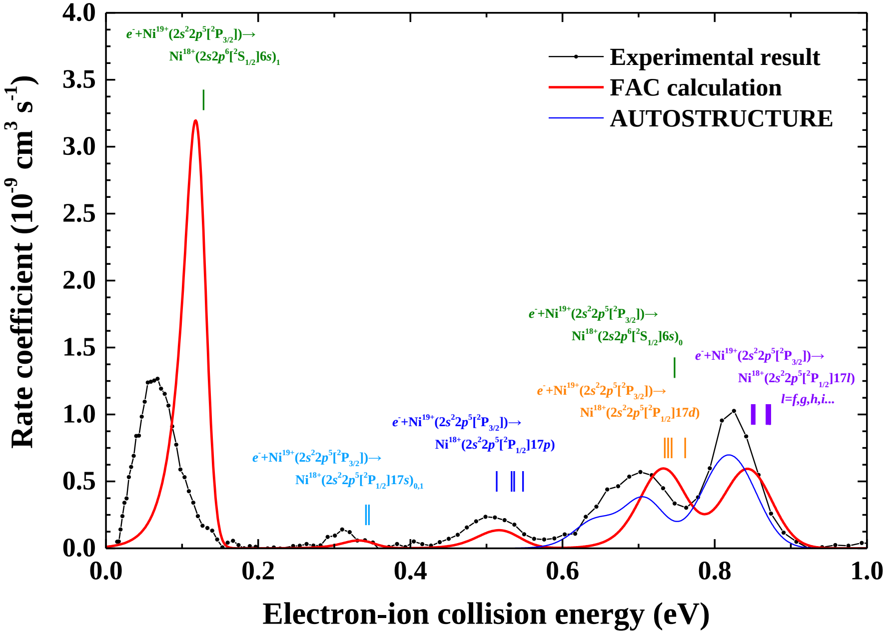
II、物理成果：F-like $^{58}Ni^{19+}$

实验测量结果 vs. FAC理论计算结果



S. X. Wang et al. Astrophys. J. (to be submitted)

II、物理成果：F-like ^{58}Ni^{19+}

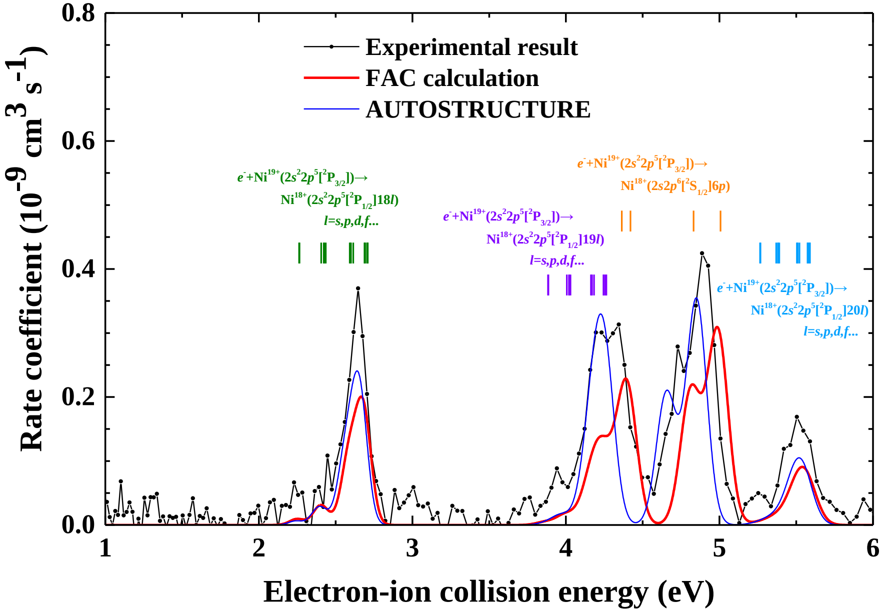


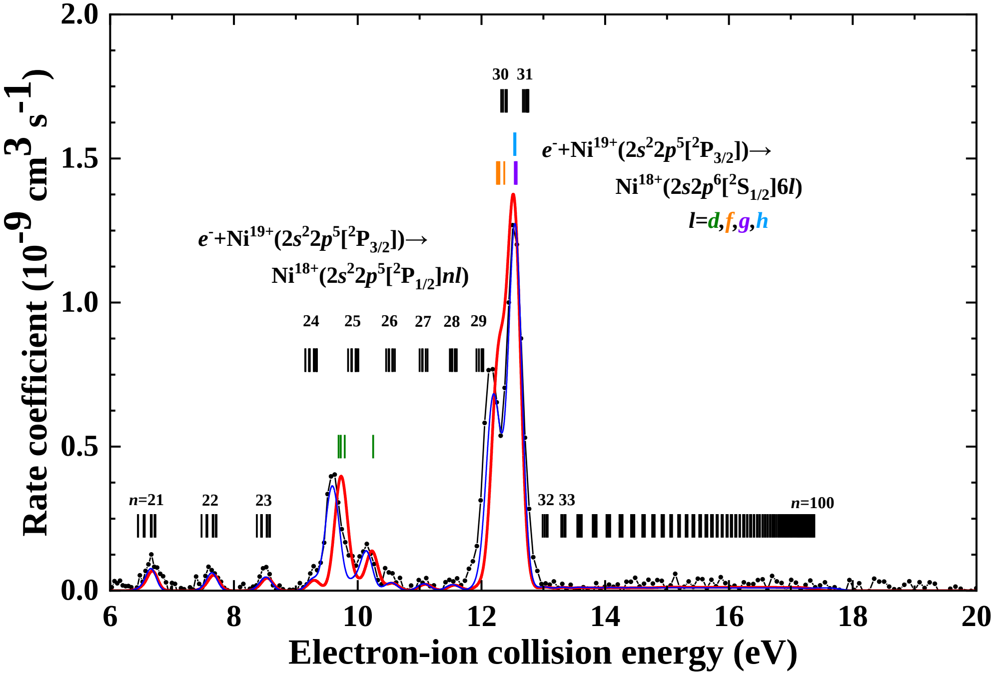
> 低能部分的共振实验和理论存在一定差异；

尤其是共振：

$$e^- + Ni^{19+}\left(2s^2 2p^5\left[{}^2P_{3/2}\right]\right)$$

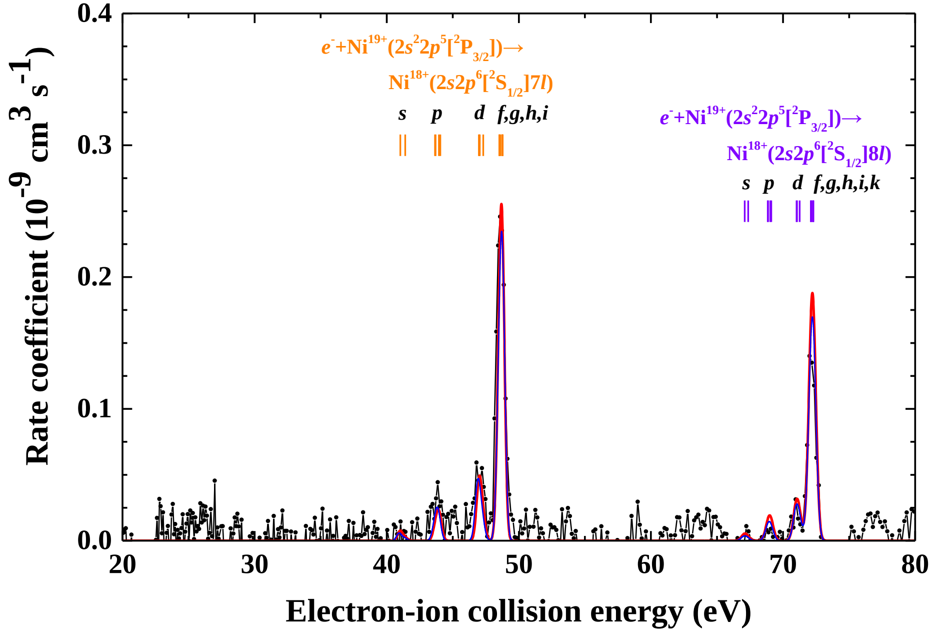
$$\to Ni^{18+}\left(2s2p^6\left[{}^2S_{1/2}\right]6l_j\right)_J^{**}$$

