GSI Workshop 02/12/09-10

Crystal-Assisted Virtual X-Ray Spectroscopy

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Resonant Excitation with Virtual Photons・・・・Atomic & Nuclear Systems

$\Delta E = h\nu = \gamma n h \upsilon / a$ ($\sim 10^{-15} X 10^{8} / 10^{-10}$ $n\gamma$ = 10^{3} $n\gamma$ eV)

High Resolution ・・・・ ~20ppm (->1ppm)

Absolute Value

High Sensitivity・・・・Highly Charged Ions, Short Lived Ris, etc

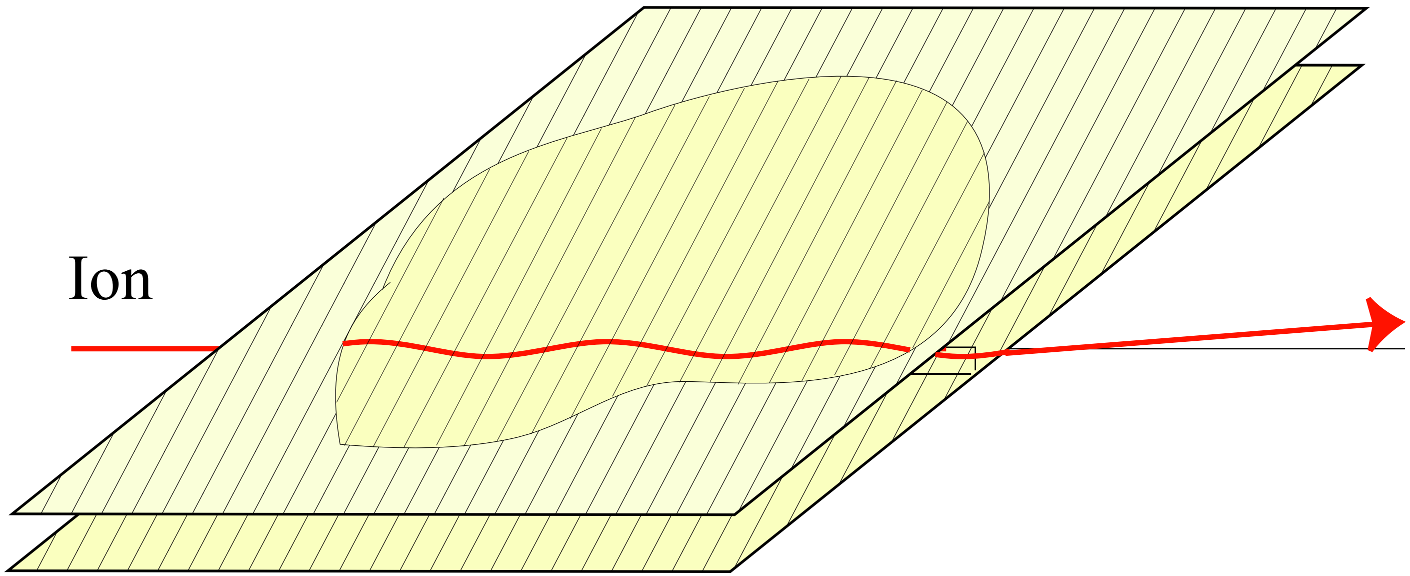
X-ray Dressed States

V.V.Okorokov : Yad. Fiz. 2,1009(1965) [Sov. J. Nucl. Phys. 2, 719(1966)]

S.Datz et al. : Phys. Rev. Lett. 40, 843(1978)

T.Azuma et. al. : Phys. Rev. Lett. 83, 528(1999)

Resonant Coherent Excitation under Planar Channeling Condition



$$E = \frac{\gamma h \nu}{a}\left(\frac{k \cos\theta}{A} + \frac{l \sin\theta}{B} \right)$$

