Low-energy Nuclear Physics program at CNS

Nobuaki Imai
今井 伸明

Low Energy Nuclear Reaction Group

Q. Whether do I belong to Shimoura-san's lab?

A. No. I don't. I'll run my own lab.

Research

- Nuclear Astrophysics - Exploring the Cosmos
- Low-energy nuclear reaction
- Nuclear Spectroscopy for Extreme Quantum System (NUSPEQ)
- Quark Physics
- Spin-Isospin Physics
- SHARAQ Project
- Heavy-Ion Accelerator Technology

See http://www.cns.s.u-tokyo.ac.jp/index.php?Research

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Contents

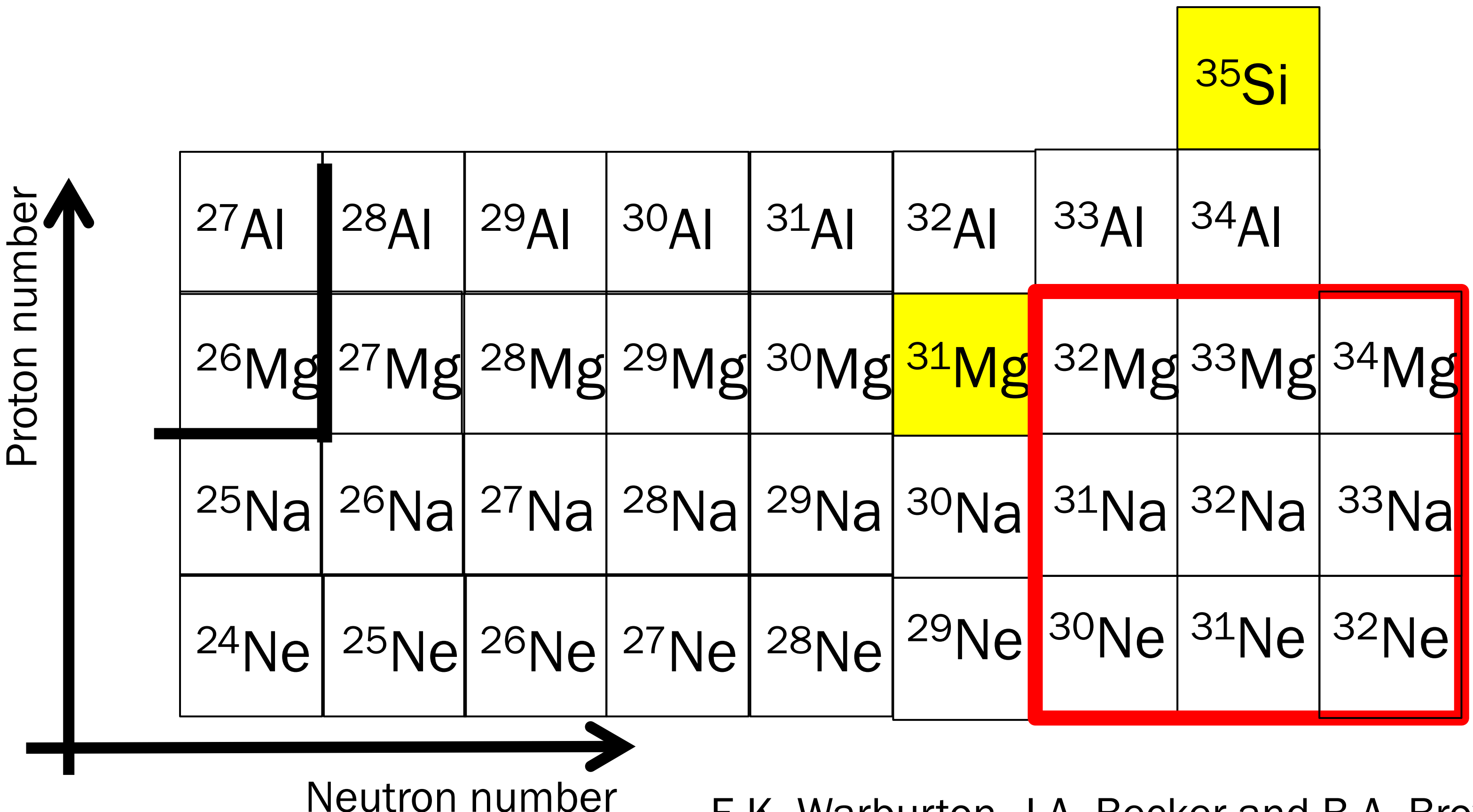
- Nuclear structure study via proton resonance elastic scattering

- Developing exotic targets

NUCLEAR STRUCTURE STUDY

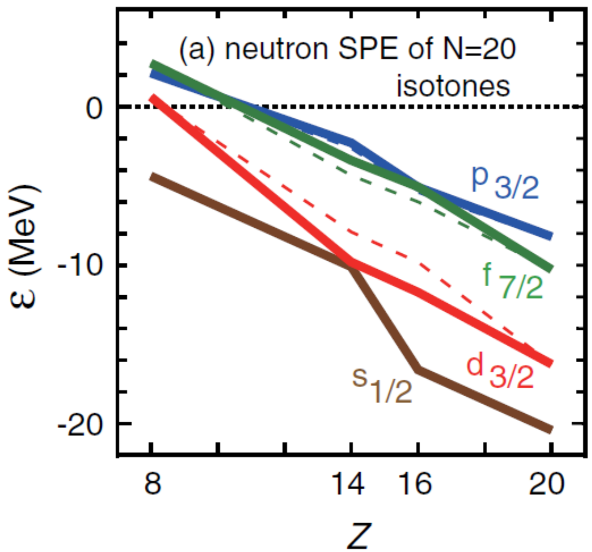
Island of inversion

- Mass information around ^{32}Na
- 2hw configuration is dominant in g.s.



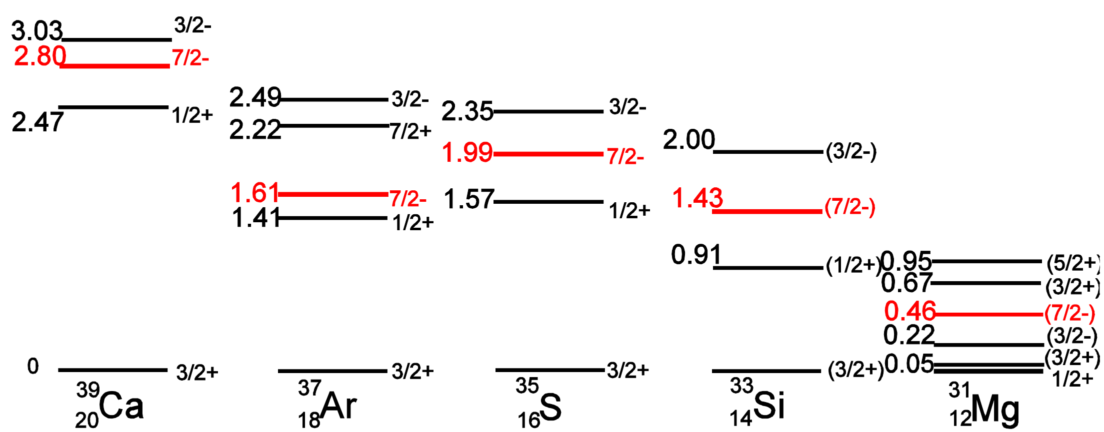
E.K. Warburton, J.A. Becker and B.A. Brown, Phys. Rev. C41, 1147 (1990)

Single particle energies at 'Island of inversion'



T. Otsuka et al, PRL104,012501

- Energy gap between *pf-sd* orbits.
- Single particle states will be a direct evidence of the shell evolution.