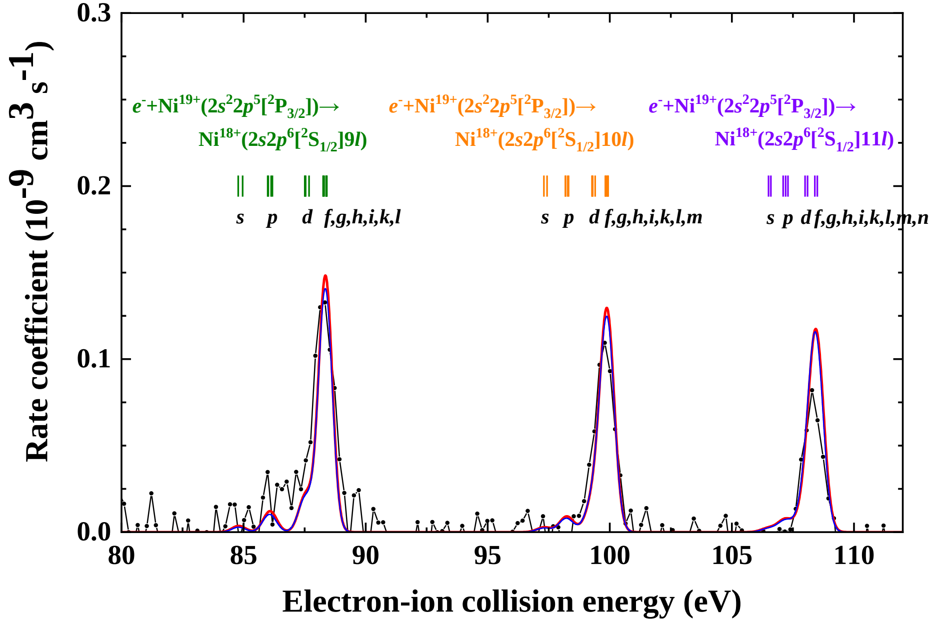




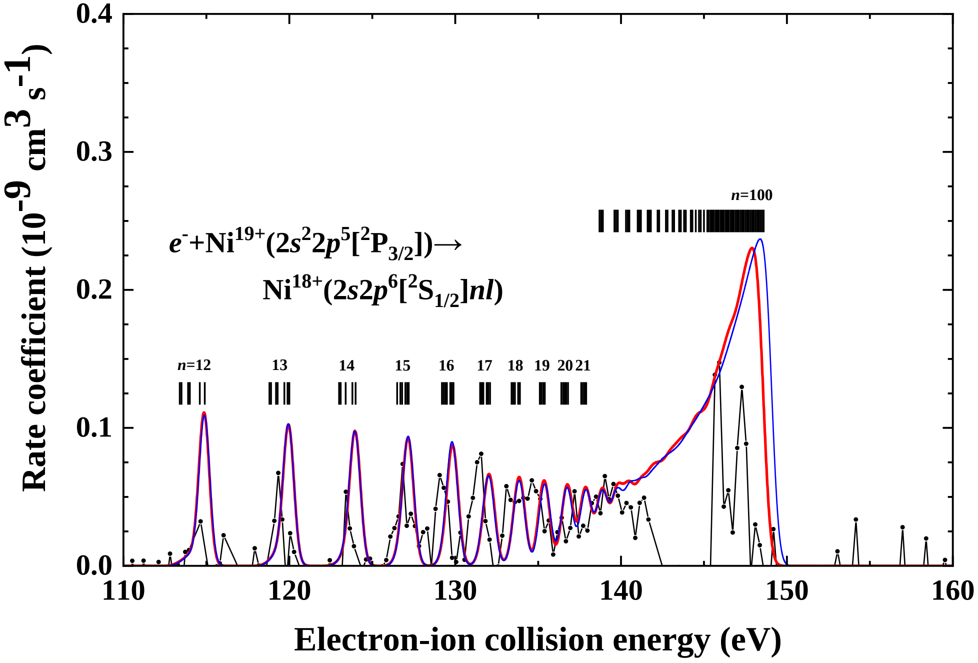
S. X. Wang et al. Astrophys. J. (to be submitted)