$\gamma = (1 - (\upsilon/c)^2)^{-1/2}$

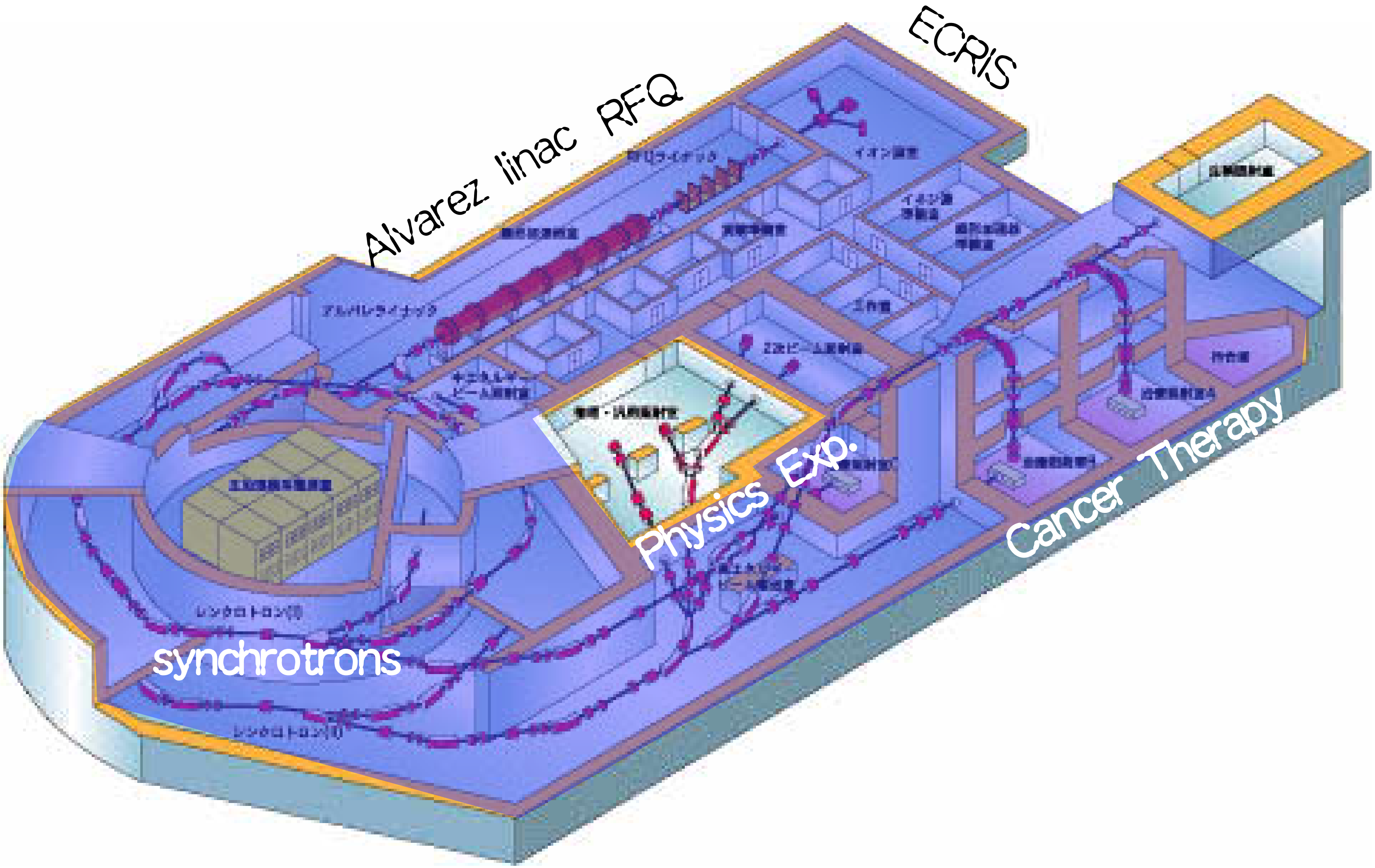
υ : ion velocity

θ : angle between ion velocity & crystal string in the plane

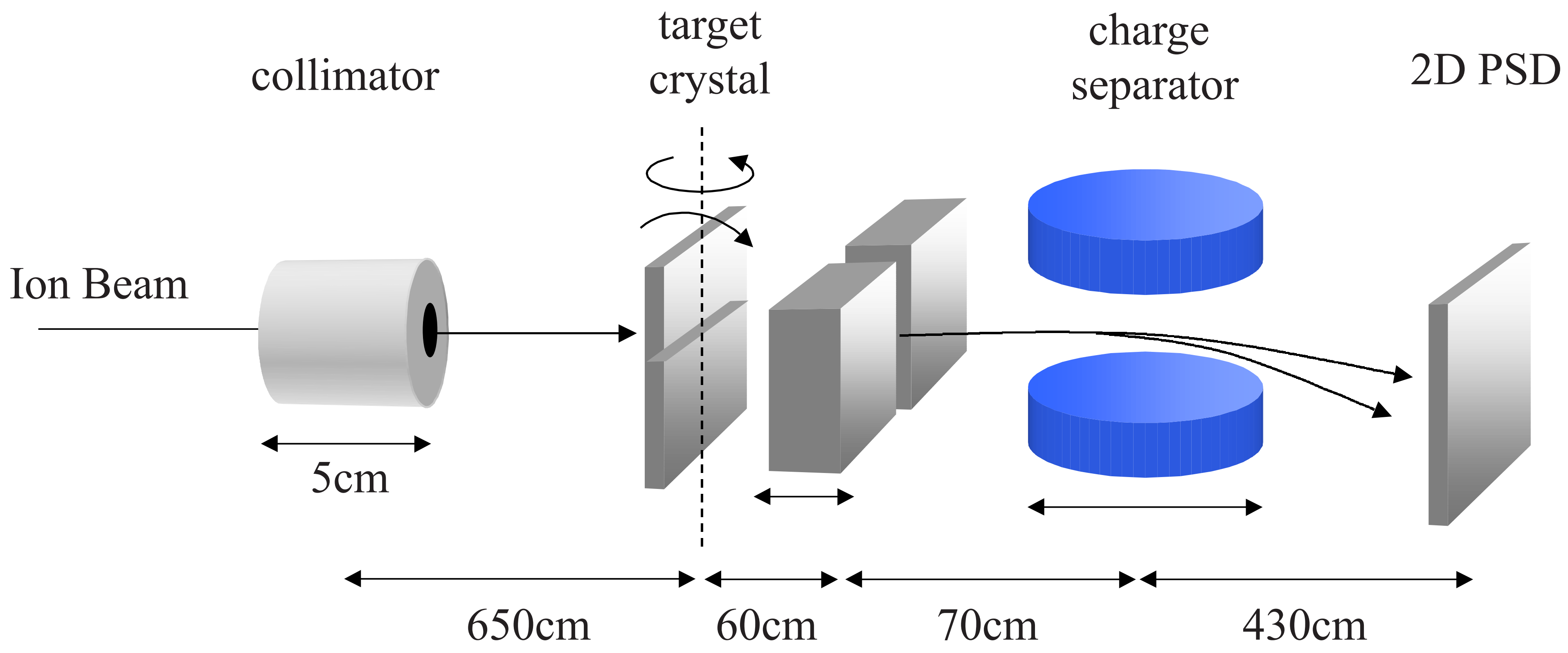
a : lattice constant

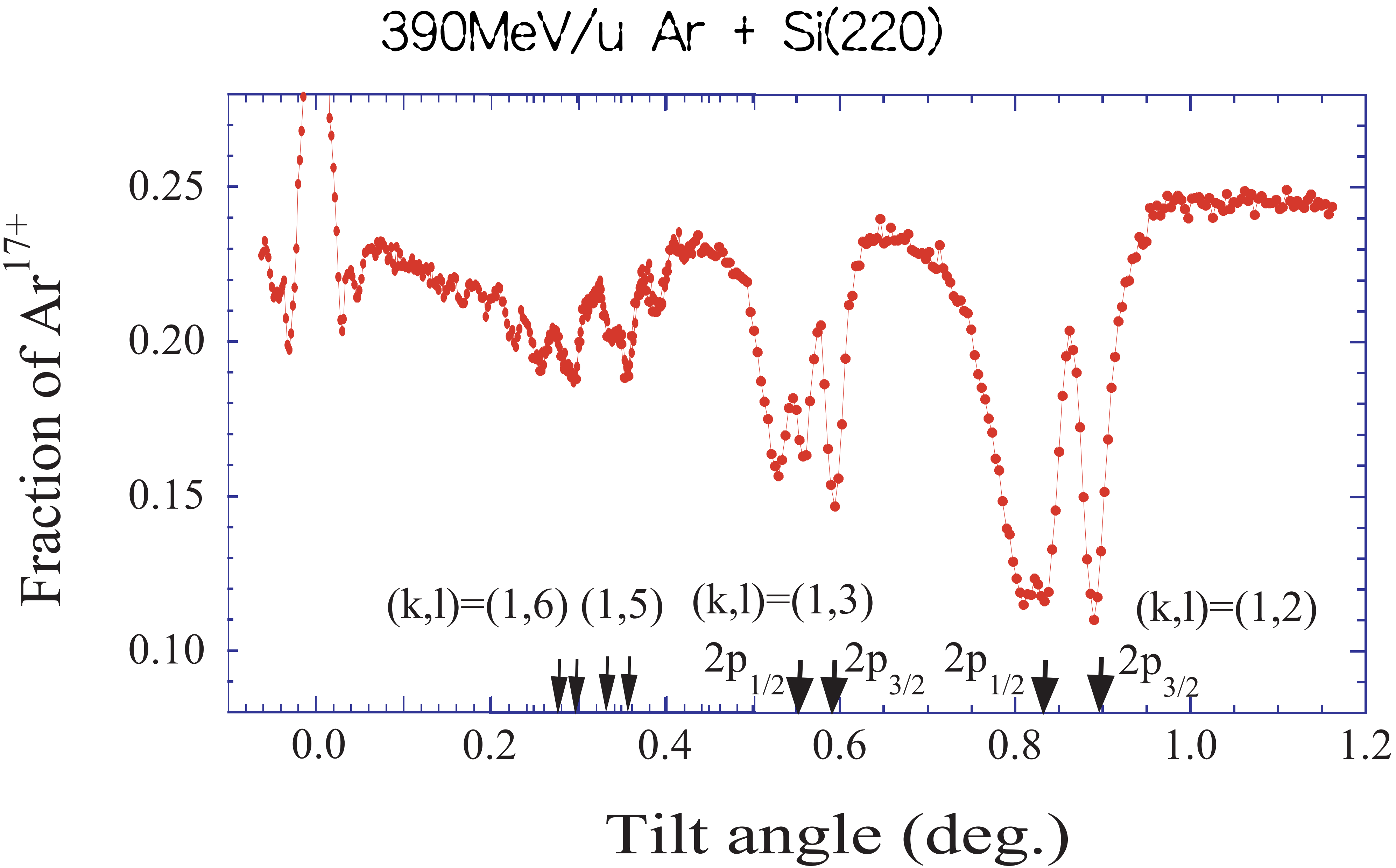
k, l : integer

HIMAC Accelerator Configulation

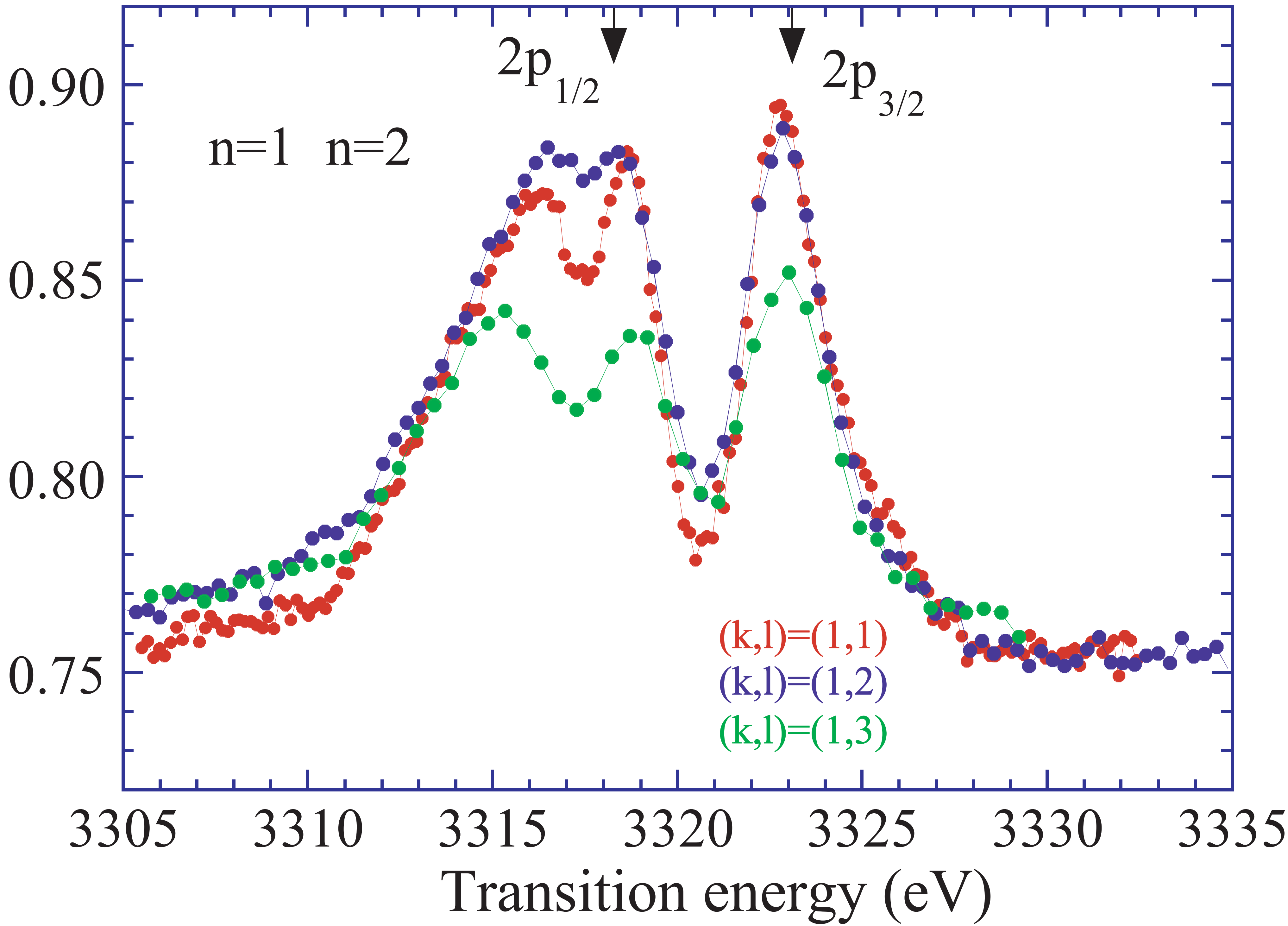


Experimental Setup for Virtual Photon Spectroscopy



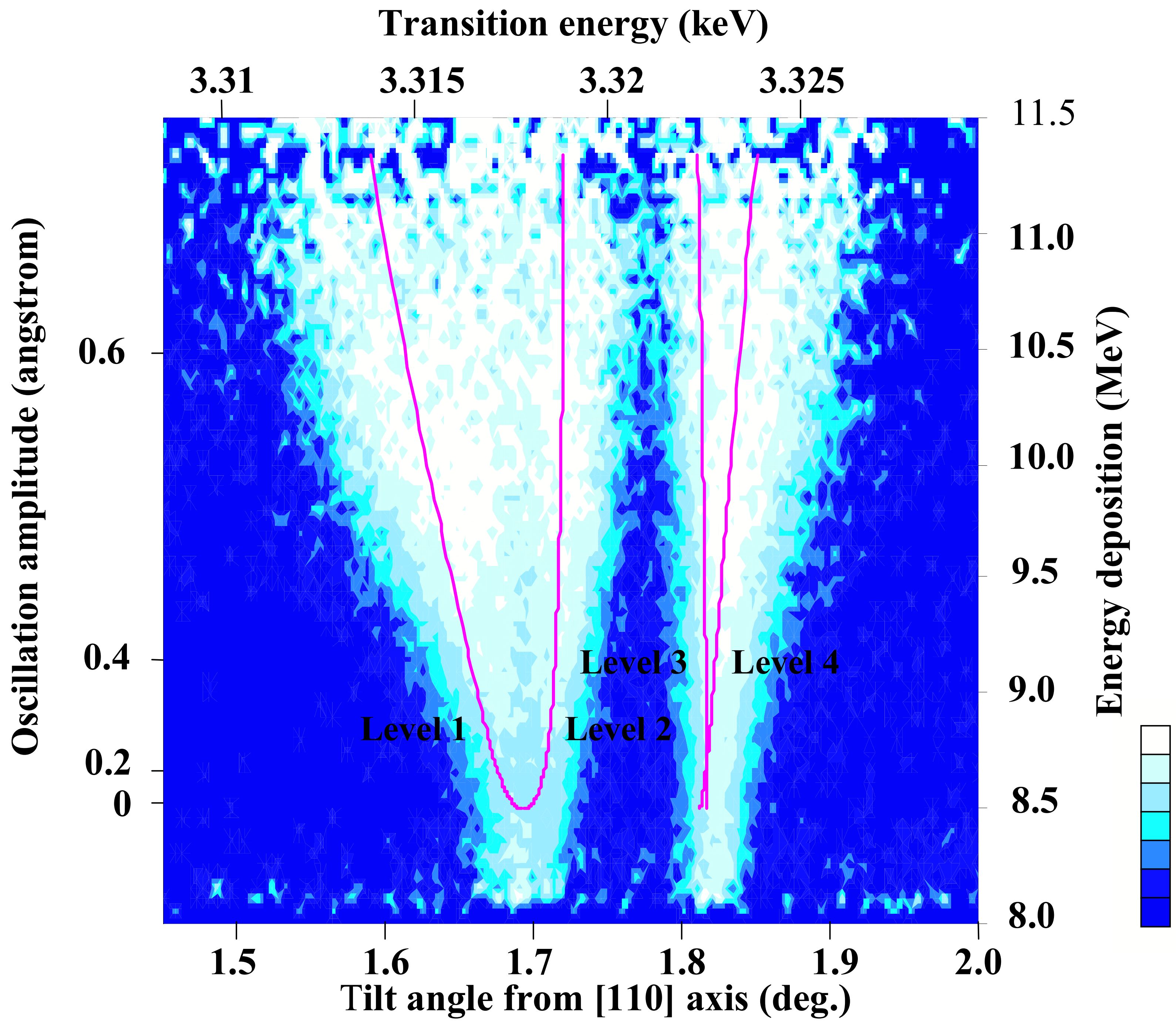