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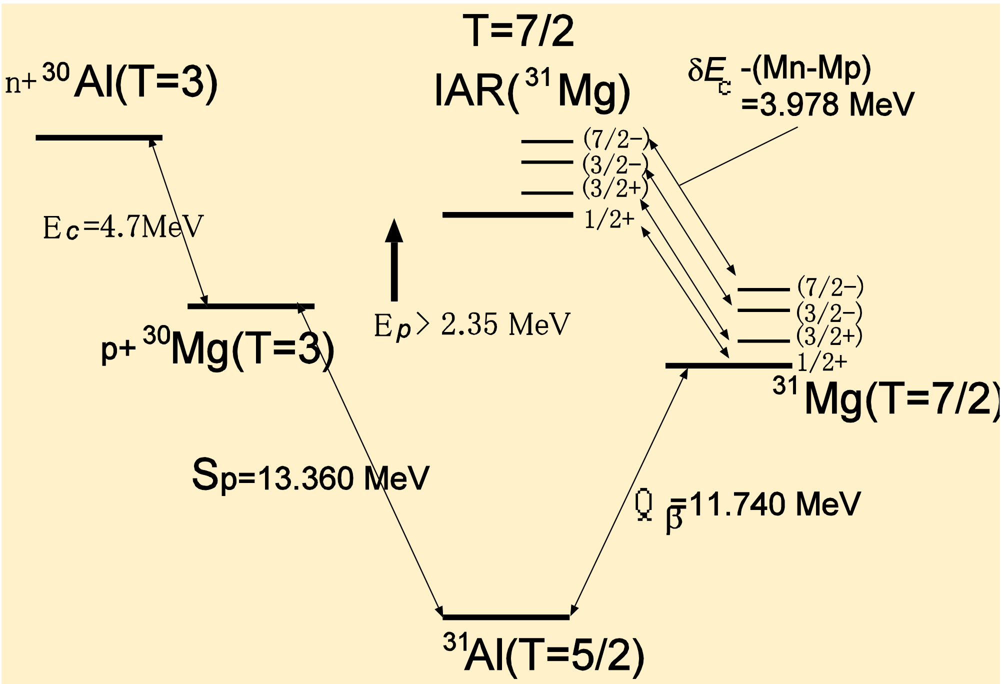
Isobaric Analog Resonances of bound states in a neutron-rich nucleus

- Same Isospin as the parent state
- Tz = T-1/2
- Same configuration as the parent state

Resonance shape
= angular momentum (l)
Resonance width
= total width (Γ_{tot})
Resonance height
= proton width (Γ_p) ~ S^{pp}



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Thick target inverse kinematics proton resonance elastic scattering with RIBs

Excitation function of $d\sigma/d\Omega(\theta_{lab.}\sim 0)$

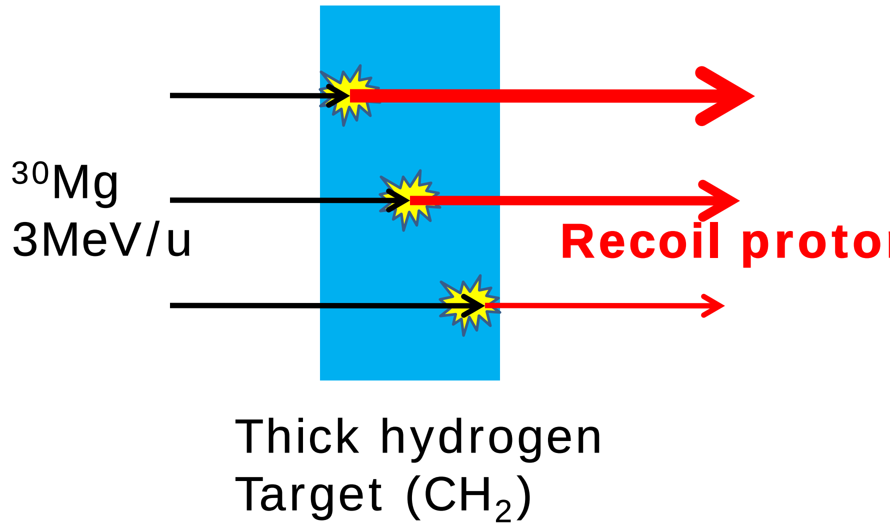
cf.) V.Z. Goldberg, ENAM98

1. High-energy recoil proton

   ~ 4x E_{reso}

2. One fixed energy
3. Large cross section

   ~ several 10 mb/sr



S^{pp} vs S^{dp}

IAR | 1n-transfer

^{116}Sn(p, p)^{116}Sn							^{116}Sn(d, p)^{117}Sn			
E_p(c.m.) (MeV)	$E - E_0$ (MeV)	l_p	$I\pi$	Γ_p (keV)	Γ (keV)	$\Gamma_p/(\Gamma_p)_{sp}$	E (MeV)	l_n	$I\pi$	σ/σ_{sp}
6.869	0.000	0	1/2+	16.5	42	0.38	0.0	0	1/2+	0.65
7.022	0.153	2	(3/2 5/2)+	8.3	37	0.52	0.16	2	3/2+	0.55
7.873	1.004	2	(3/2 5/2)+	1.8	42	0.051	1.03	2	5/2+	0.061
8.038	1.169	2	(3/2 5/2)+	1.4	35	0.035	1.19	2	5/2+	0.033

Table 1-2 Comparison between $T = 17/2$ states in $^{117}_{51}$Sb and $^{117}_{50}$Sn. The table compares the properties of the isobaric analog states observed in proton scattering on ^{116}Sn (Richard *et al.*, *loc. cit.*, Fig. 1-9) and (*d*, *p*) reactions on the same target (E. J. Schneid, A. Prakash, and B. L. Cohen, *Phys. Rev.* **156**, 1316, 1967). Column one gives the proton energy in the center-of-mass system. The energy in column two measures the excitation of the resonance state from the energy E_0 of the lowest $T = 17/2$ state in ^{117}Sb. Column eight gives the excitation energy of the corresponding states in ^{117}Sn. The single-particle proton widths $(\Gamma_p)_{sp}$ employed in column seven have been calculated by J. P. Bondorf and H. Lütken (private communication, 1967). The results of the coupled channel calculation are rather similar to those obtained by considering the scattering of a single proton in the nuclear potential and multiplying the width (as given by Eq. (3F-65)) by the factor $(2T_0 + 1)^{-1}$, which represents the probability of the proton channel in the state (1-66).

SYMMET

Bohr and Mottelson, Nuclear Structure Vol. 1, p48-

Overlap with the excited state

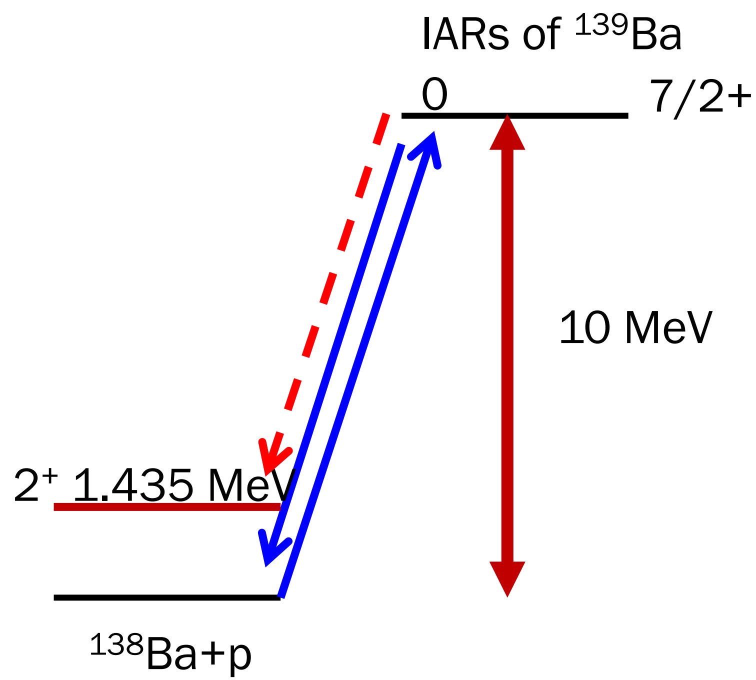
- Decay channels to the excited states

cf.) ^{138}Ba(p,p')