II、物理成果：F-like $^{58}\mathrm{Ni}^{19+}$



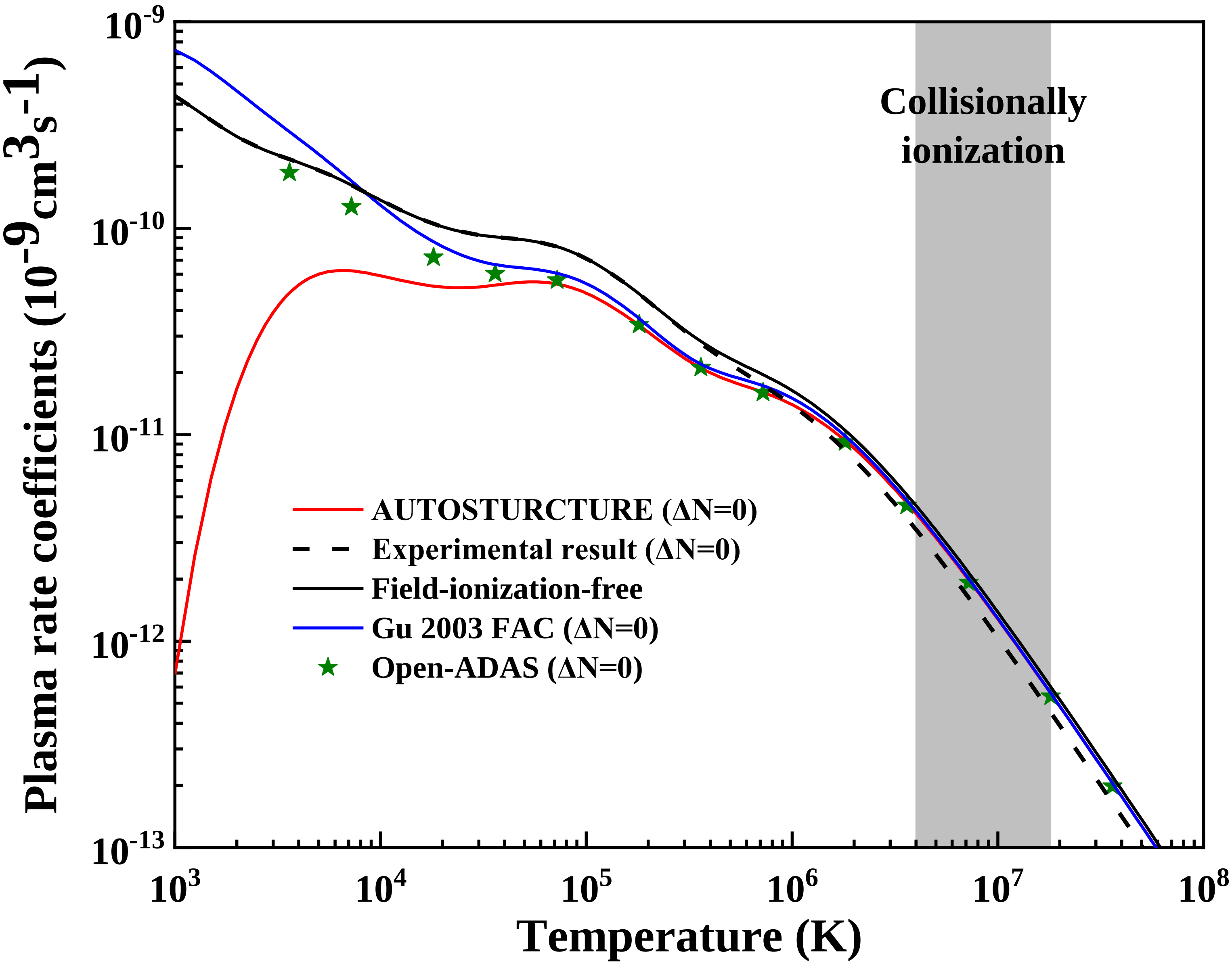


- ➢ 高能部分的共振理论和实验符合很好；
- ➢ 110eV之后的实验测量受到电子冷却系统的影响效果不佳，数据质量较差；



S. X. Wang et al. Astrophys. J. (to be submitted)

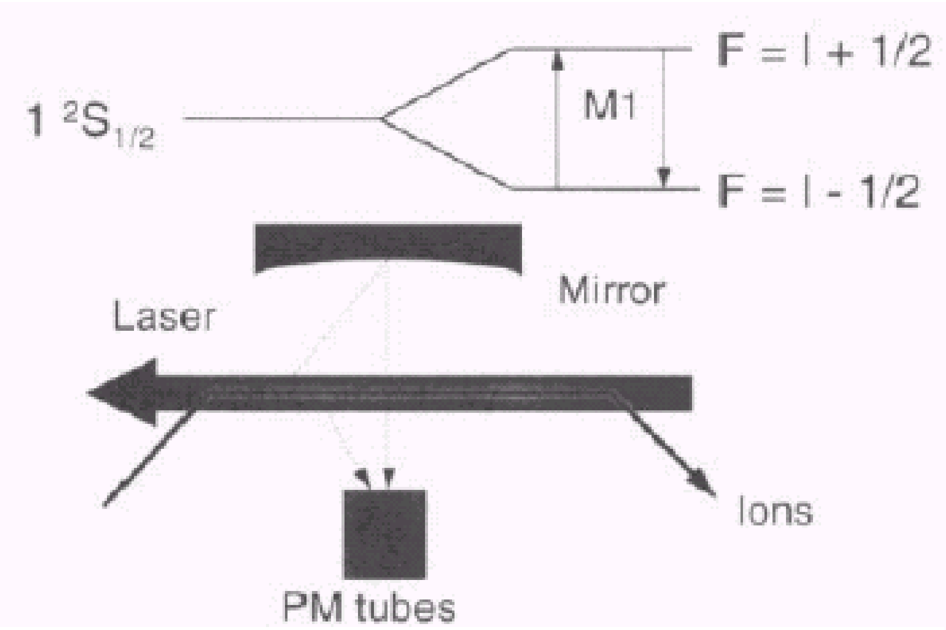
II、物理成果：F-like $^{58}Ni^{19+}$



S. X. Wang et al. Astrophys. J. (to be submitted)

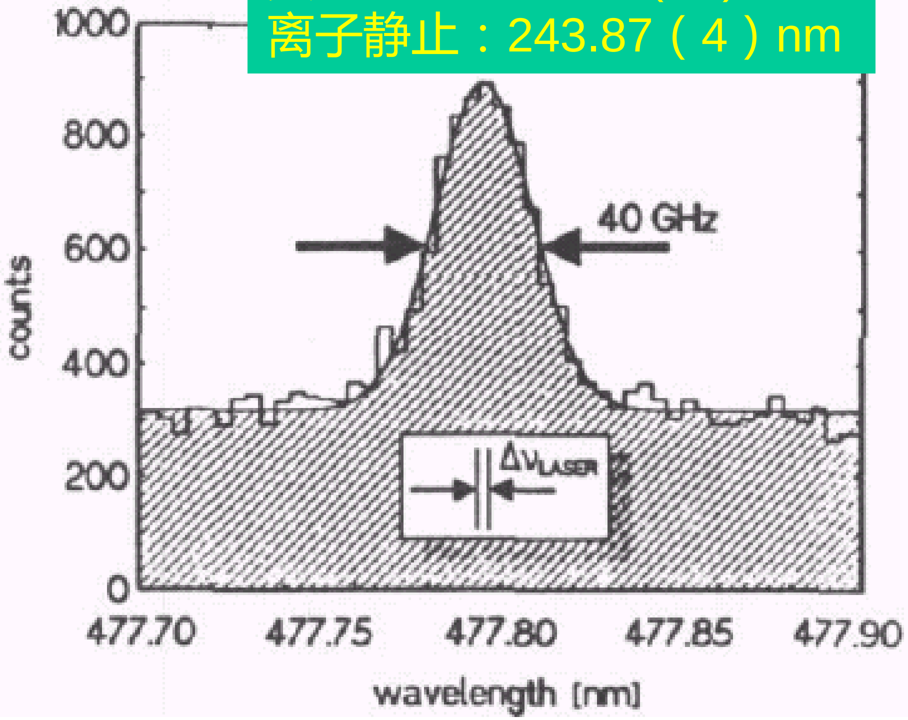
II、物理成果：H-like $^{208}Bi^{82+}$

- 目前离子冷却储存环上的光子－离子碰撞主要用于研究高电荷态离子的超精细分裂，超精细劈裂$\propto Z^3$，高电荷态类氢系统的超精细劈裂将到达可见光区甚至紫外区。
- 高**Z**重核的超精细劈裂必须考虑相对论效应、兰姆移位和原子核的结构及自旋
- 对相关的理论工作（例如**QED**、相对论效应、原子核理论等）将有极大的推动作用。
- 由于激光技术的不断进步，可以预计这方面的工作会有极大进展。