390MeV/u Ar + Si(220)
Fraction of Ar17+
Tilt angle (deg.)
0.10
0.15
0.20
0.25
0.0
0.2
0.4
0.6
0.8
1.0
1.2
(k,l)=(1,6) (1,5)
(k,l)=(1,3)
(k,l)=(1,2)
2p1/2
2p3/2
2p1/2
2p3/2

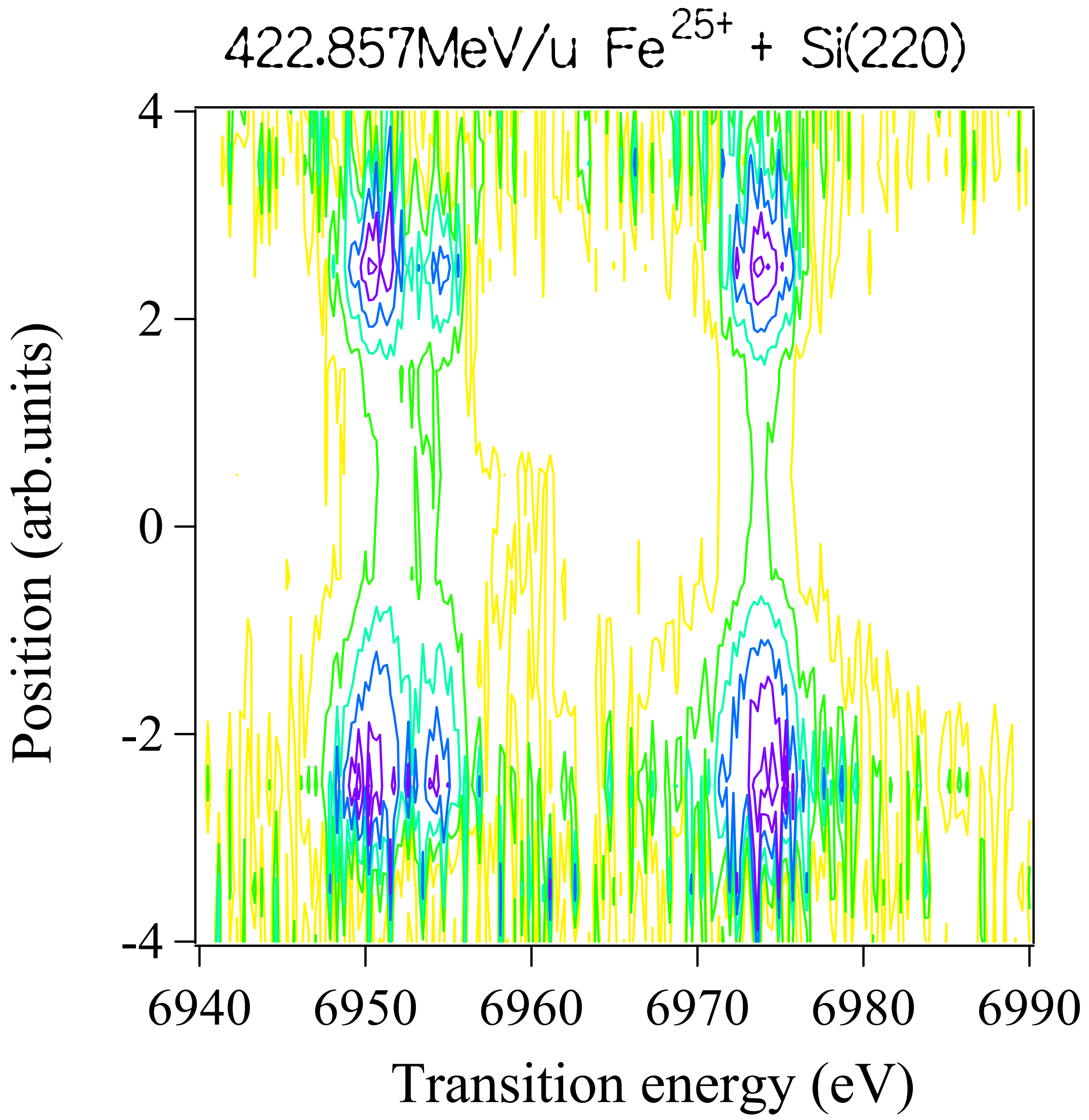


0.90
0.85
0.80
0.75
2p1/2
2p3/2
n=1 n=2
(k,l)=(1,1)
(k,l)=(1,2)
(k,l)=(1,3)
3305
3310
3315
3320
3325
3330
3335
Transition energy (eV)

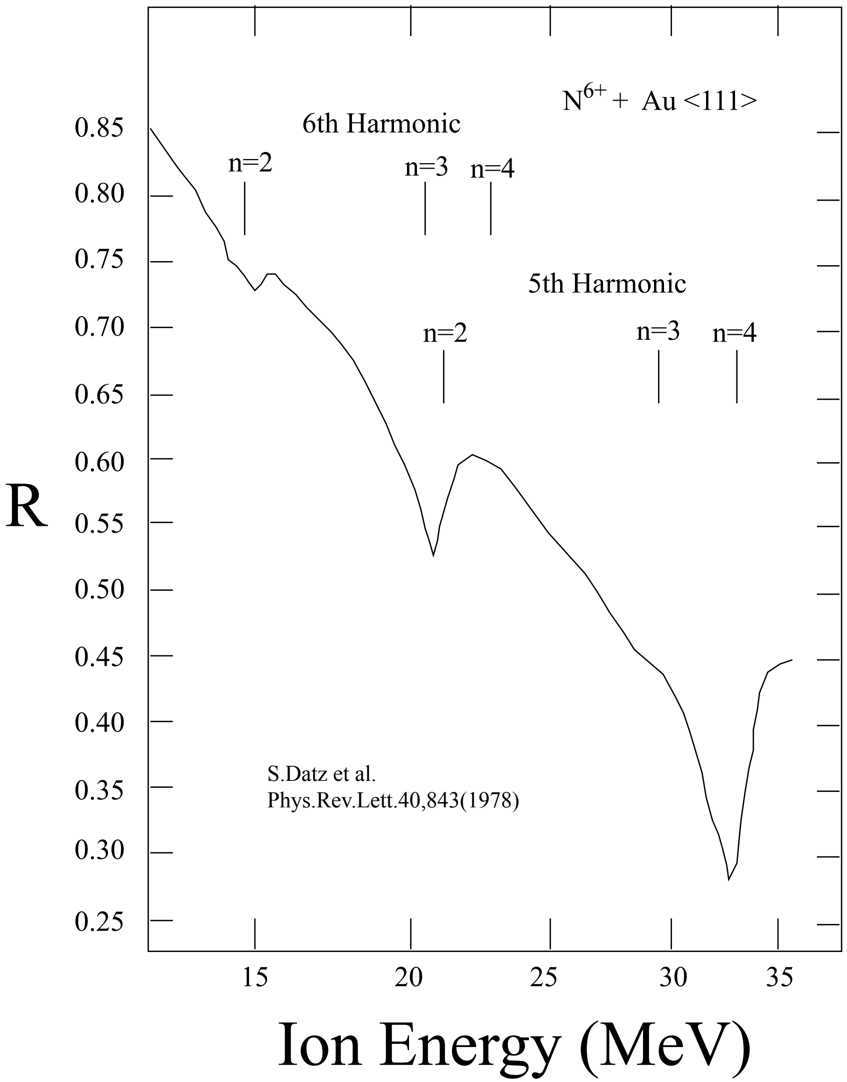
Deposition Energy Differential Excitation