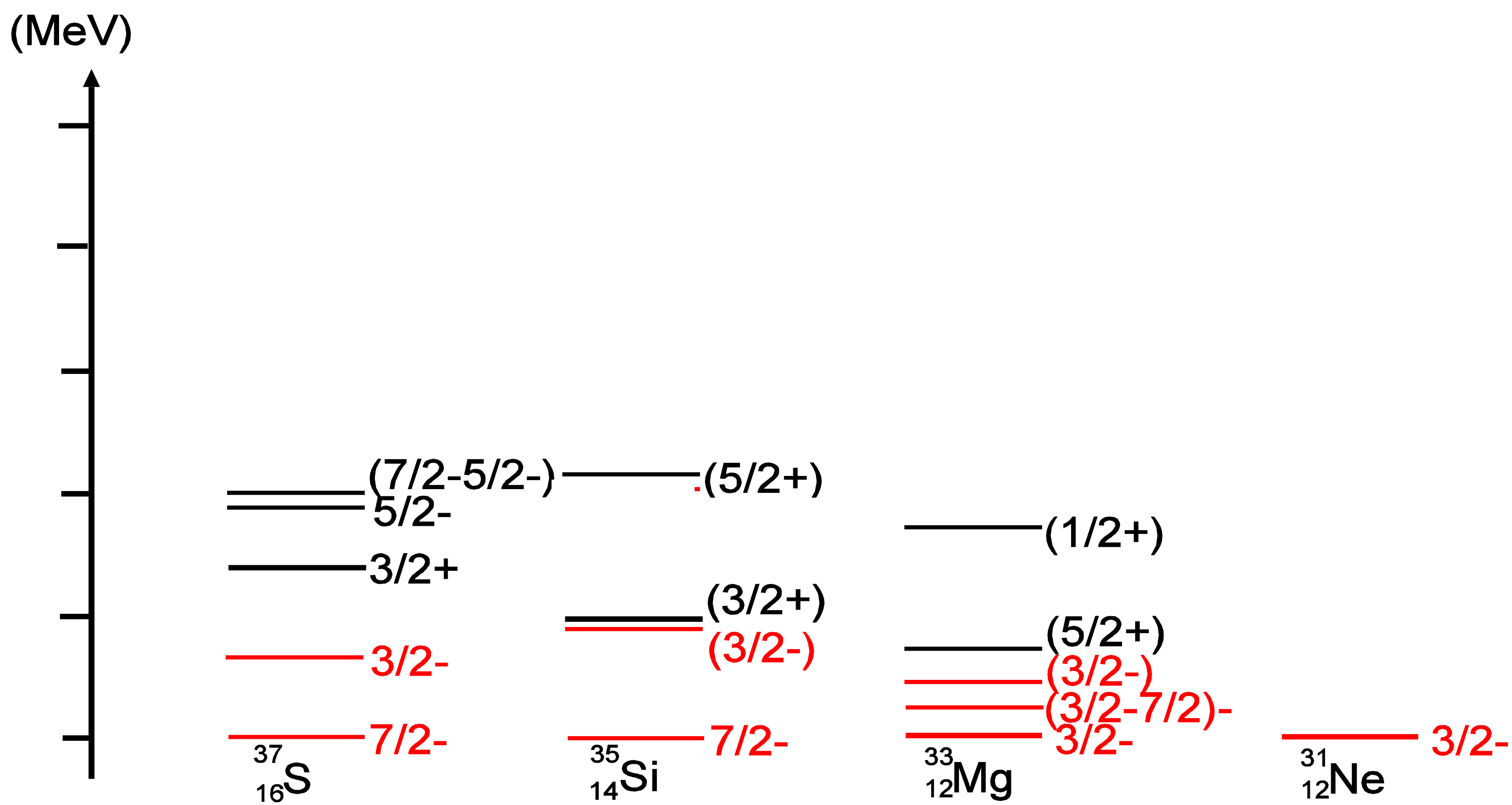
$$|\psi_{IAR}\rangle = a|0^+_{g.s.};7/2^+\rangle + \beta|2^+_2;3/2^+\rangle + \ldots$$

$\alpha = 0.9 +/- 0.1$
$\beta = 0.02$

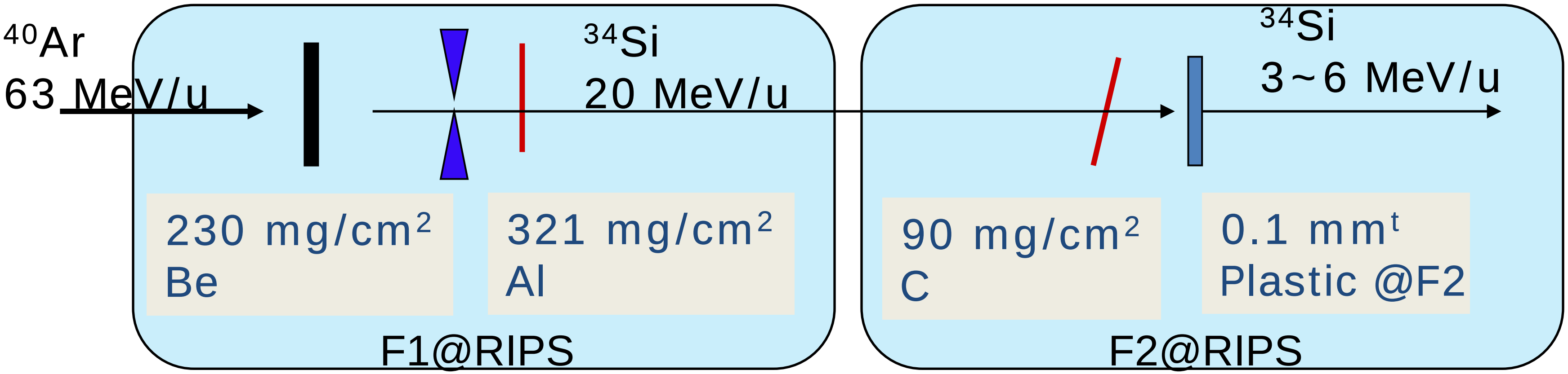
S. A. A. ZAIDI, P. VON BRENTANO,
D. RIECK and J. P. WURM
PhysicsLetters 19, 45 (1965).

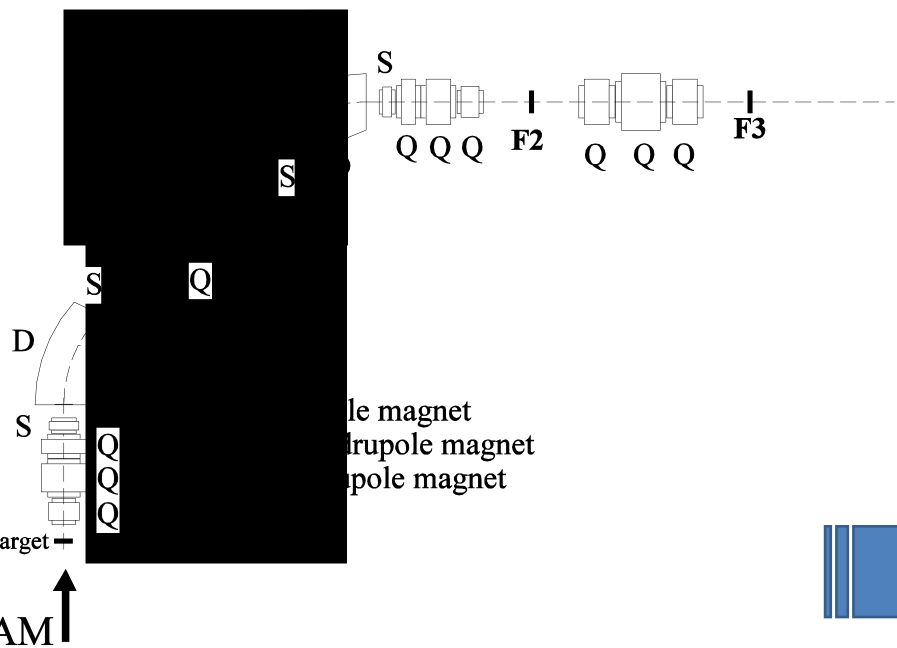


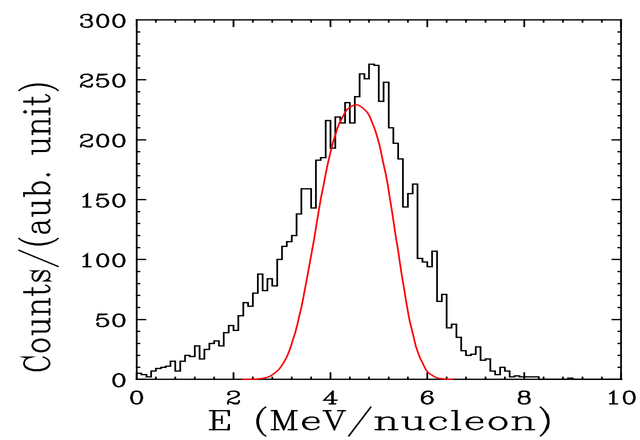
^{35}Si (*N*=21)


(MeV)
(7/2-5/2-)
5/2-
3/2+
3/2-
7/2-
$^{37}_{16}$S
(5/2+)
(3/2+)
(3/2-)
7/2-
$^{35}_{14}$Si
(1/2+)
(5/2+)
(3/2-)
(3/2-7/2)-
3/2-
$^{33}_{12}$Mg
3/2-
$^{31}_{12}$Ne