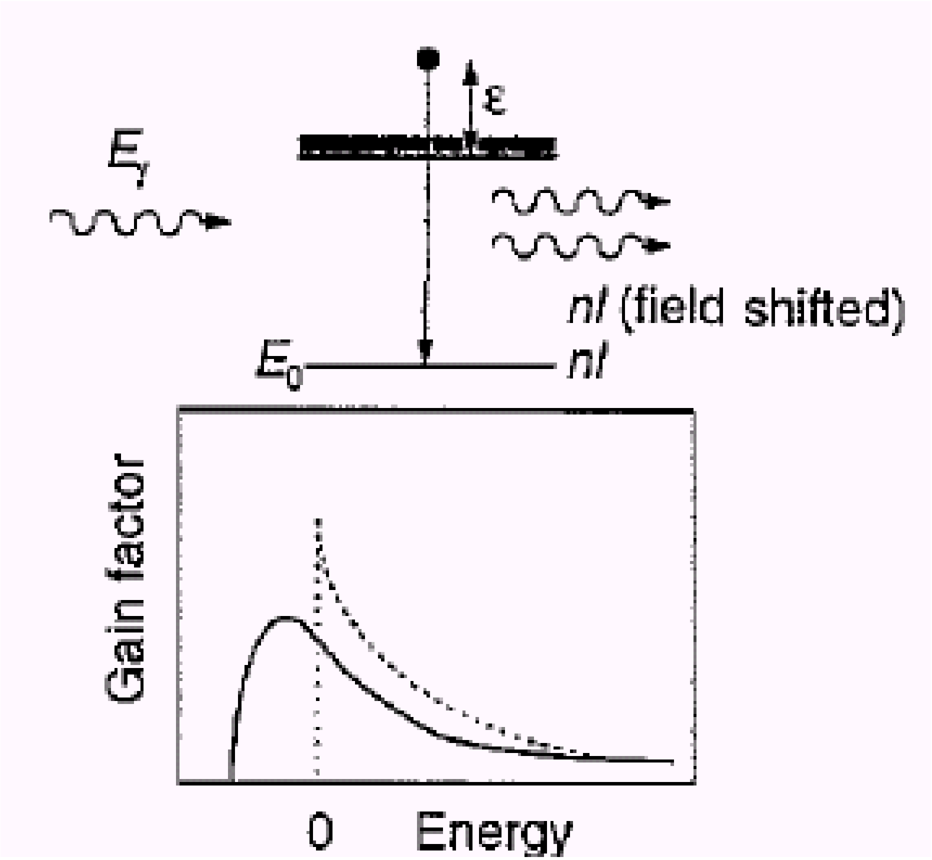
$^{208}Bi^{82+}$，其核自旋I为9/2

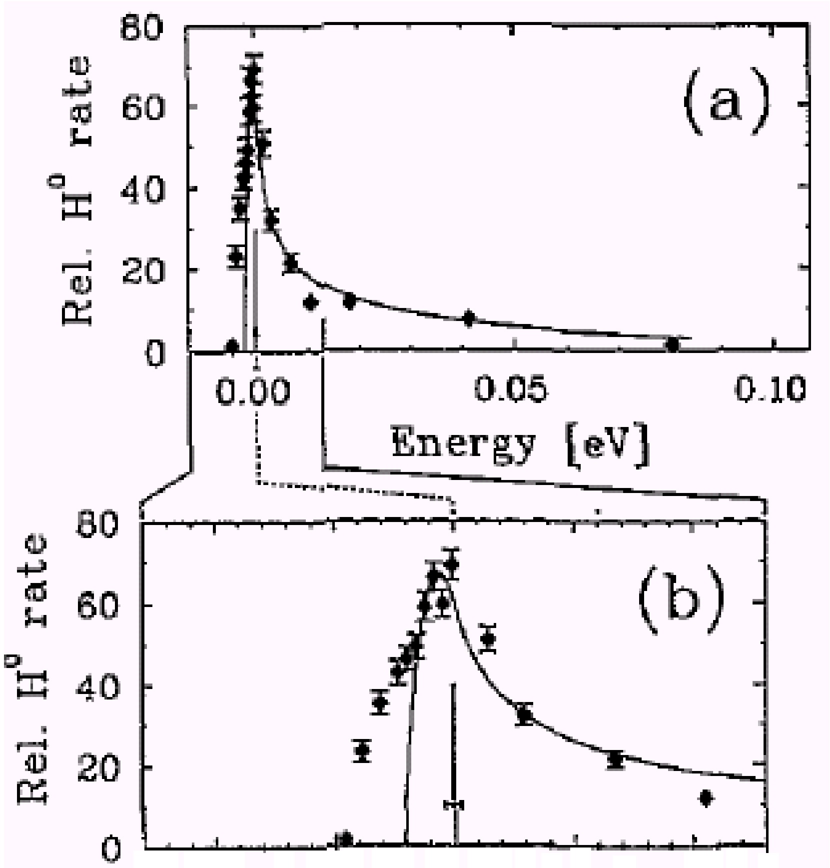
实验室：477.794（4）nm
离子静止：243.87（4）nm



II、物理成果：光子-电子-离子相互作用

$$A^{q+}+e^{-}+h\nu\rightarrow A^{(q-1)+}(nl)+2h\nu$$





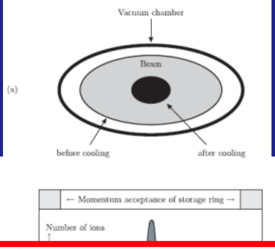
RR+受激辐射

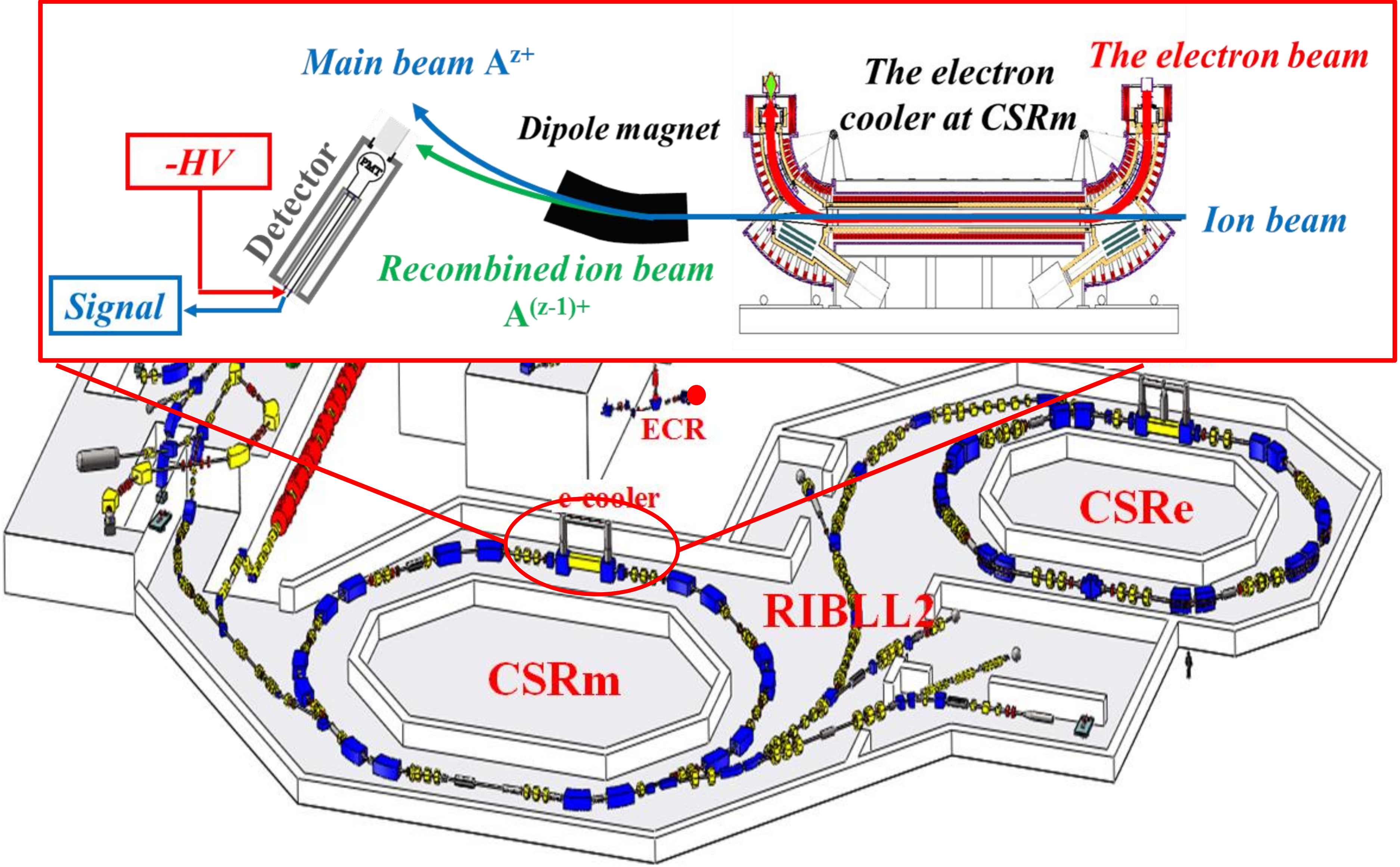
$$H^{+}+e^{-}+h\nu\rightarrow H(n=2)+2h\nu$$