Emission Angle Differential Excitation

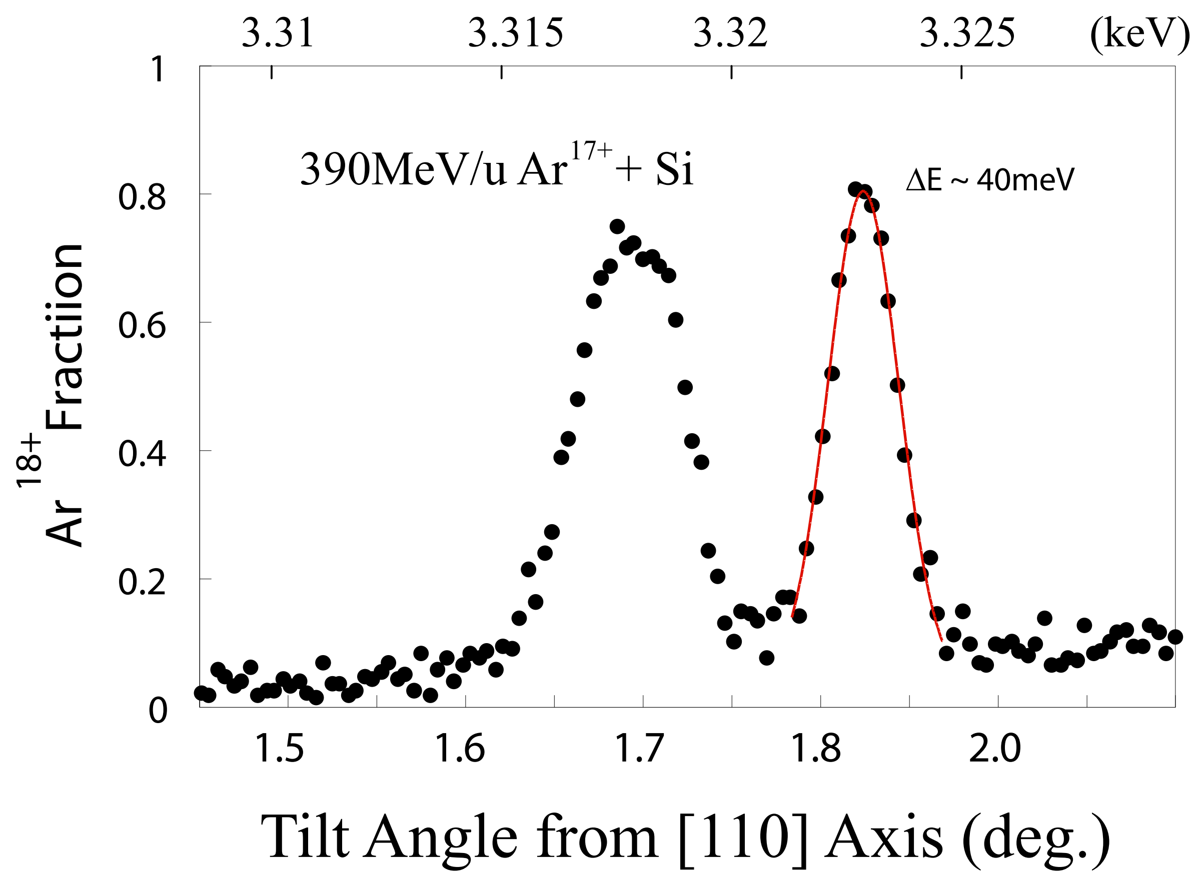


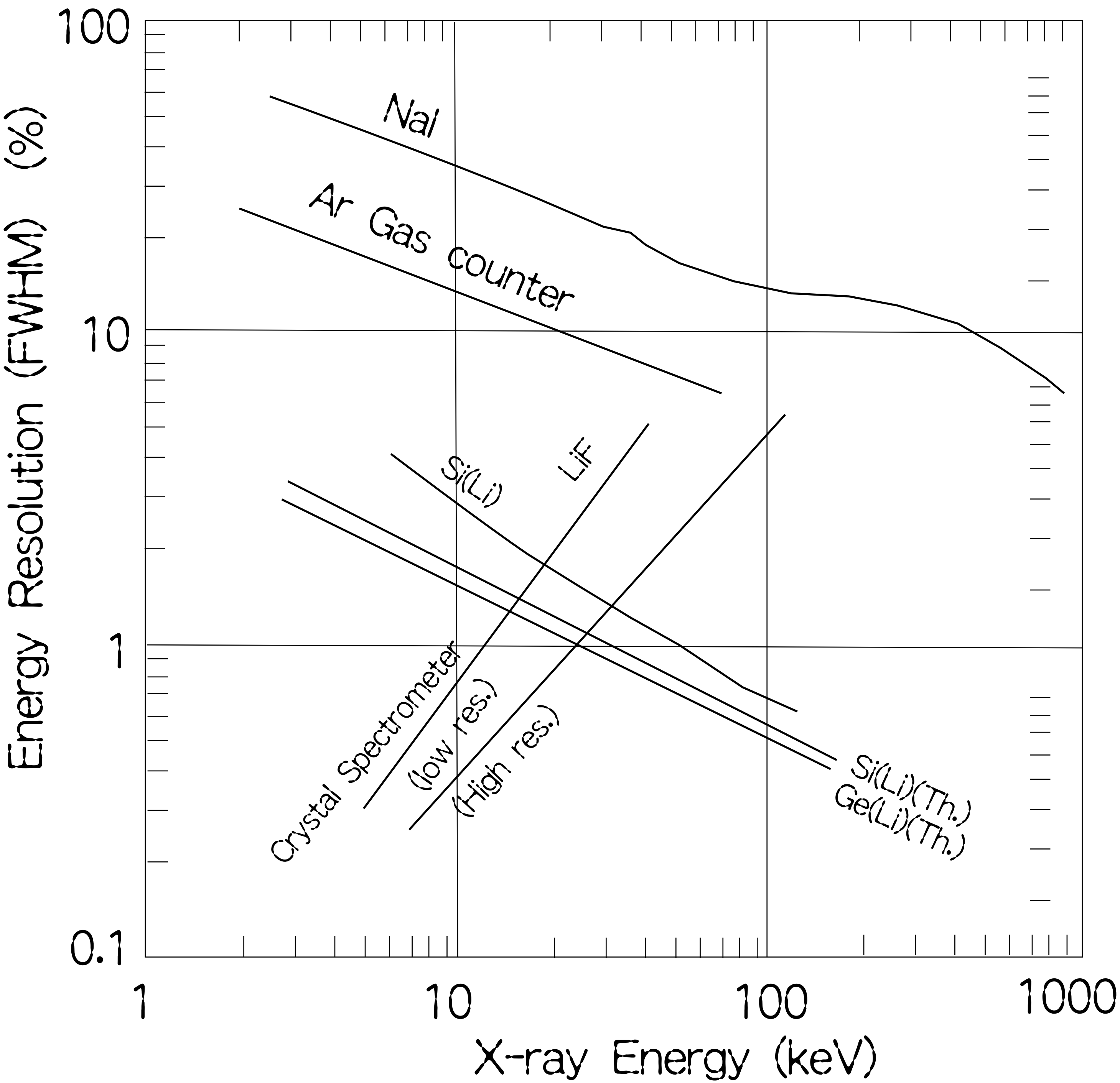
$\Delta E/E_{FWHM} \sim 6\%$



S.Datz e al., Phys.Rev.Lett.40,843(1978)

$\Delta E/E_{FWHM} \sim 600ppm$





100
10
1
0.1
1
10
100
1000
X-ray Energy (keV)
Energy Resolution (FWHM) (%)
NaI
Ar Gas counter
Si(Li)
LiF
Crystal Spectrometer
(low res.)
(High res.)
Si(Li)(Th.)
Ge(Li)(Th.)