Energy degraded ^{34}Si beam

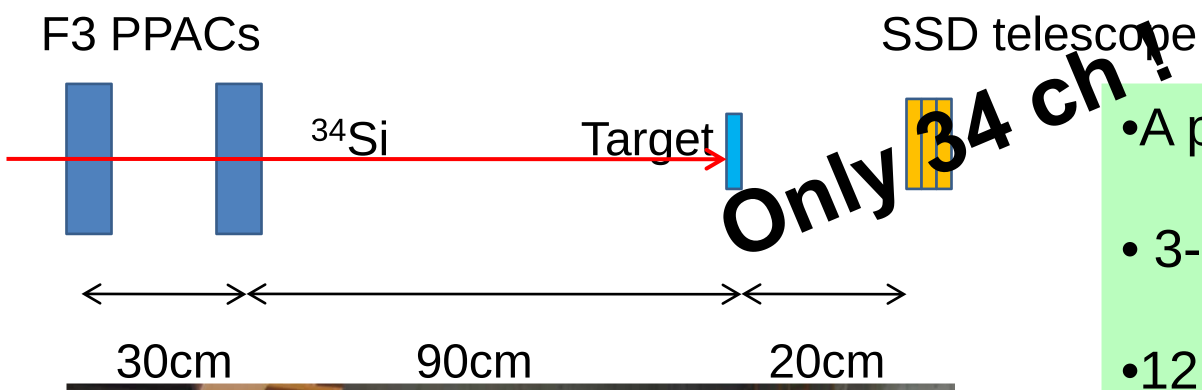






OEDO beam line @BigRIPS

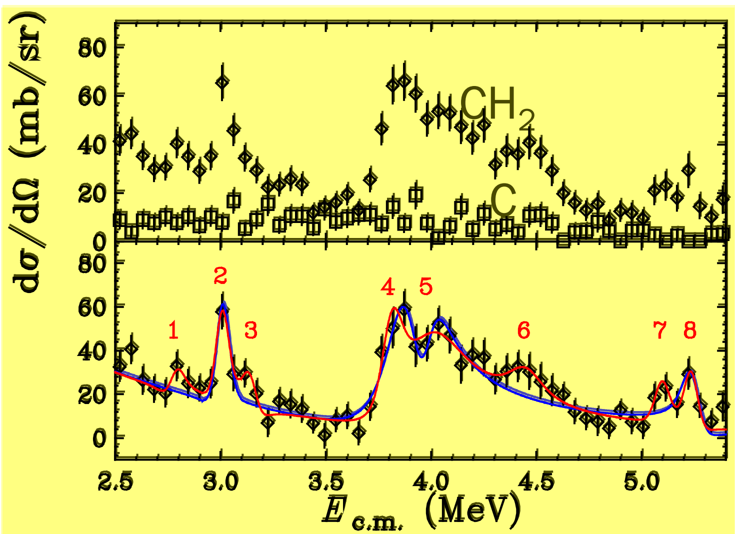
Experimental setup



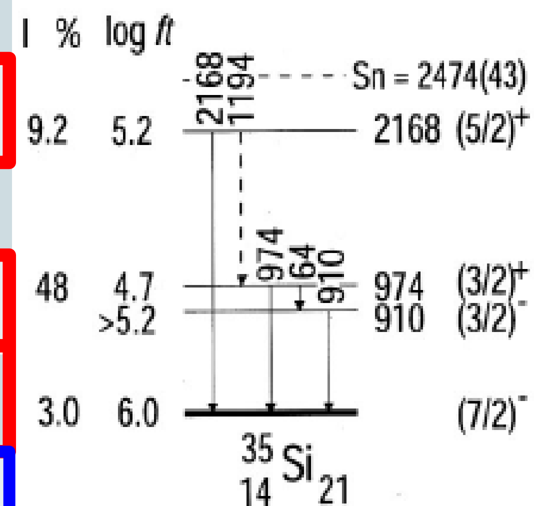
- A pair of PPACs
  - incident angle
- 3-6 MeV/u ^{34}Si beam
  - beam energy: F2pl-F3PPAC
- 12 mg/cm^2 CH_2 target
  - ^{34}Si beam stop
  - only protons are emitted
- SSDs (dE1-dE2-E) @0 deg.
  - dE1: 16(x)x16(y) ch
  - scattering angle

R-matrix fitting

^{34}Si: CH2 1 days accumulation
C 0.5 days



#	l	$\Gamma_{p(keV)}$	$\Gamma_{tot(keV)}$	Er (keV)
1	0	4.6 (28)	4.4(81)	2783.(24)
2	3	1.6 (4)	1.6(28)	3006.(2)
3	2	3.3 (27)	10.4(200)	3151.(24)
4	2	26.7 (69)	84.0(250)	3809(18)
5	1	185 (43)	354(87)	3990(36)
6	0	58.4 (370)	215(150)	4450(44)
7	2	3.8 (9)	3.8(9)	5099(12)
8	1	20.9 (120)	32.0(220)	5200(15)