离子的动力学参数：辐射复合和双电子复合

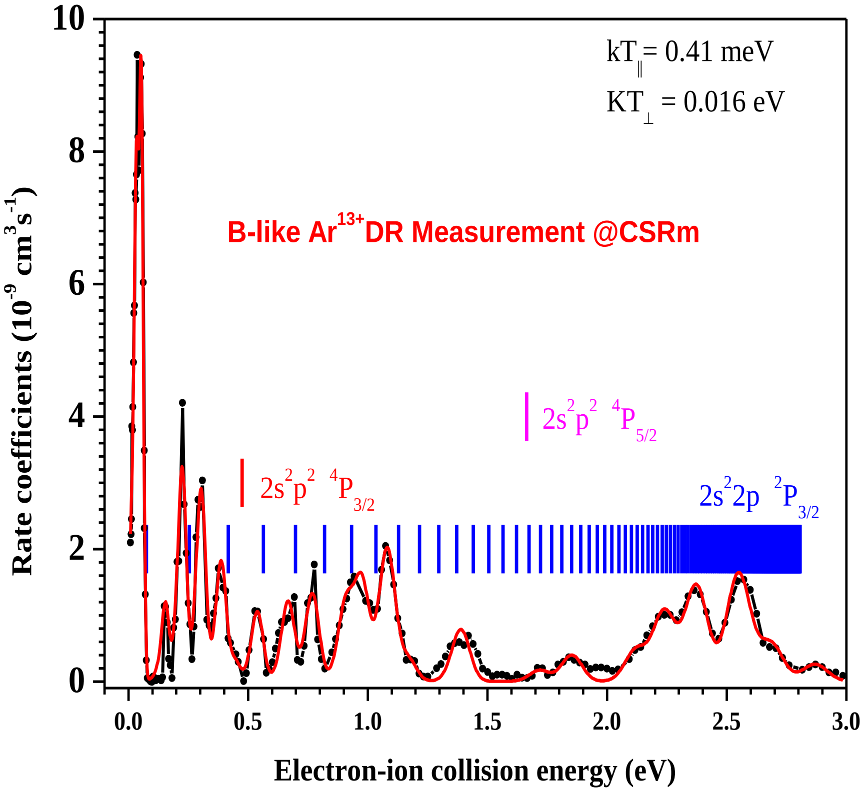
- 背景
- 研究方法
- 现状
- 展望

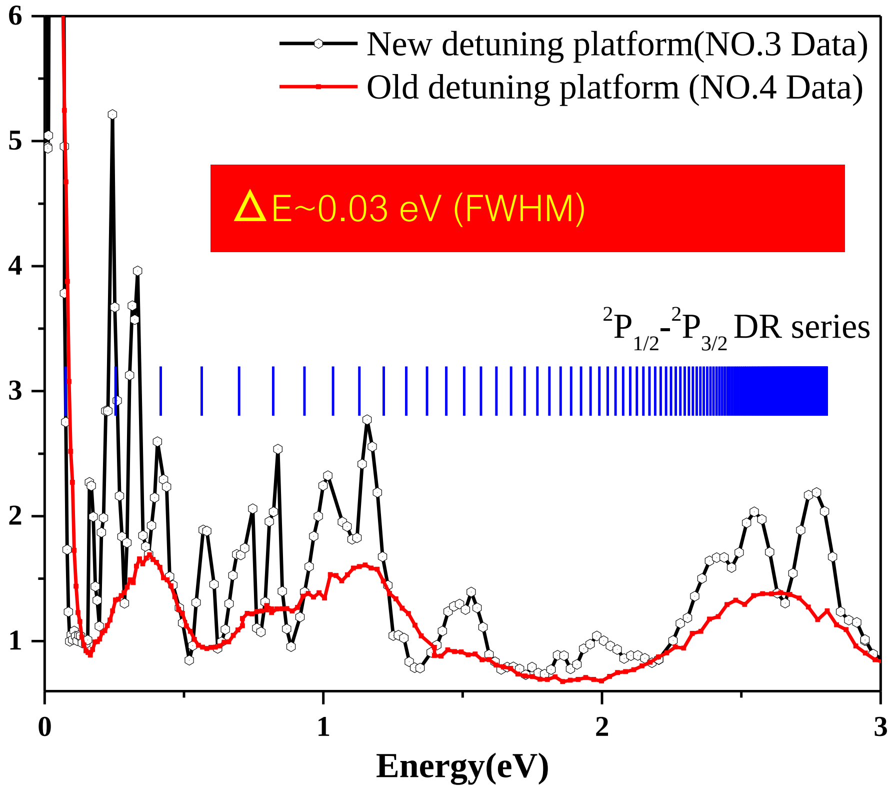
装置发展


Vacuum chamber
Beam
(a)
before cooling
after cooling
← Momentum acceptance of storage ring →
Number of ions


Main beam A^{z+}
Dipole magnet
-HV
Detector
PMT
Signal
Recombined ion beam
$A^{(z-1)+}$
The electron cooler at CSRm
The electron beam
Ion beam
ECR
e-cooler
CSRe
RIBLL2
CSRm