Corrections : Crystal Potential

$\Delta\varepsilon = \langle 1s|U|1s\rangle - \langle n|U|n\rangle \sim k(n^2/q)^2/2$ (~0.4eV for Ar1s-2p in Si)

Rabi Oscillation :

$\tau = 2M^2 \sin(\Omega t)/\Omega$ (~6μm for 390MeV/u Ar in Si)

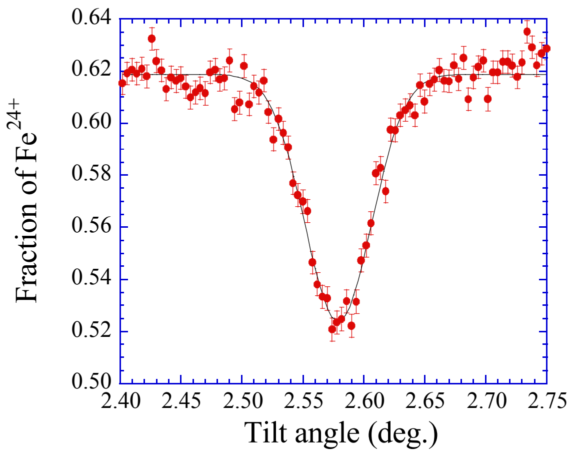
where $\Omega=(\Delta^2+4M^2)^{1/2}$, $\Delta=(\varepsilon_2-\varepsilon_1)-2\pi n\gamma\upsilon/a$

(Virtual-) Photon Flux ~ 10^{24} photons/mm^2/sec/eV

Spectroscopy of He-like Fe^{24+} ion

(1) Observation of RCE of Fe^{24+}

[$1s^2 \rightarrow 1s2p\ ^1P_1$]



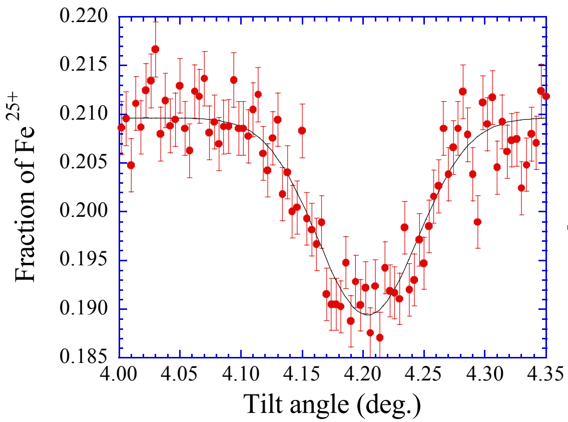
(2) Observation of RCE of Fe^{25+}

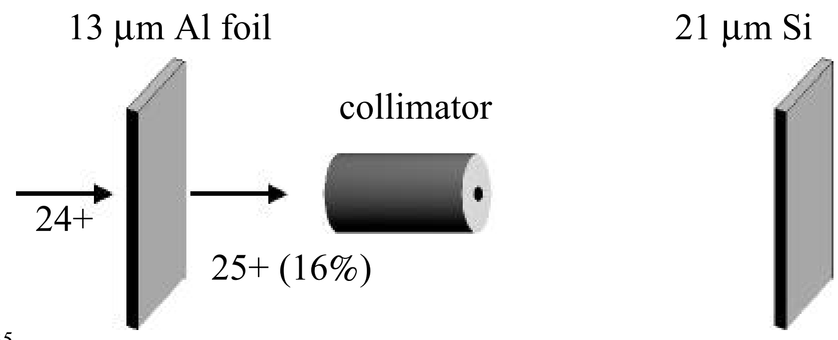
[$1s \rightarrow 2p(j=3/2)$]

θ , E_{trans} (theory)

$\Downarrow$

ion velocity v





Fe^{24+}	Cheng et al Rel. CI PRA50,2150('94)	Drake Unif. th. Can. J.Phys. 66,586('88)	Plante et. al. All-order unpub. ('94)	Indelicate et al. MCDF J.Phys.B20, 651('87)	Beiersdorfer et al. PRA40,150('89)	Briand et al. PRA29,3143('84)	present
$^1P_1$	6700.539	6700.404	6700.427	6700.603	6700.73 +- 0.20	6700.90 +- 0.25	6700.22 +- 0.16
$^3P_1$	6667.692	6667.552	6667.567	6667.669		6667.50 +- 0.25	6667.52 +- 0.17
Ar^{16+}	Cheng et al Rel. CI PRA50,2150('94)	Drake Unif. th. Can. J.Phys. 66,586('88)	Plante et. al. All-order unpub. ('94)	Indelicate et al. MCDF J.Phys.B20, 651('87)	Deslattes et al. J.Phys.B17 L689('84)	Briand et al. PRA28,1413('83)	present
$^1P_1$	3139.617	3139.577	3139.582	3139.649	3139.55 +- 0.04	3139.57 +- 0.25	3139.27 +- 0.15
$^3P_1$	3123.574	3123.530	3123.534	3123.567	3123.52 +- 0.04	3123.60 +- 0.25	3123.30 +- 0.16

Limiting Factors of the Resolution

Coherent Length:

$l_{ion} \sim (q^4 \rho_{el} \sigma_{ion}(\upsilon/q)/n^4)^{-1}$ (~15μm for 390MeV/u Ar(2p) in Si[110])

$l_{dexc} \sim 25(\gamma\upsilon/a^3 q^4)$ (~4.6μm for 390MeV/u Ar(2p) in Si[110])

$l_{osc} \sim \upsilon/\omega_{osc}$ (~2μm for 390MeV/u Ar in Si[110])

$\omega_{osc} \sim (kq/m\gamma)^{1/2}$ ($U=kx^2/2$: k~0.033a.u. for Si[110])

$\Delta\varepsilon/\varepsilon \sim a/l_{min}$ (~10^{-5} for 390MeV/u Ar in Si[110])

Energy Loss:

$\Delta\upsilon_{E\text{-}loss}/\upsilon$ (~ 3×10^{-6}/μm for 390MeV/u Ar in Si[110])

Thermal Expansion

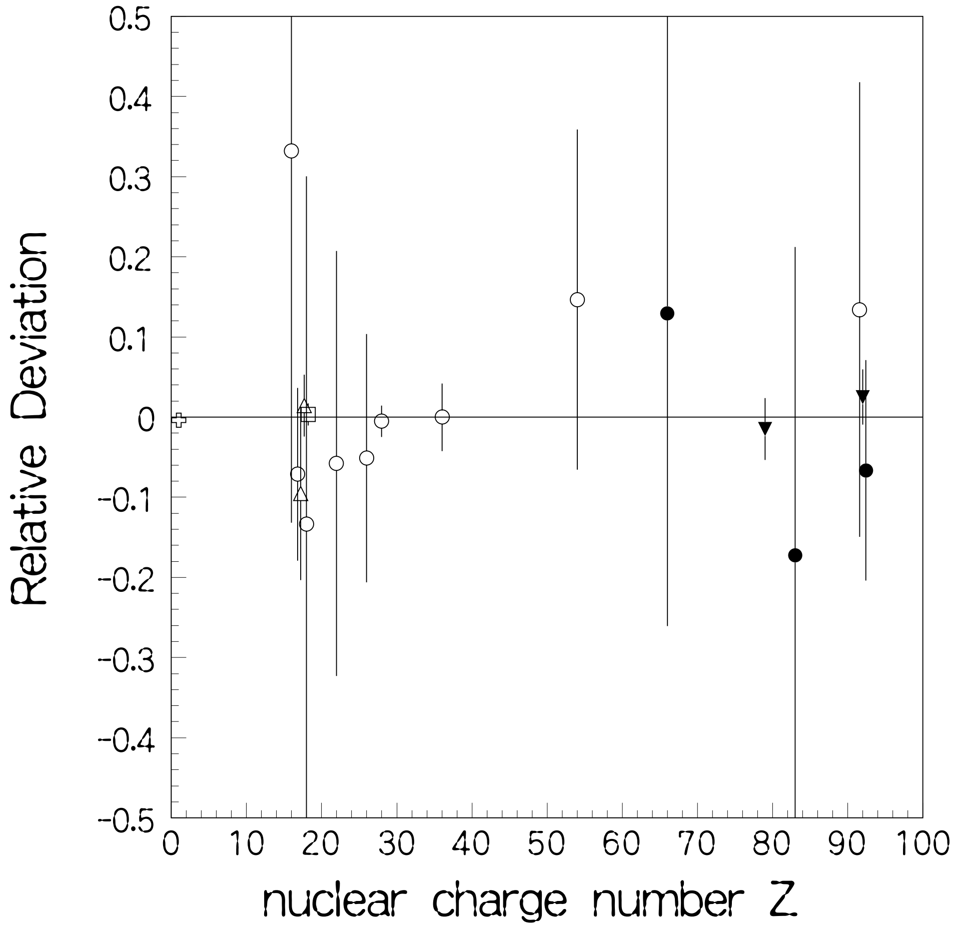
κ (~ 2.5×10^{-6}/K)

Case Study: Possible Accuracy of 1s Lamb Shift

$R \sim {}_{Lamb}\ \ {}_{1s\text{-}2p} \sim 10^{-6}Z^{4}\ \ {}_{R}/Z^{2}\ \ {}_{R} \sim 10^{-6}Z^{2}$