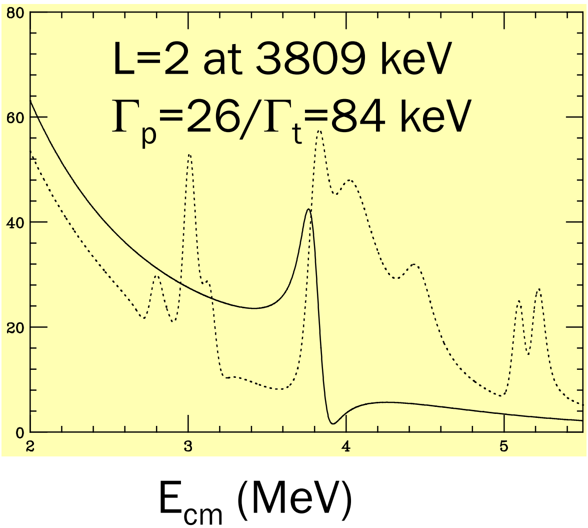


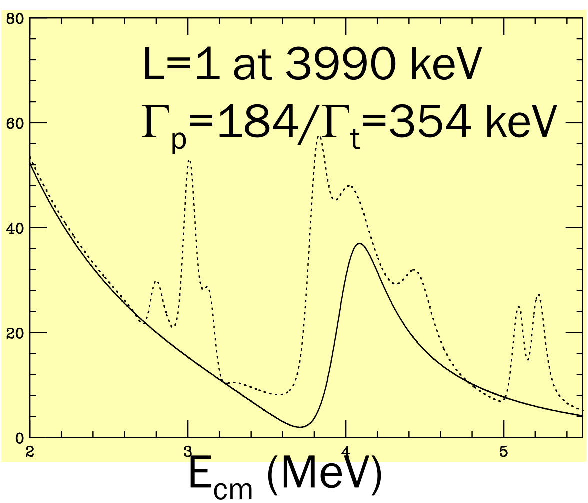
X^2 /ndf = 24.1/32 = 0.75

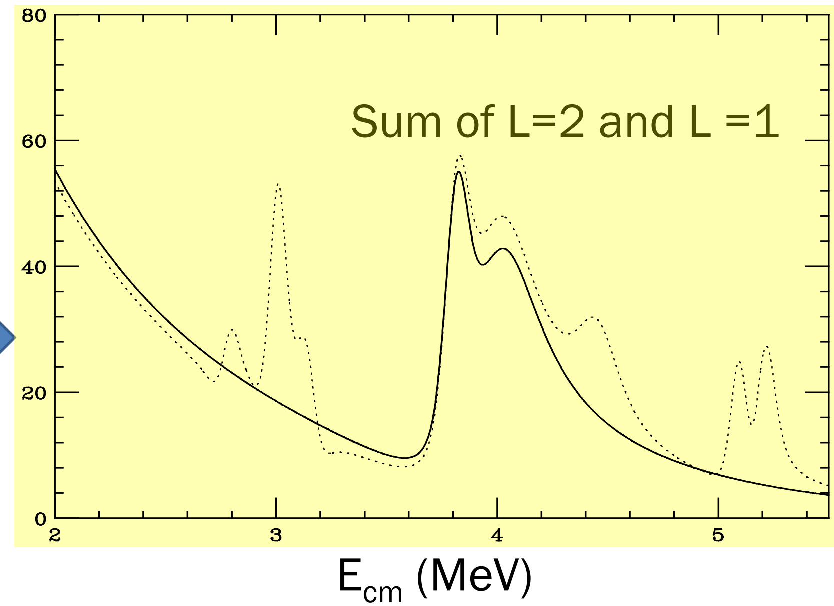
N. Imai et al., PRC85, 034313

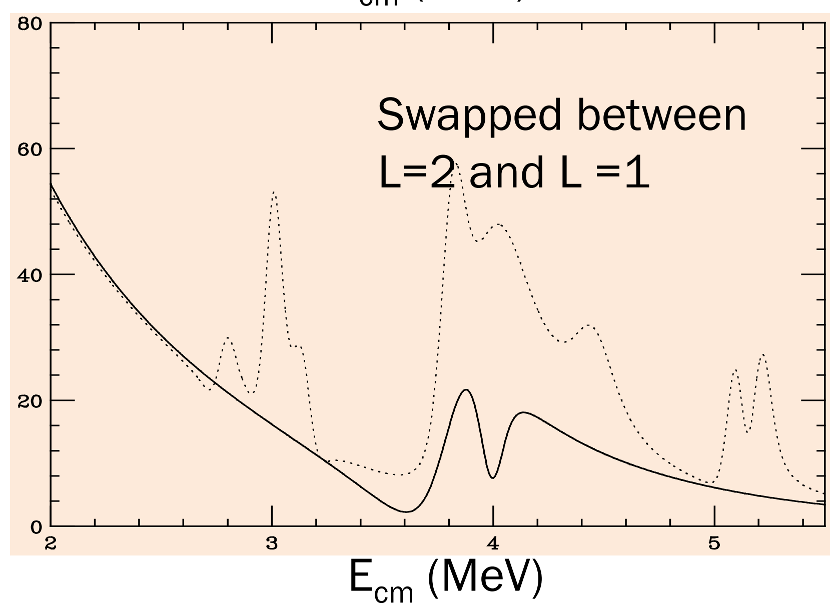
S. Nummela et al., PRC 63, 044316

Sum of single resonances









(p,p) v.s. (d,p) for ^{35}Si

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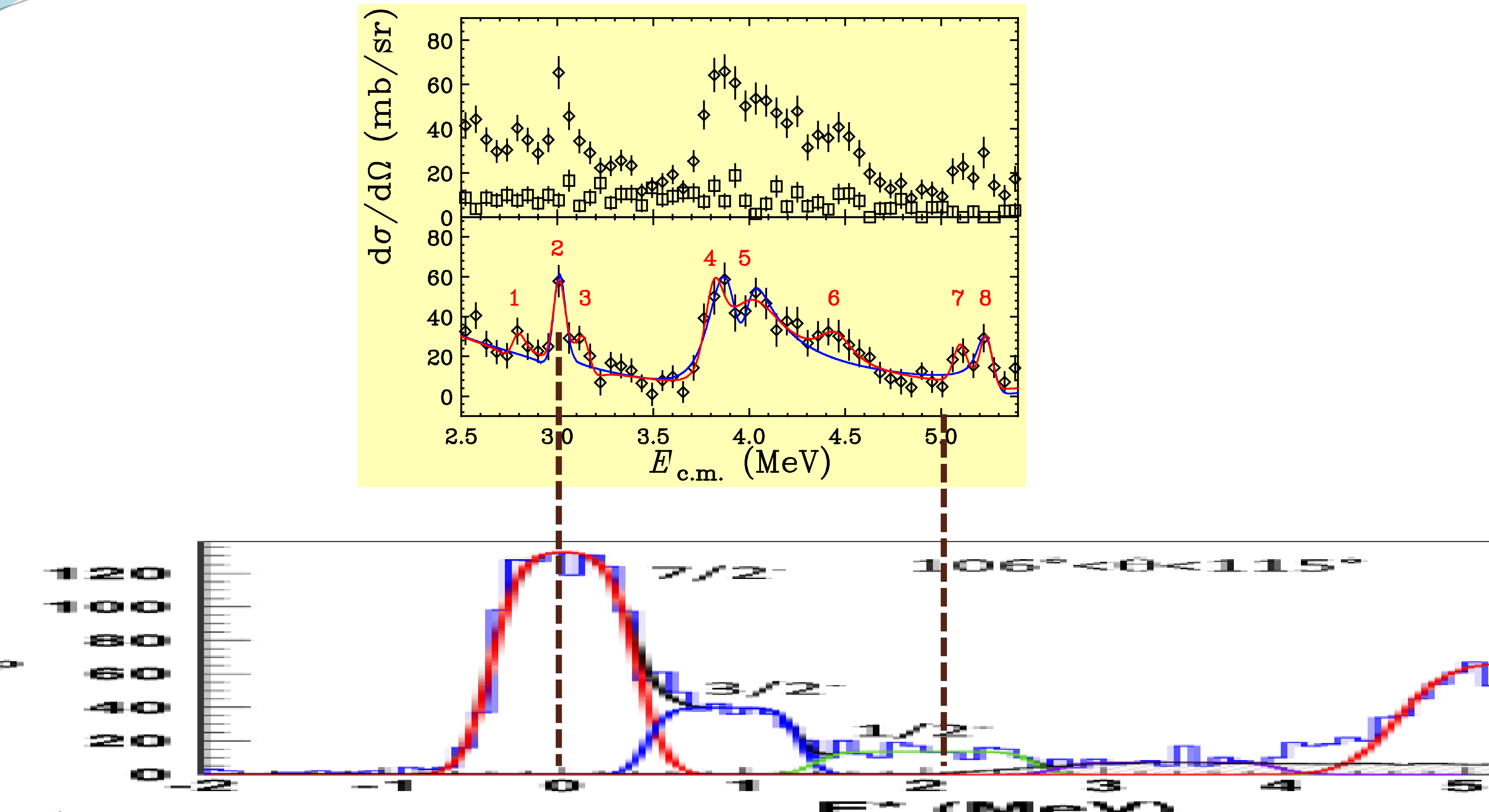

RIKEN NiSHiNA

G. Burgunder, O. Sorlin et al.,
Phys. Rev. Lett. 112,042502('14)

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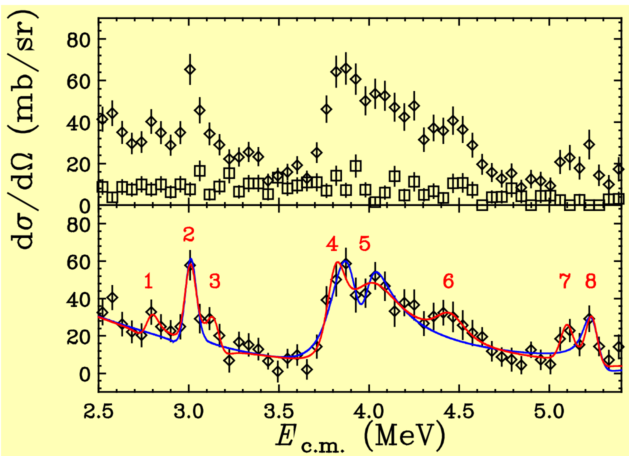
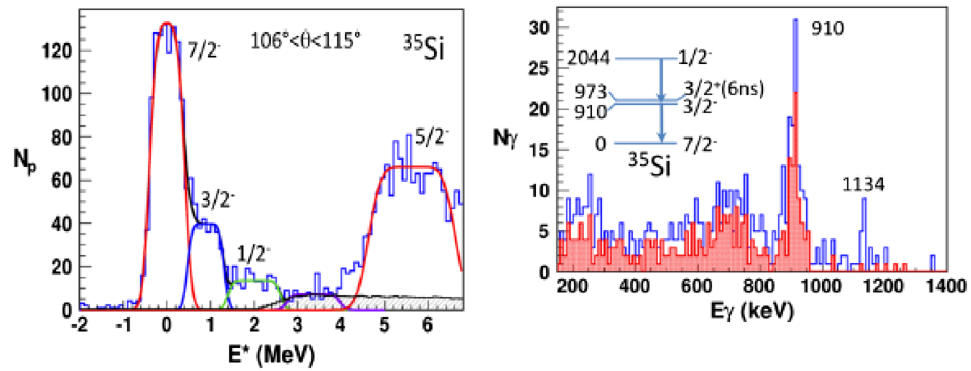
Inconsistency of *S*



N.I et al., PRC85, 034313(2012).