Recombination of B-like Ar^{13+}@CSRm

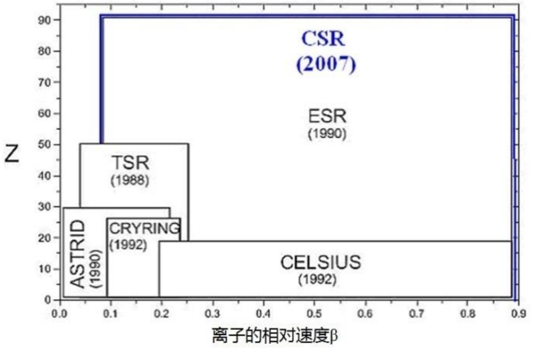


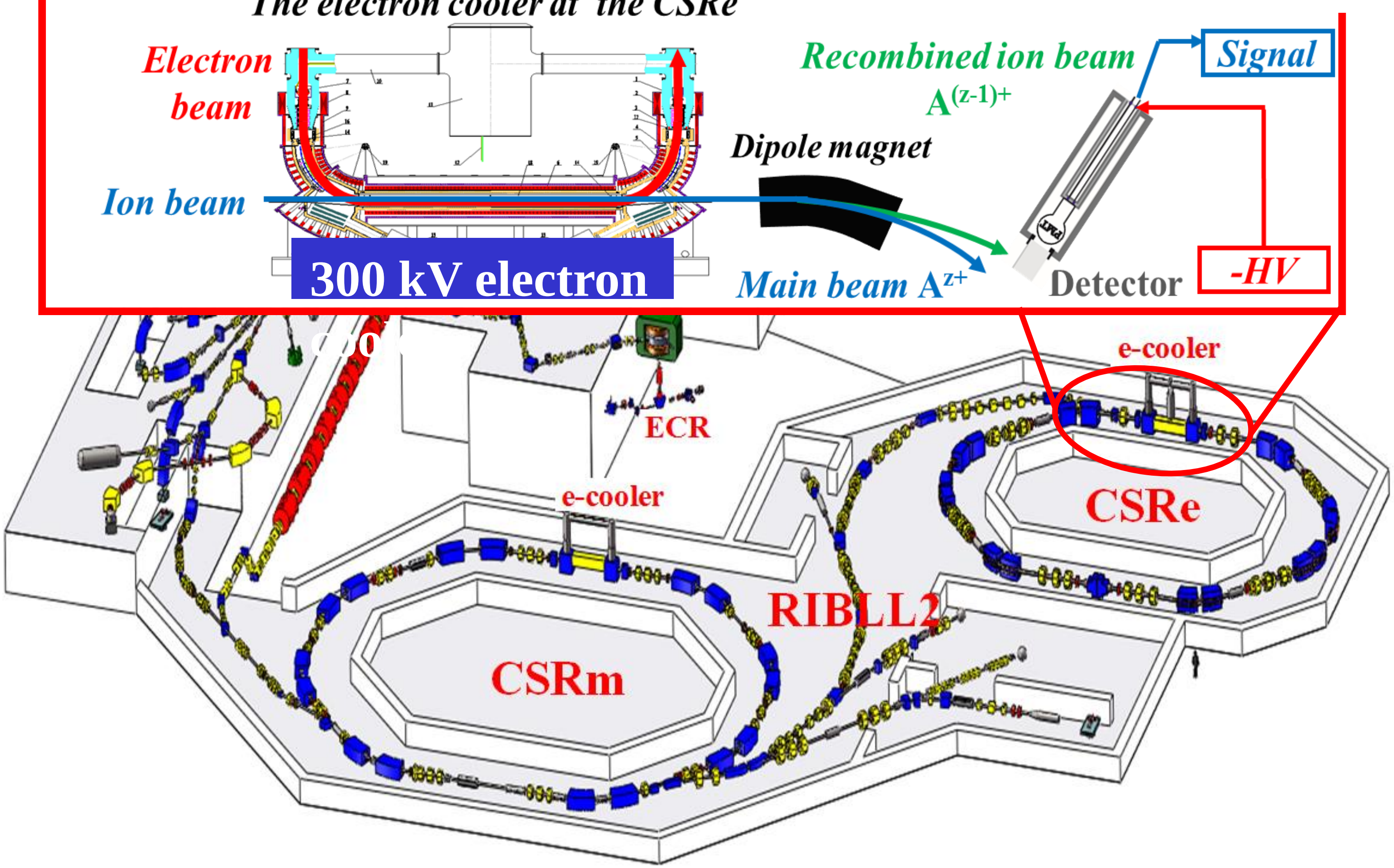


The energy resolution was greatly improved by using the new detuning power supply.

Z. K. Huang et al. (to be submitted)

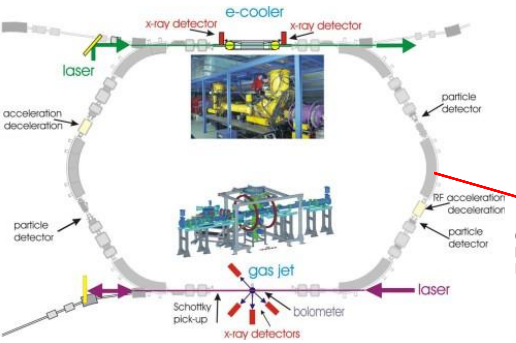
兰州重离子冷却储存环


CSR
(2007)
ESR
(1990)
TSR
(1988)
CRYRING
(1992)
ASTRID
(1990)
CELSIUS
(1992)
Z
90
80
70
60
50
40
30
20
10
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
离子的相对速度β

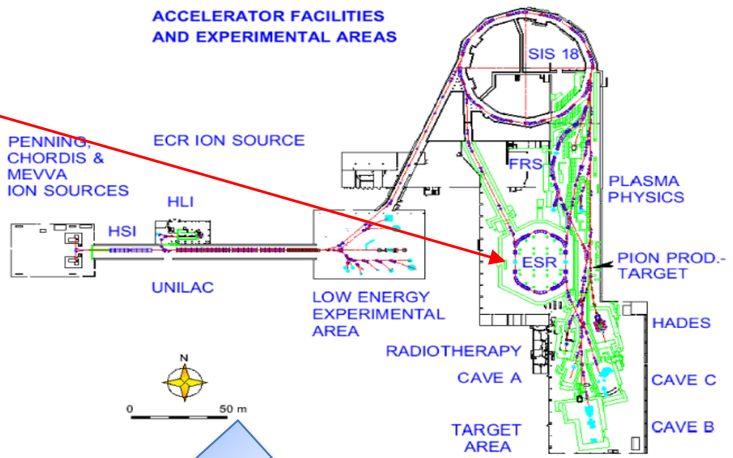

The electron cooler at the CSRe
Electron beam
Ion beam
300 kV electron
Recombined ion beam $A^{(z-1)+}$
Signal
Dipole magnet
Main beam A^{z+}
Detector
-HV
e-cooler
ECR
e-cooler
CSRe
RIBLL2
CSRm