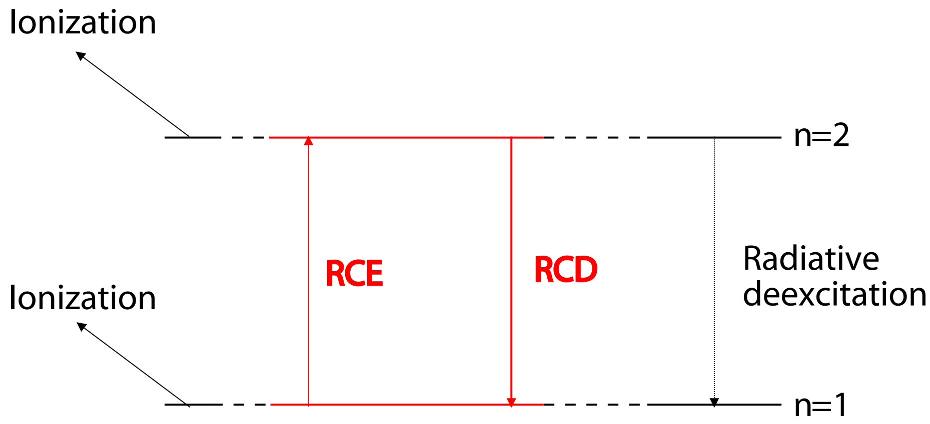
If ${}_{1s\text{-}2p}$ is determined with the precision of ppm, relative accuracy of 1s Lamb shift could be

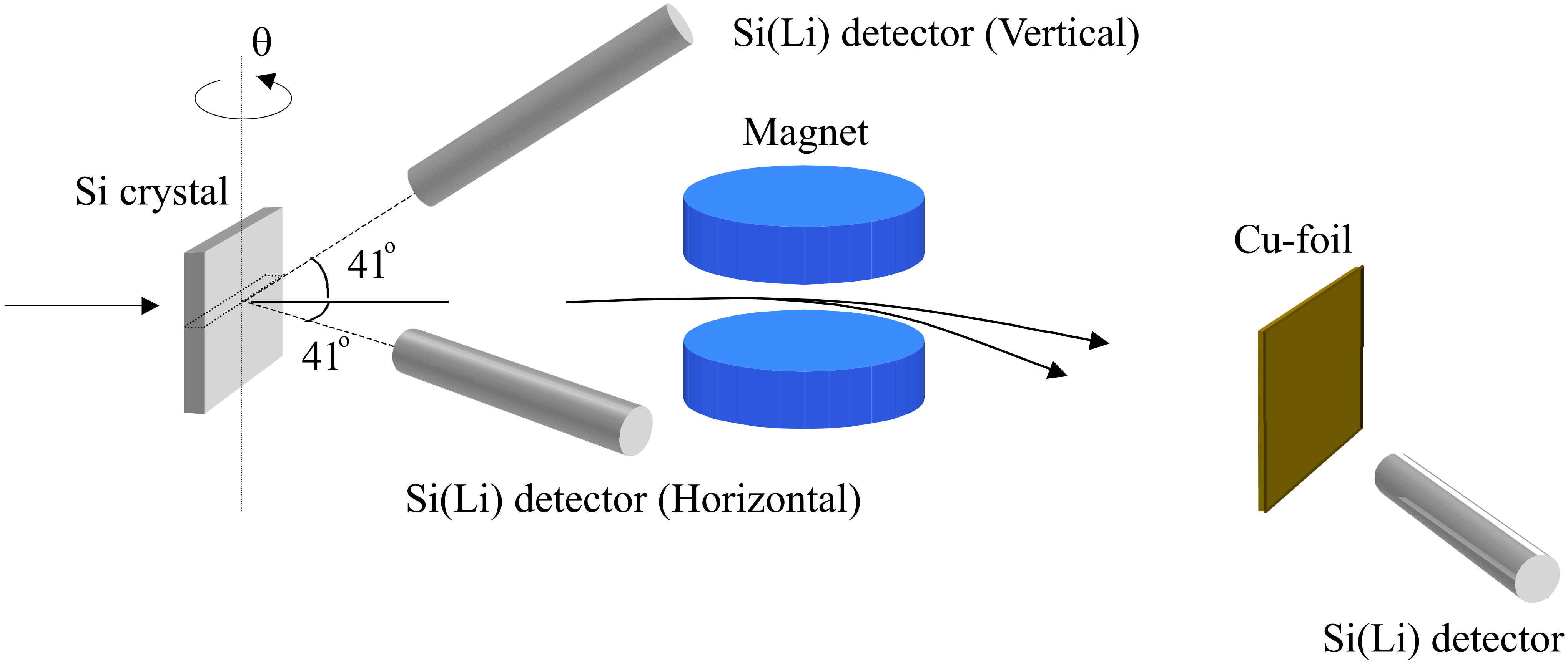
$R_{Lamb} \sim\ \ {}_{Lamb}\ \ {}_{Lamb} \sim Z^{-2}$



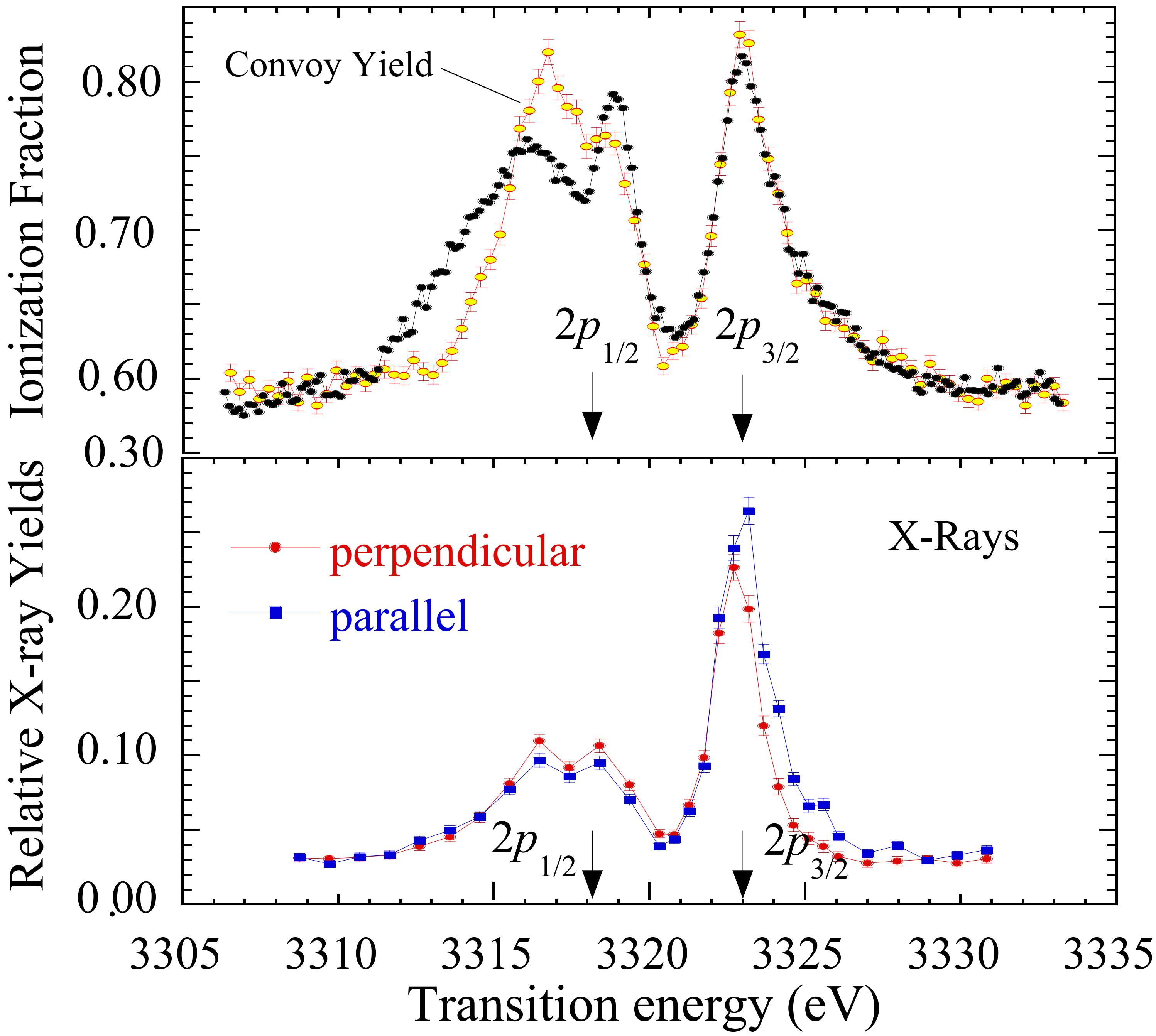
P.J.Mohr,G.Plunien, and G.Soff, Phys.Rep.293,227(1998)