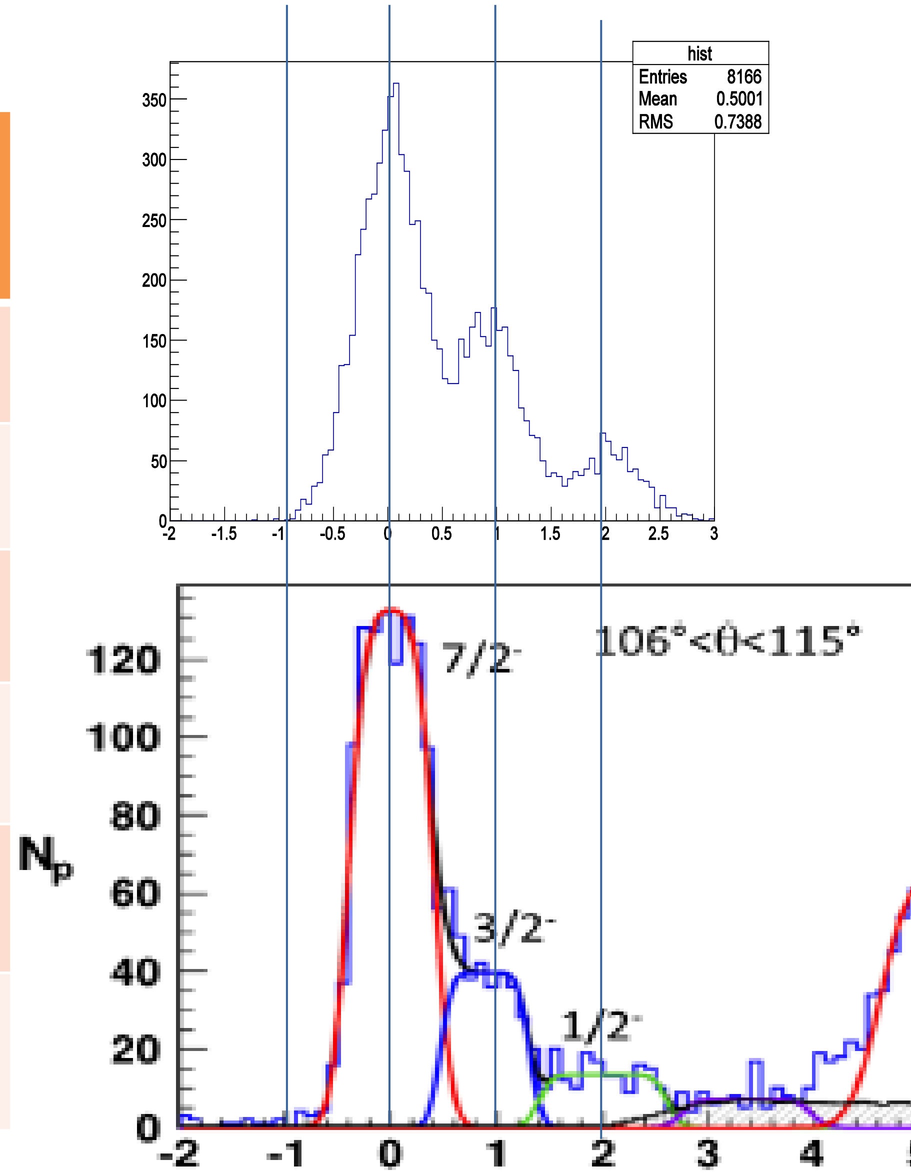
G. Burgunder, O. Sorlin et al.,
Phys. Rev. Lett. 112,042502('14)

Ex (keV)	J^π	S
g.s.	$7/2^-$	0.56 (6)
910	$3/2^-$	0.69(10)
2041	1/2-	0.73(10)

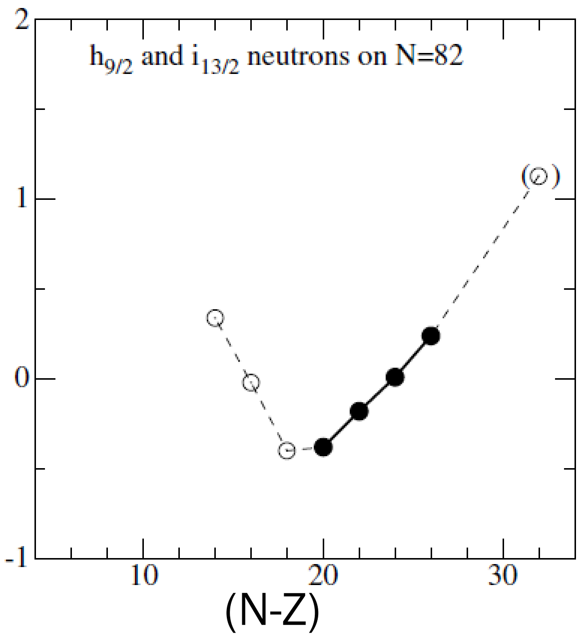
l	E_R (keV)	E_{ex}^{pp} (keV)	Γ_p (keV)	Γ_{tot} (keV)	Γ_{tot}/Γ_p	S $j = \ell+1/2$
0	2783(24)	−223(24)	4.6(28)	4.6(81)	1.0 (16)	
3	3006(2)	0.0	1.6(4)	1.6(28)	1.0 (17)	0.63(16)
2	3151(24)	145(24)	3.3(27)	10.4(200)	3.2 (56)	0.19(13)
2	3809(18)	803(18)	26.7(69)	84.0(250)	3.1 (5)	[illegible]
1	3990(36)	984(36)	185(43)	354(87)	1.9 (1)	1.37(32)
0	4450(44)	1444(44)	58.4(370)	215(150)	3.7 (11)	0.45(28)
2	5099(12)	2093(12)	3.8(9)	3.8(78)	1.0 (20)	0.04(1)
1	5200(15)	2194(15)	20.9(120)	32.0(220)	1.5 (0.6)	0.12(7) ➔0.33(23)for $1/2^-$

Expected spectrum from our result

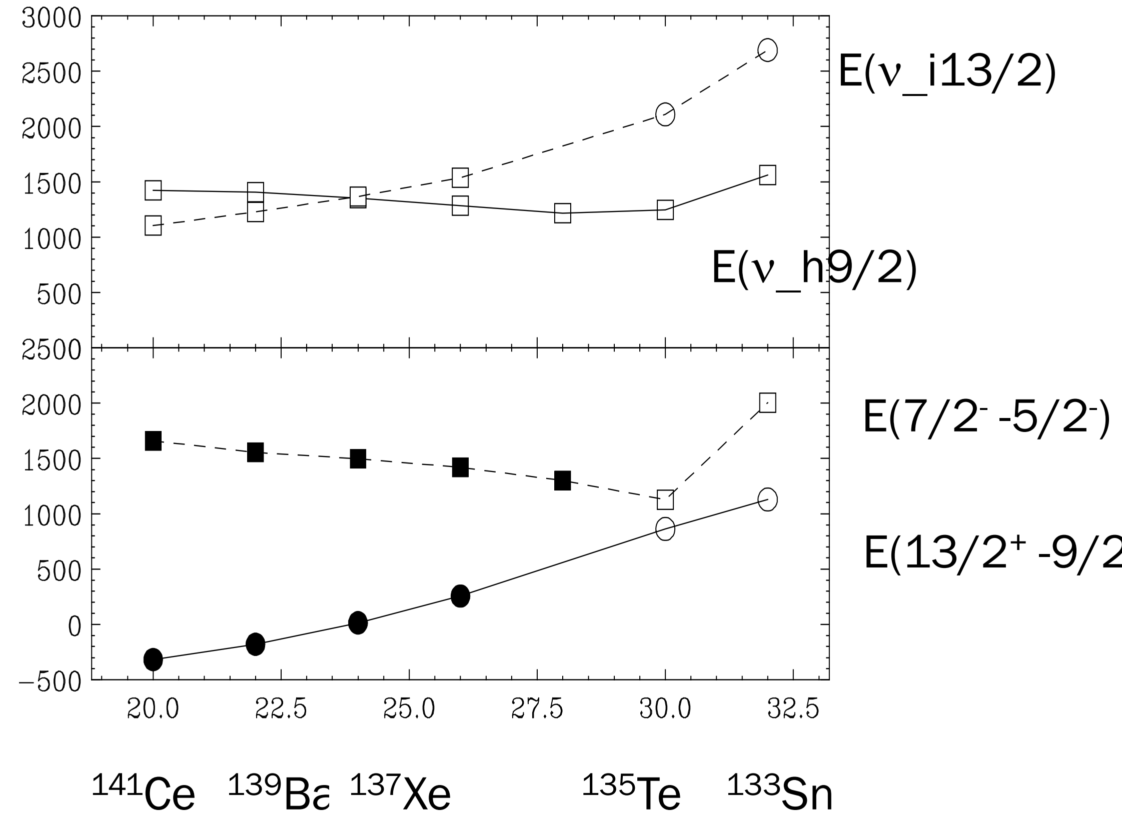
Ex (keV)	Jp	dσ/dΩ $_{DW}$ (θ_{cm}=40) (arb. unit)	S^{pp}	S^{dp}
0	$1f_{7/2}$	7.8	0.63	0.56
910	$2p_{3/2}$	1.46	1.37	0.69
974	$1d_{3/2}$	3.6	0.79	
1444	$2s_{1/2}$	1.8×10^{-2}	0.45	
2041	$2p_{1/2}$	1.3	0.33	0.73
2168	$1d_{5/2}$	1.0	0.04	



Future plan; around ^{133}Sn

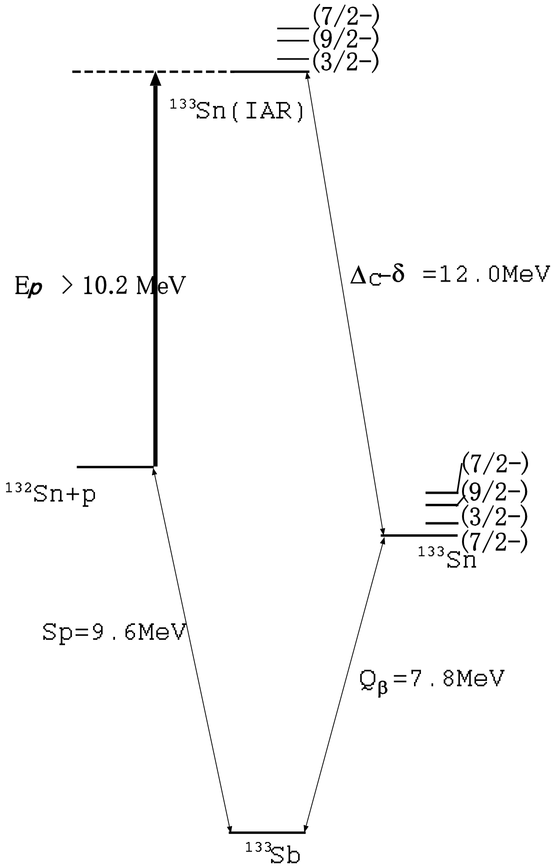


J.P. Schiffer et al., PRL 92, 162501(2004).