重离子冷却储存环

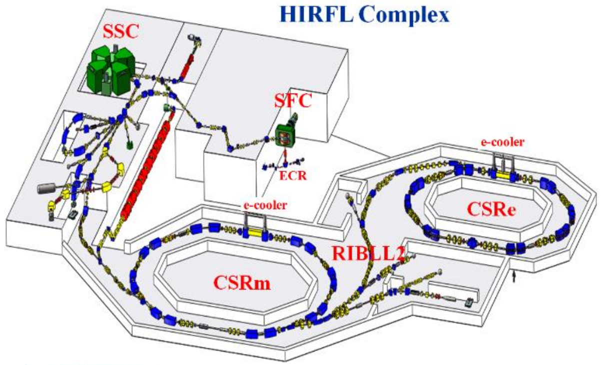
ESR



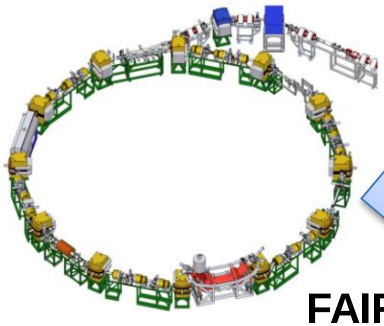
GSI

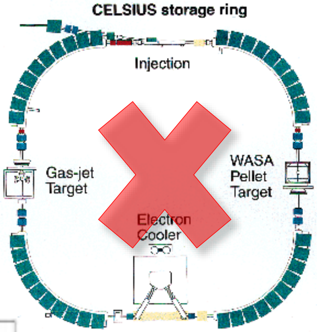


CSR



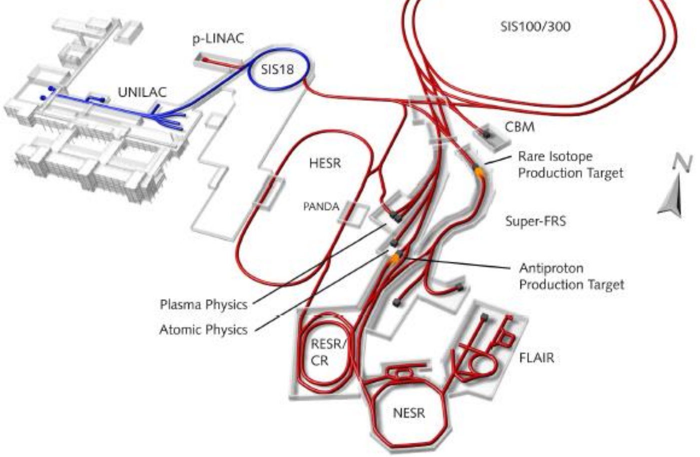
CRYRING



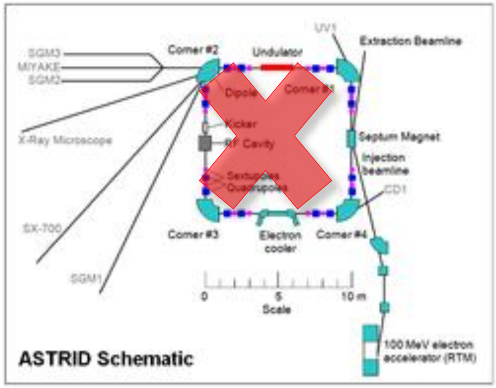


CELSIUS

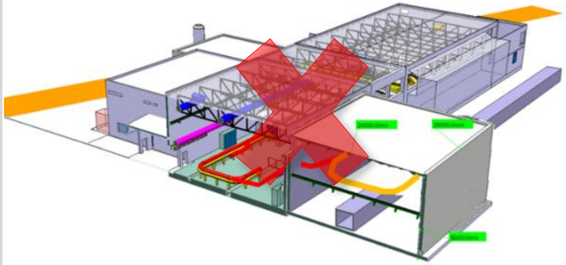
FAIR



ASTRID



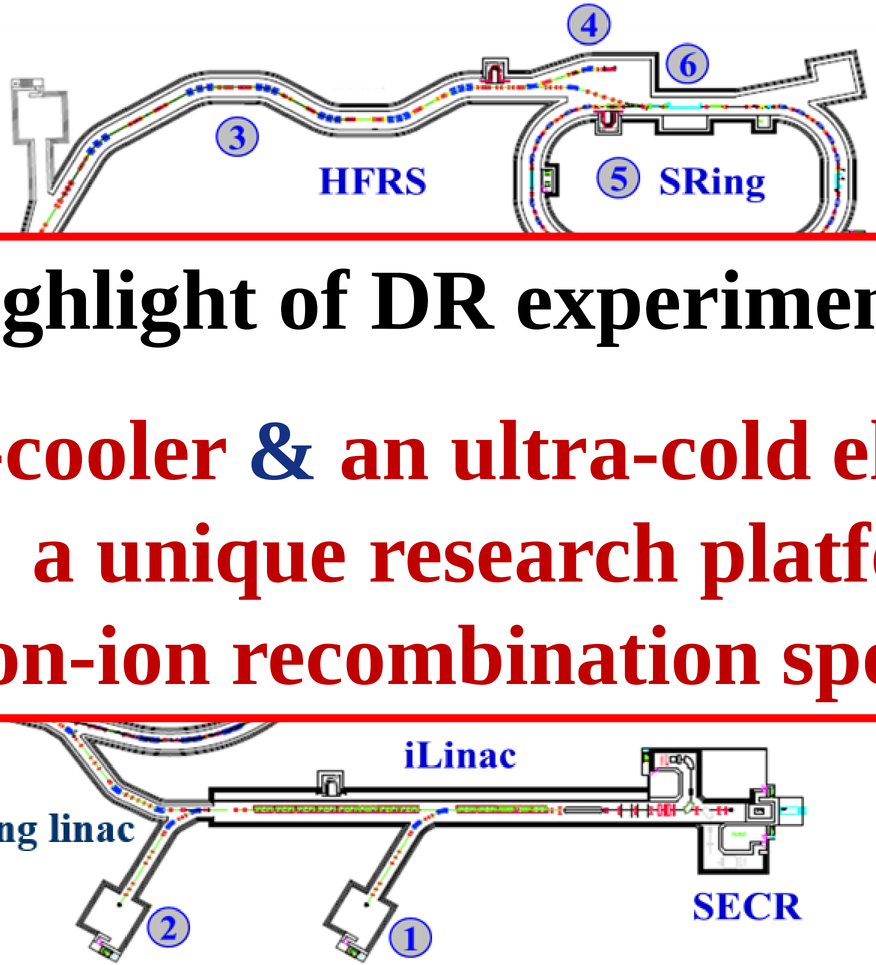
TSR



M. Larssont, Rep. Prog. Phys., 58, 1267, 1995

A. Muller, Adv. Atom. Mol. Opt. Phys., 293, 55, 2008

Outlook-future DR experiment at the HIAF-SRing



SRing: Spectrometer ring
Circumference:290m
Rigidity: 13Tm
Electron/Stochastic cooling
Separated electron target

BRing: Booster ring
Circumference: 530 m
Rigidity: 34 Tm
Beam accumulation

The highlight of DR experiments at HIAF

electron-cooler & an ultra-cold electron-target
a unique research platform
electron-ion recombination spectroscopy!

iLinac: Superconducting linac
Length:100 m
Energy: 17MeV/u(U^{34+})

Z.K. Huang, et al. Nucl. Instr. Meth. B (2017)

2015.12.31，国家发改委批转立项，15.0137亿元，广东省配套基础设施，建设工期7年。

总结展望

未来基于CSRe的双电子复合实验

- 提供天体物理需求离子的复合速率系数

  【提供基准数据；检验理论】

- 提供ITER需要的钨离子的复合速率系数

  【提供基准数据；检验理论】

- 开展高电荷态重离子的双电子复合实验

  【检验强场QED效应】

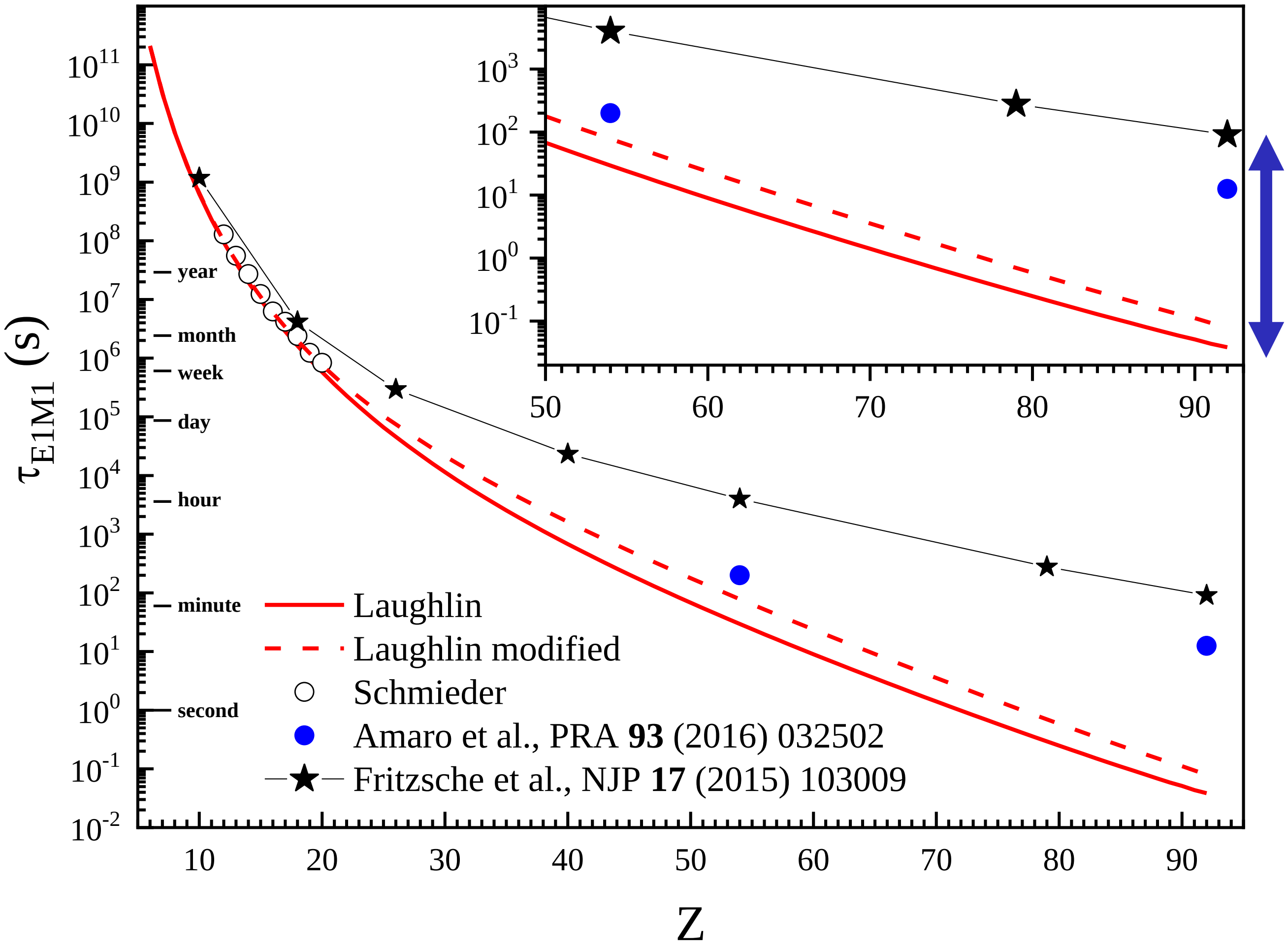
- 利用放射性束流开展双电子复合实验

  【利用DR研究原子核相关信息】

- ……

展望

Possibility to determine the lifetime of E1M1 Two-Photon 2*s*2*p* $^3P_0 \rightarrow 2s^2\ ^1S_0$ Decay