Excitation Dynamics : X-rays & Convoy Electrons

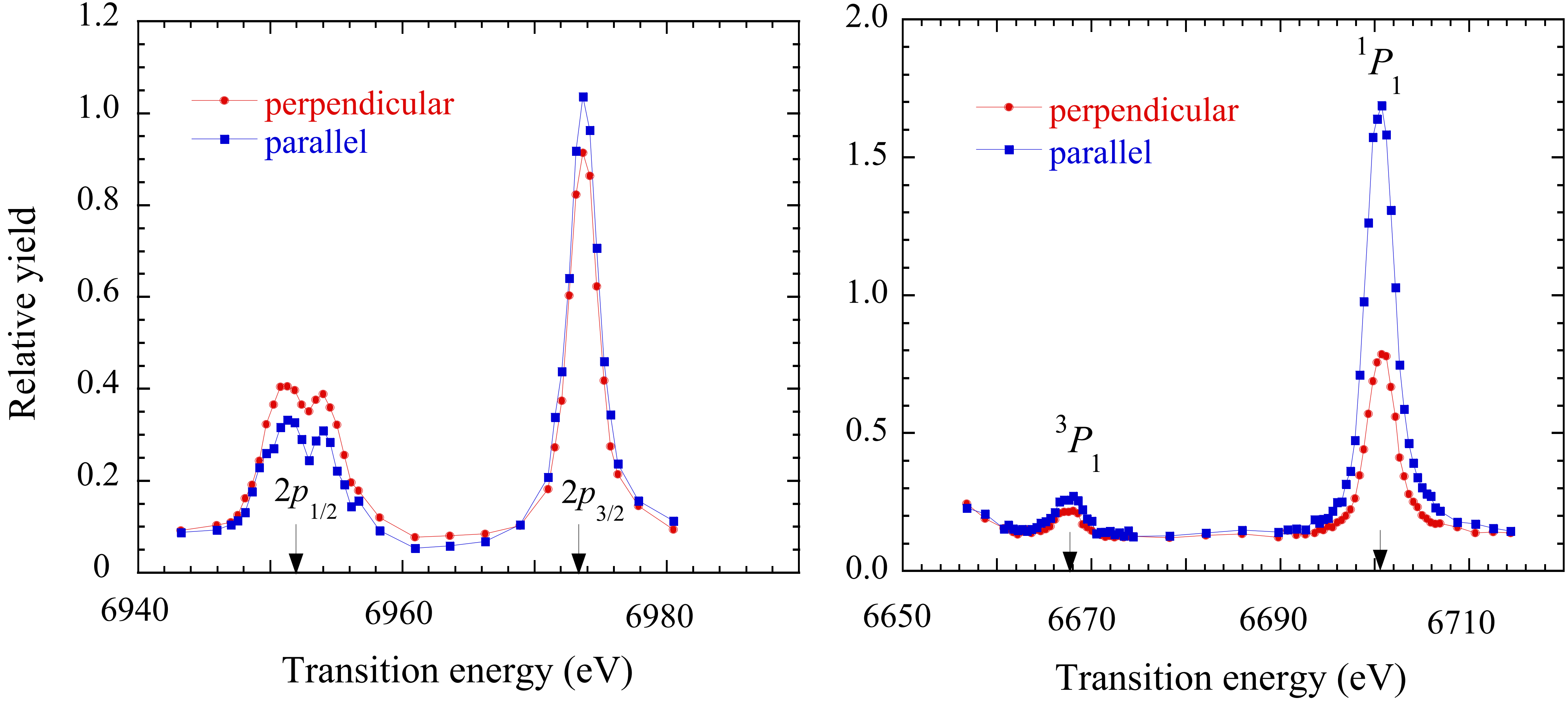


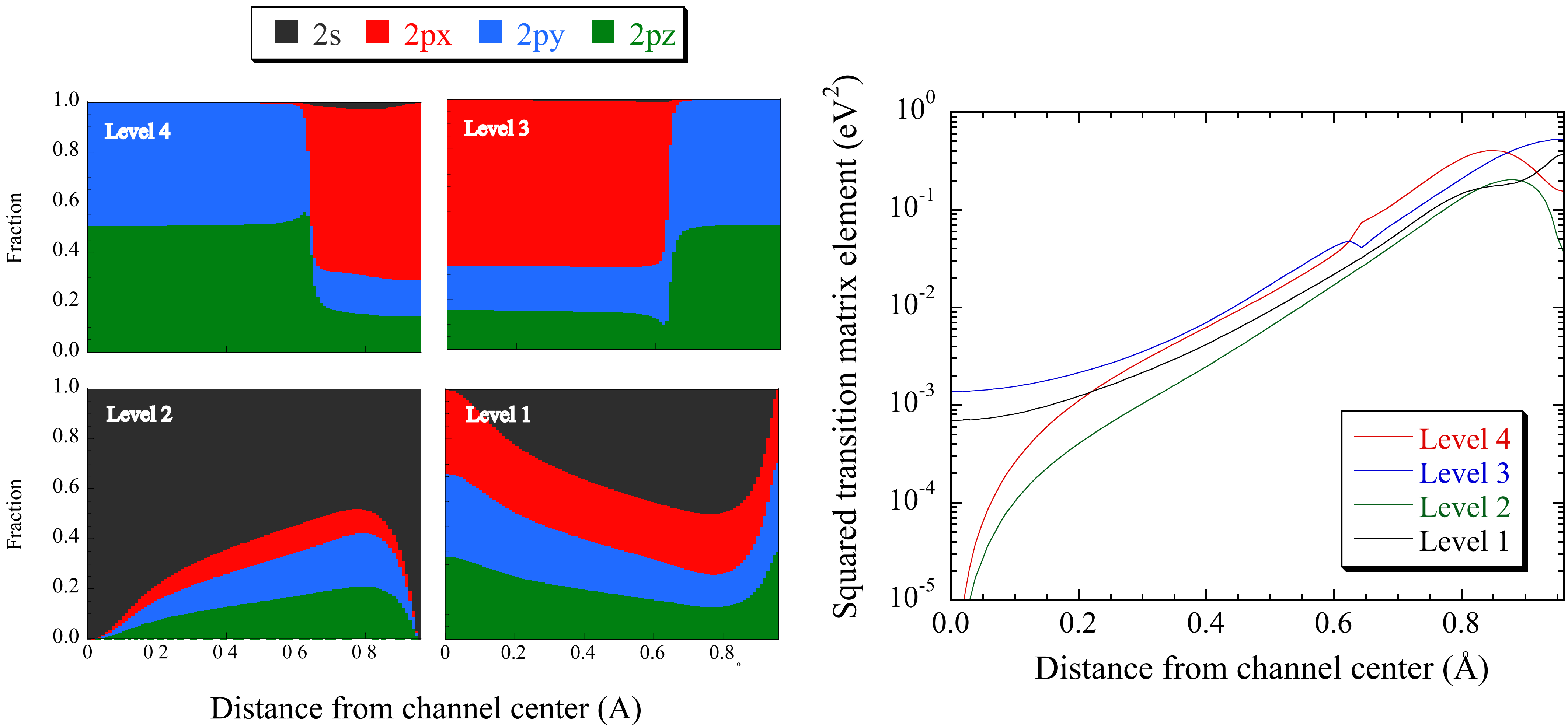


390MeV/u Ar^{17+} Resonance Profile for Charge State, Convoy, & X-ray Yields

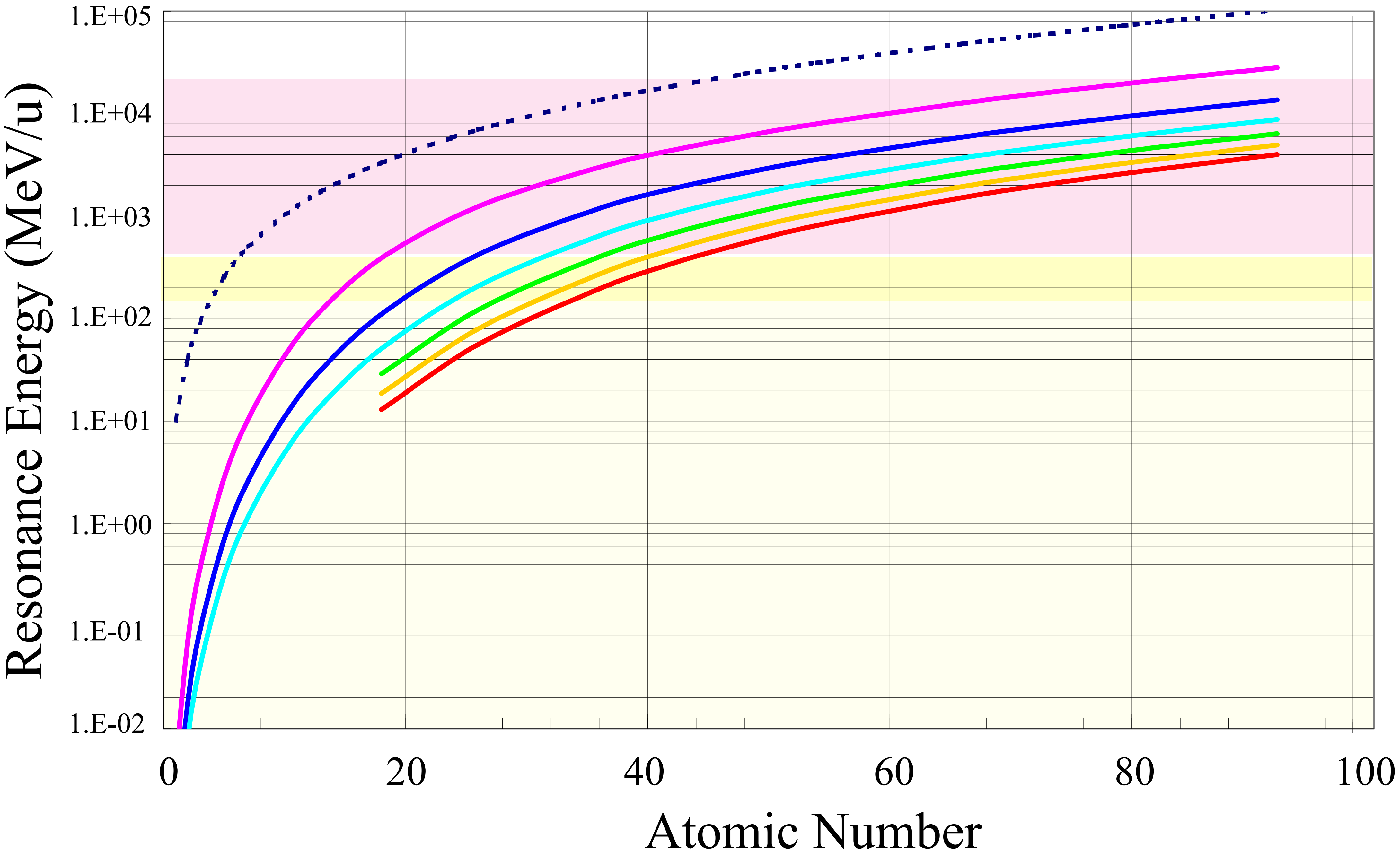


X-ray Emission from Fe^{25+} & Fe^{24+}

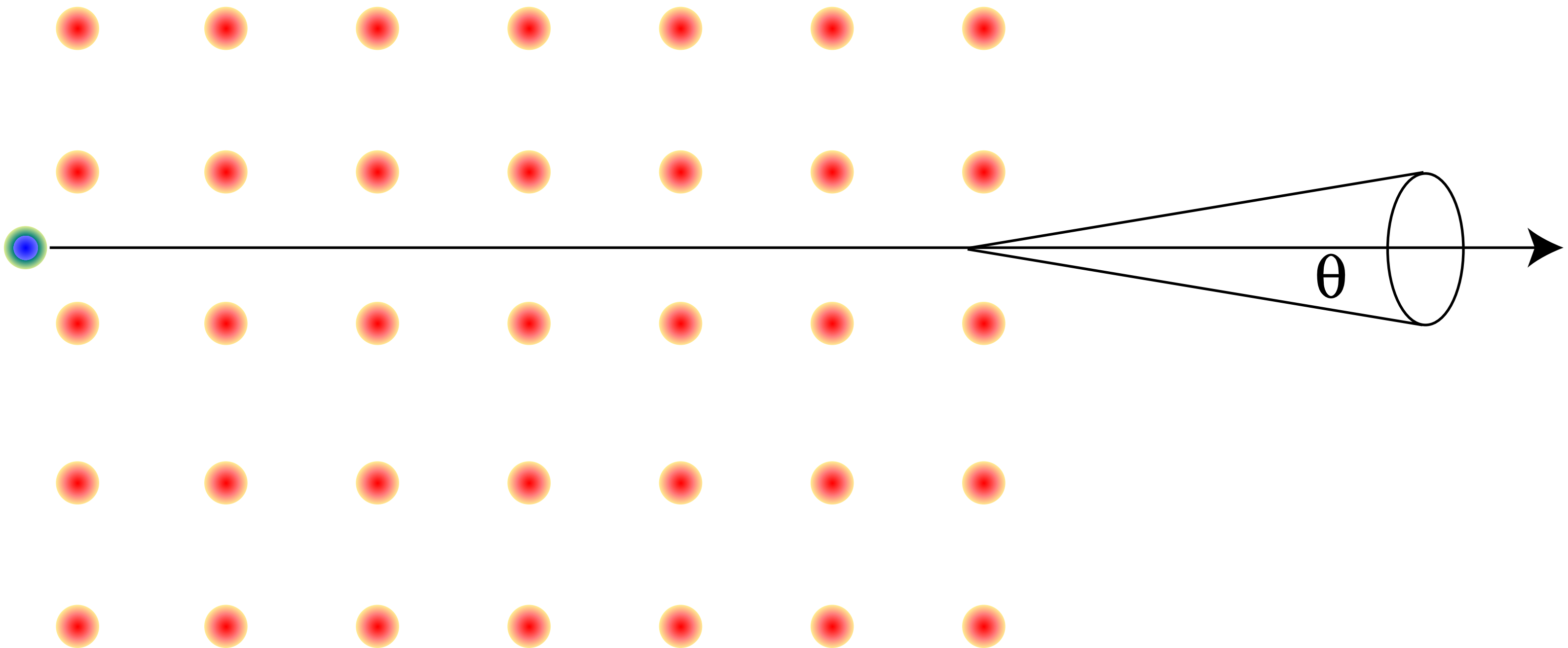



2s
2px
2py
2pz
Level 4
Level 3
Level 2
Level 1
Fraction
1.0
0.8
0.6
0.4
0.2
0.0
0
0.2
0.4
0.6
0.8
Distance from channel center (A)
Squared transition matrix element (eV^2)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Level 4
Level 3
Level 2
Level 1
Distance from channel center (Å)

Resonance Energy of 1s-2p in Si[110]



X-ray energies from rce process for relativistic ions

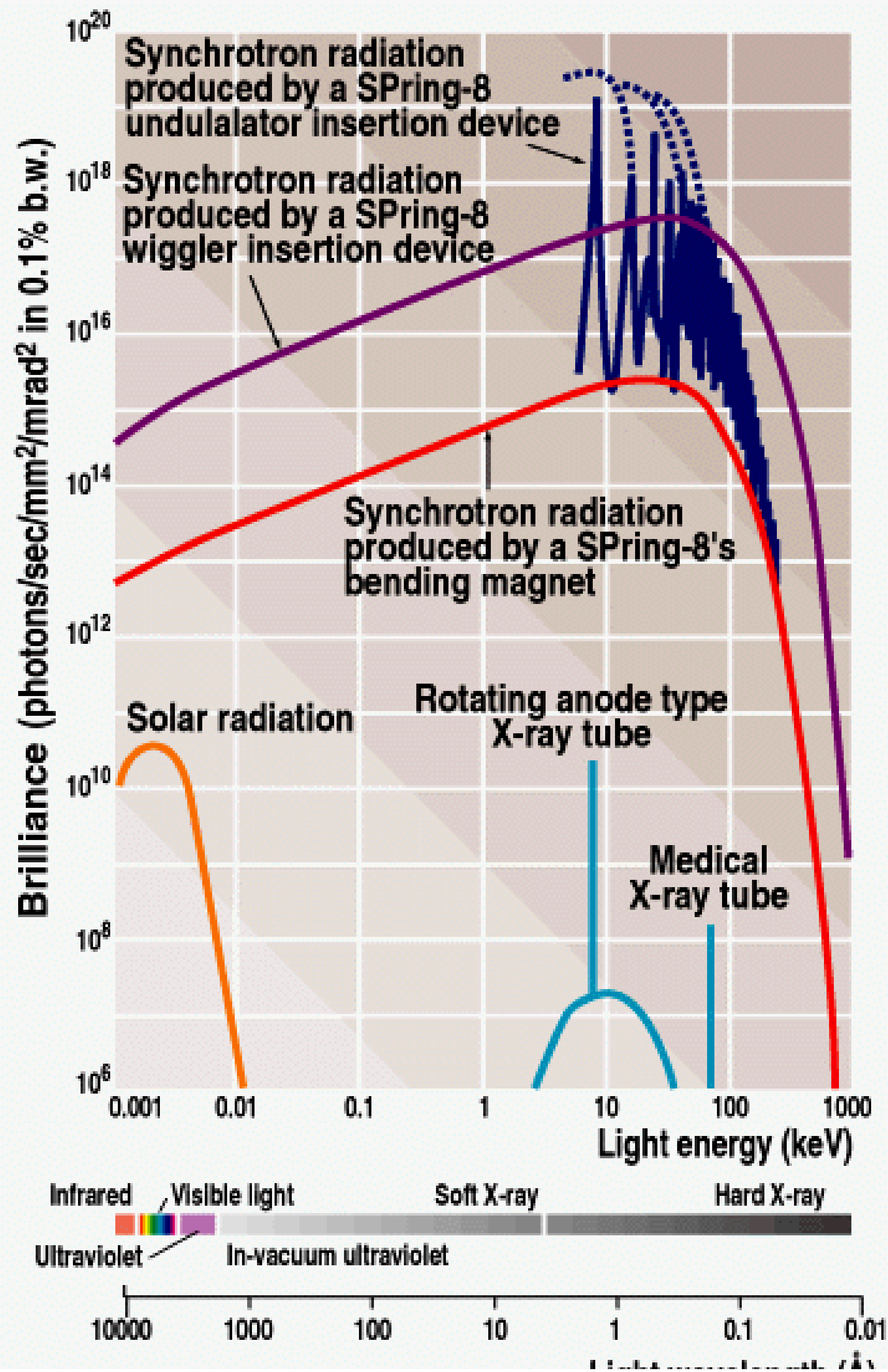


angular distribution : $\theta \sim 1/\gamma$

$$\varepsilon = \gamma(1 + \beta \cos\theta)\,\Delta E \underset{\substack{\gamma \to \infty \\ \theta \to 0}}{\longrightarrow} (2\gamma - \gamma\theta^2/2)\,\Delta E$$

@20GeV/u U

$\varepsilon \sim 3$MeV