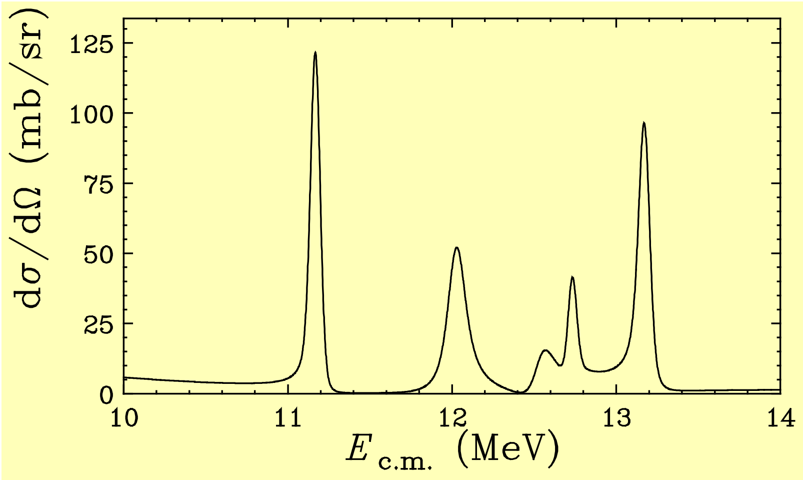


Decrease of spin-orbit int.

^{132}Sn(*p,p*) for IARs of ^{133}Sn



E_x(keV)	E_{cm}(MeV)	J^{π}	Γ_p(keV)
0.	11.17	$7/2^-$	22.
854.	12.024	$3/2^-$	108.
1363	12.533	$1/2^-$	118
1561	12.731	$9/2^-$	5.4
2005	13.175	$5/2^-$	41.



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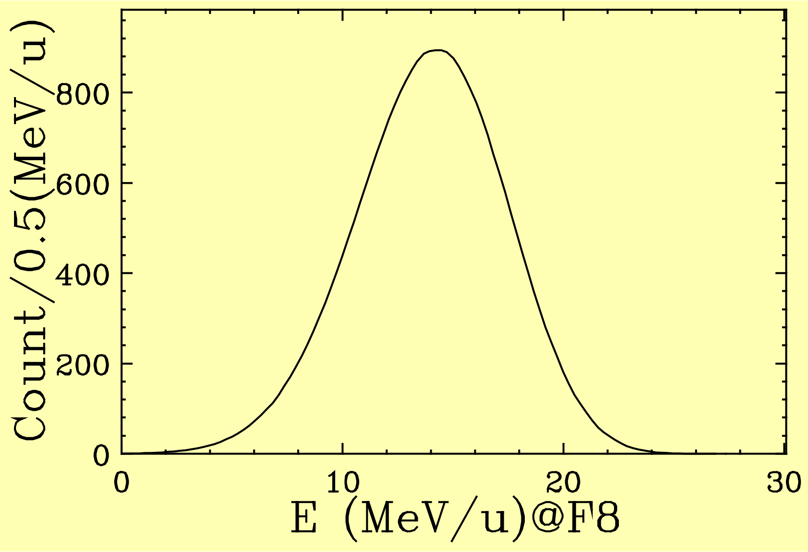
Setup for IAR of ^{133}Sn



1.7×10^3 pps/^{238}U 1pnA

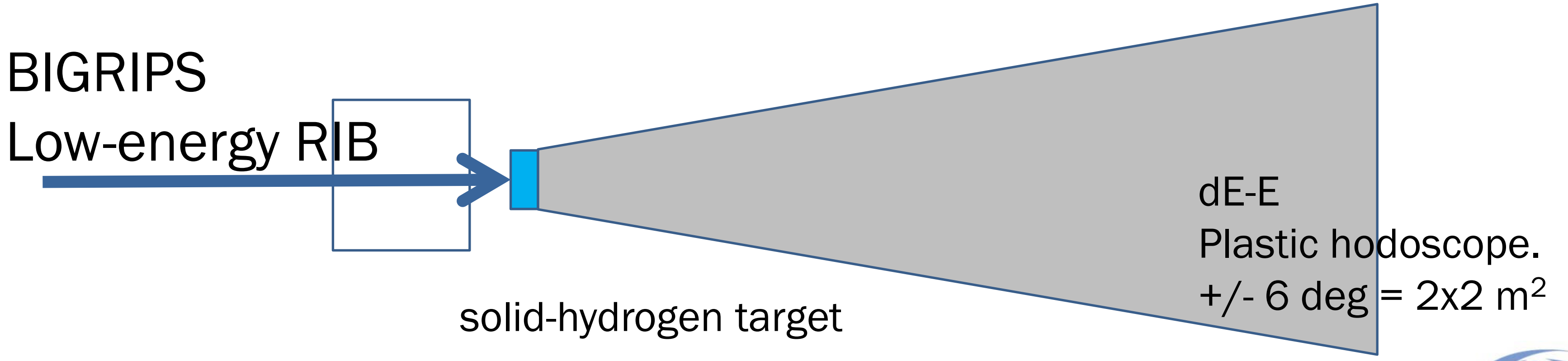
Intensity is enough

Energy distribution is too wide...

To achieve dE/E = 100keV/50 MeV

Tof of 10m flight with 100 ps resolution

will be measured.



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NEW PROJECT-PRODUCTION OF PURE ^{178M2}HF

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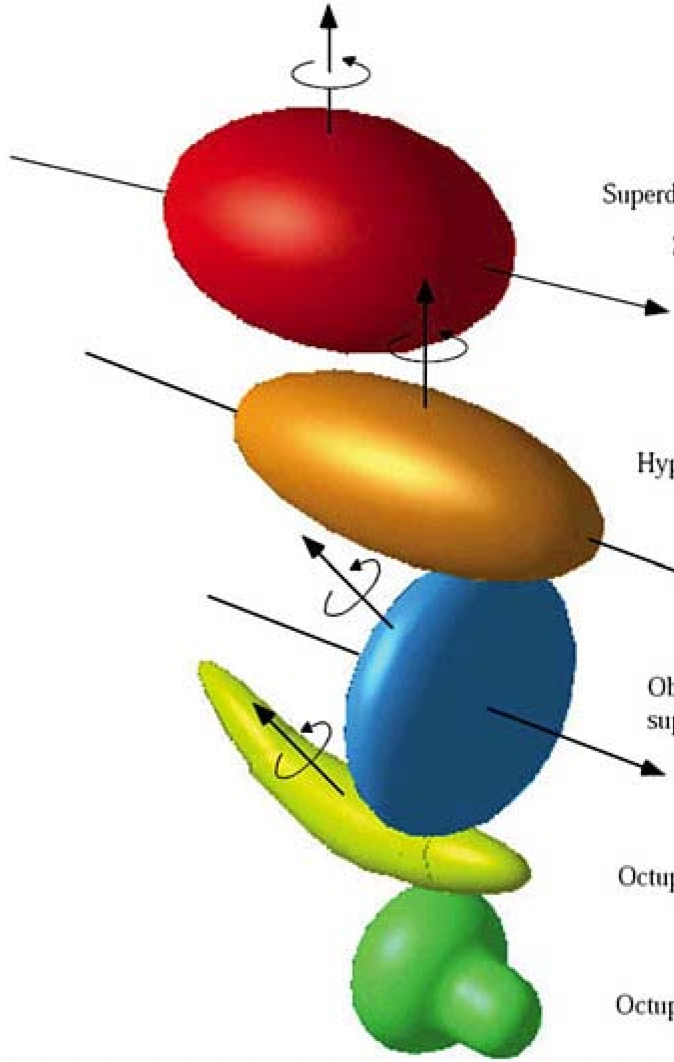
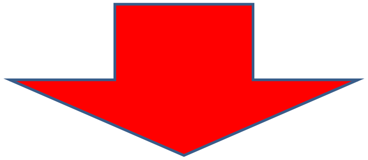
Hyperdeformation



http://www.nap.edu/openbook.php?record_id=11796

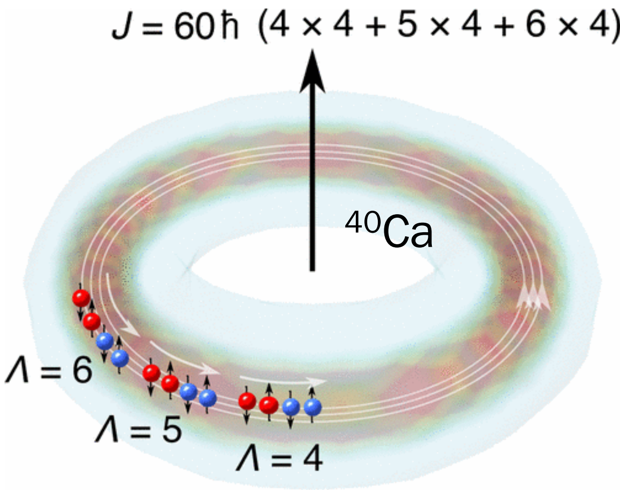
Isomer beam/target

Search for torus shape nucleus



Isomer beams(10^{10}pps)

Or isomer target



T. Ichikawa PRL 109, 23250

Other topics…

High-spin X High-spin collision

Elastic Scatt. On isomeric state

Gamma lasers …?