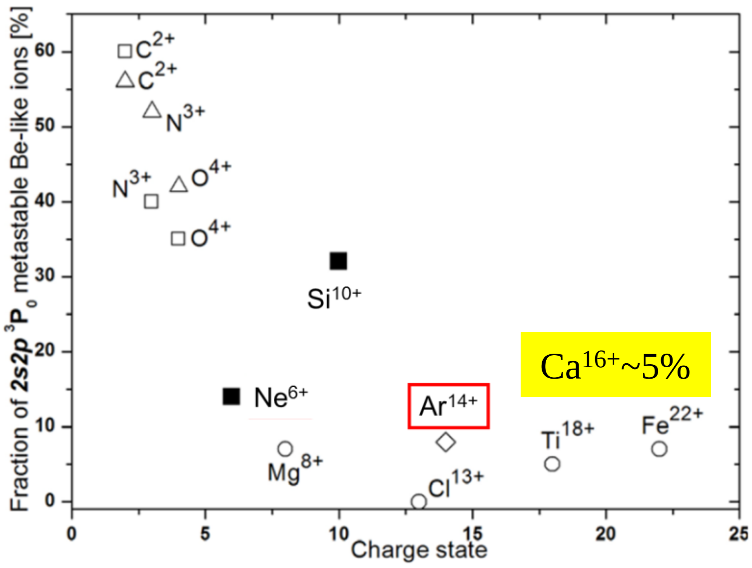
> 3 orders of magnitude

Relativistic theory

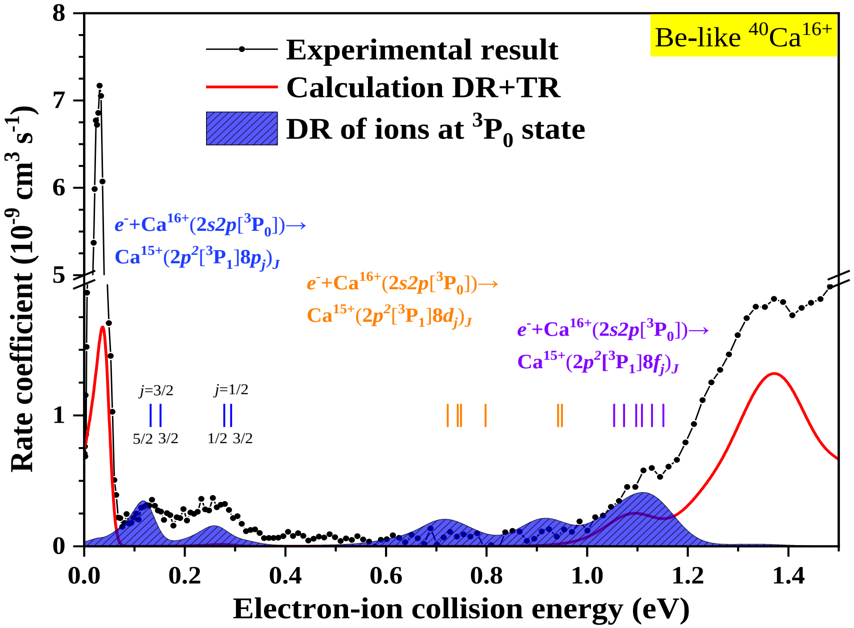
Nonrelativistic theory

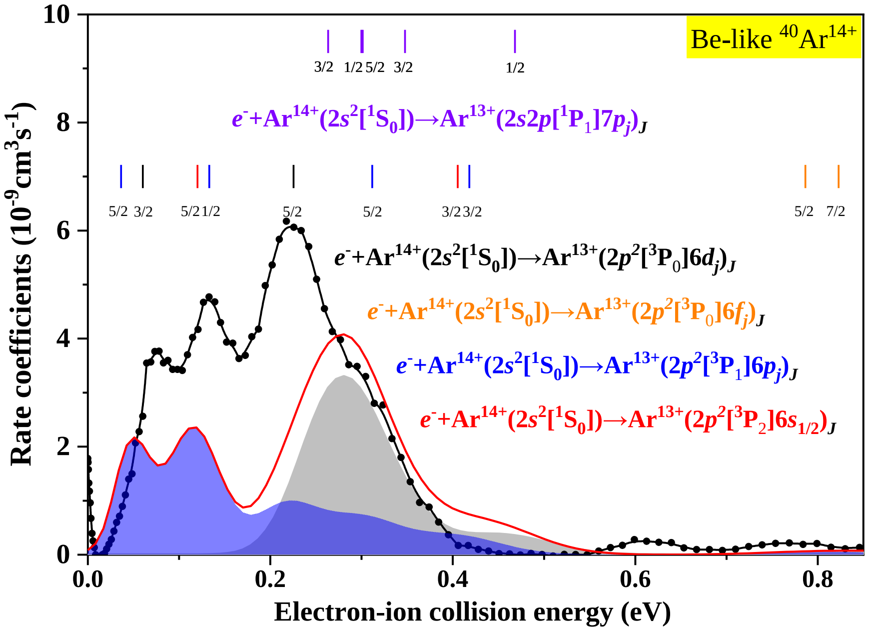
D. Bernhardt *et al.*, JPCS **388** (2012) 012007 see also: J. Grumer *et al.*, PRA **88** (2013) 022513

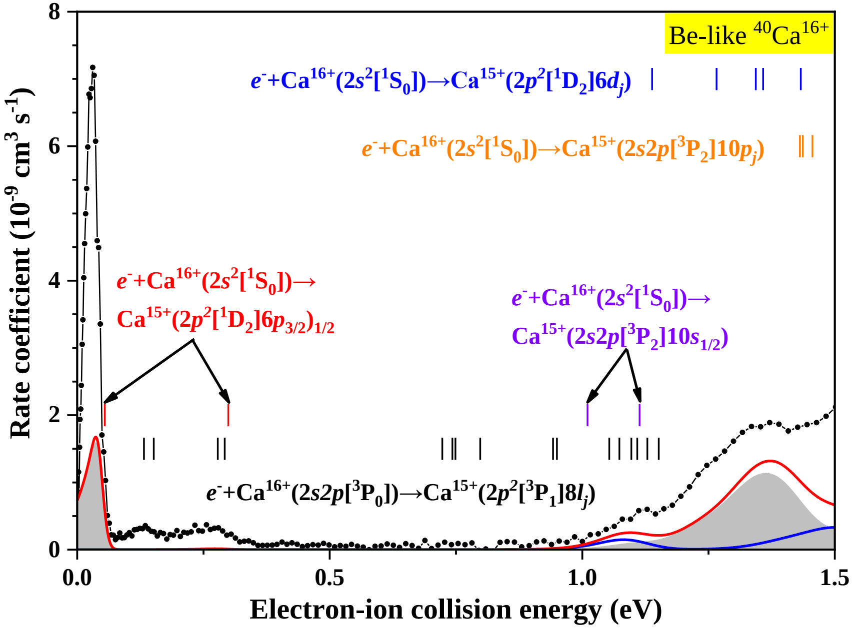
展望



I Orban *et al.*, *Phys. Scr.* **T144** (2011) 014035 (4pp)







致谢

谢谢！