Synchrotron radiation produced by a SPring-8 undulalator insertion device
Synchrotron radiation produced by a SPring-8 wiggler insertion device
Synchrotron radiation produced by a SPring-8's bending magnet
Solar radiation
Rotating anode type X-ray tube
Medical X-ray tube
Brilliance (photons/sec/mm²/mrad² in 0.1% b.w.)
10^20
10^18
10^16
10^14
10^12
10^10
10^8
10^6
0.001
0.01
0.1
1
10
100
1000
Light energy (keV)
Infrared
Visible light
Soft X-ray
Hard X-ray
Ultraviolet
In-vacuum ultraviolet
10000
1000
100
10
1
0.1
0.01

Summary

New Way of High Resolution Spectroscopy in X-ray Range

1-10 Million Ions are Enough・・・HCI, Short-Lived Nuclei

Dynamics in Ion-Crystal Interaction

X-ray Dressed States

New Polarized Gamma Ray Source・・・Conversion from Virtual Photon to Real Photon


ORNL
S.Datz
T.Ito
Y.Takabayashi
TMU
T.Azama
T.Muranaka
NIRS
E.Takada
T.Murakami
T.Kondo
Y.Yamazaki
K.Komaki

Angular Distribution of X-rays

$$I(\theta') = A \cos\theta'$$

$$\tan\theta = \frac{(1-\beta^2)^{1/2}\sin\theta'}{\cos\theta' + \beta}$$