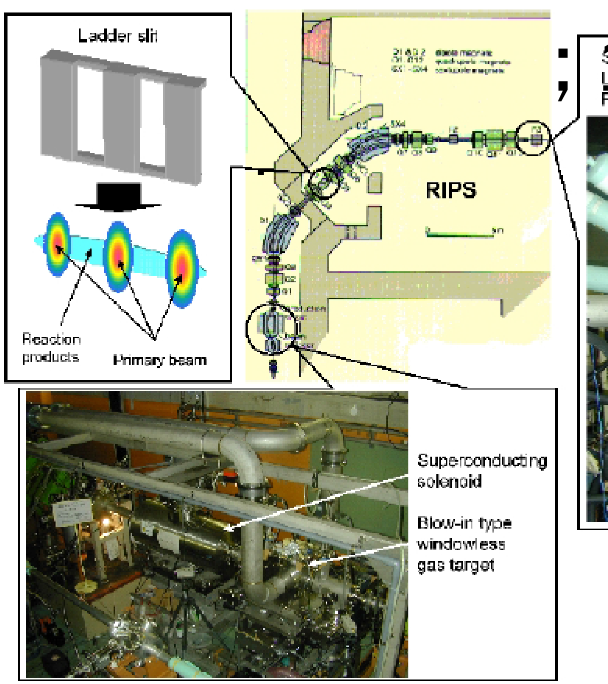
Isomer beams at RIKEN

- Fusion reaction $^{16}O(^{136}Xe,7n)^{145m}Sm(49/2^+)$

  +windows less gas target

  + solenoid

  +slits to stop primary beam

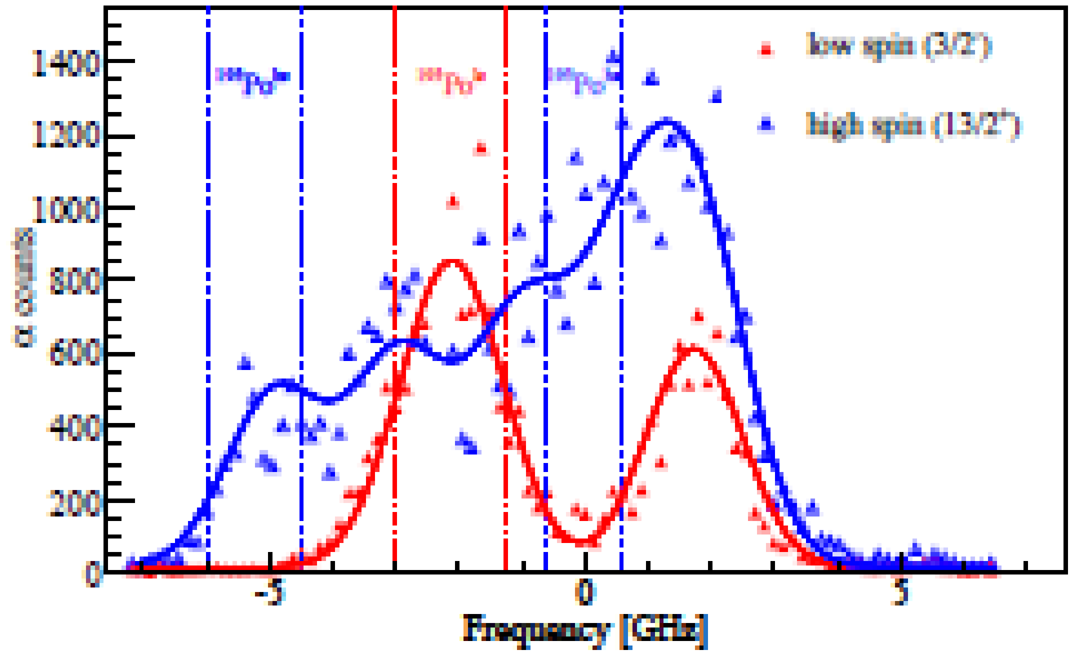


; 10^5pps Purity ~ 0.1% -- 10%

T. Kishida et al., NIMA 484 ('02) 45-55
H. Watanabe et al., NPA746, ('04)540.

Isomer beam at ISOLDE

- ^{195}Po



T.E. Cocolios, Ph. D thesis (K.U. Leuven)

Only by changing wavelength little bit !

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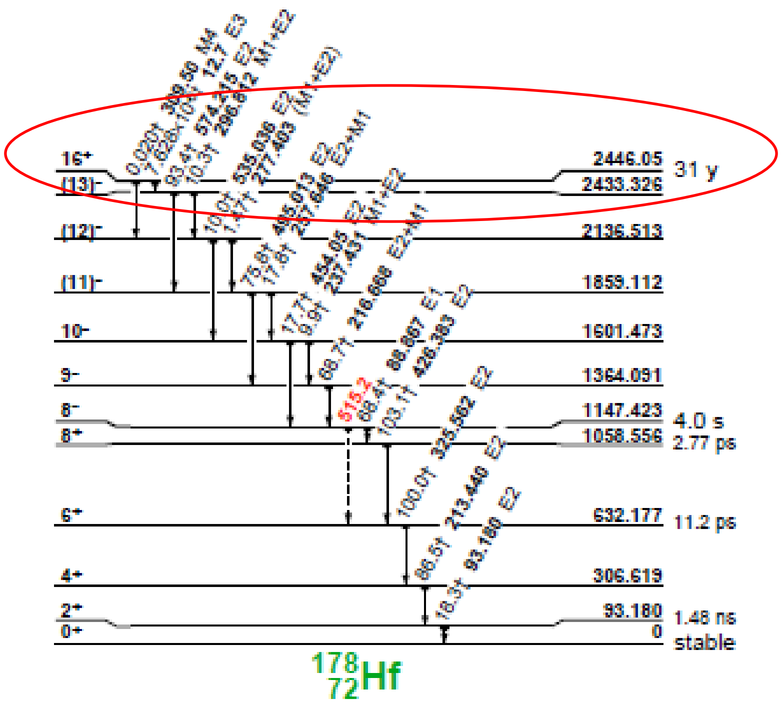
The isomer ^{178m2}Hf



- Longest half-life isomer

  $T_{1/2}$ = 31 years

  I = 16+

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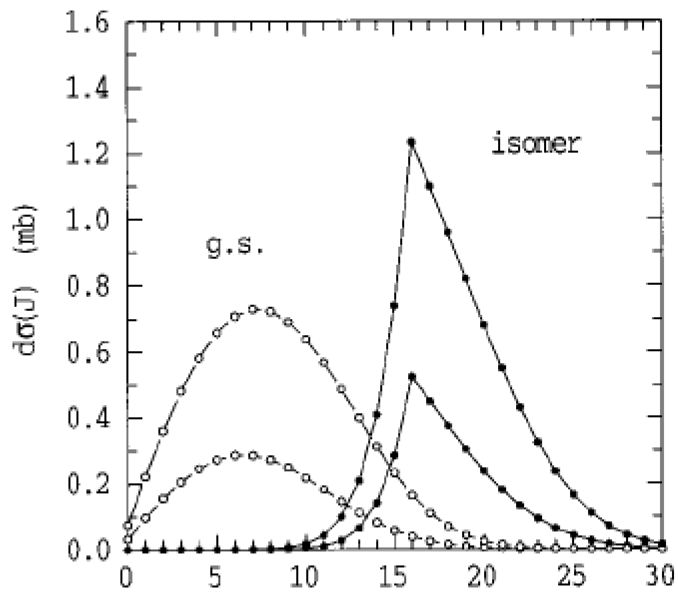
Fusion of $^{16}O + {}^{178m2}Hf(16+)$

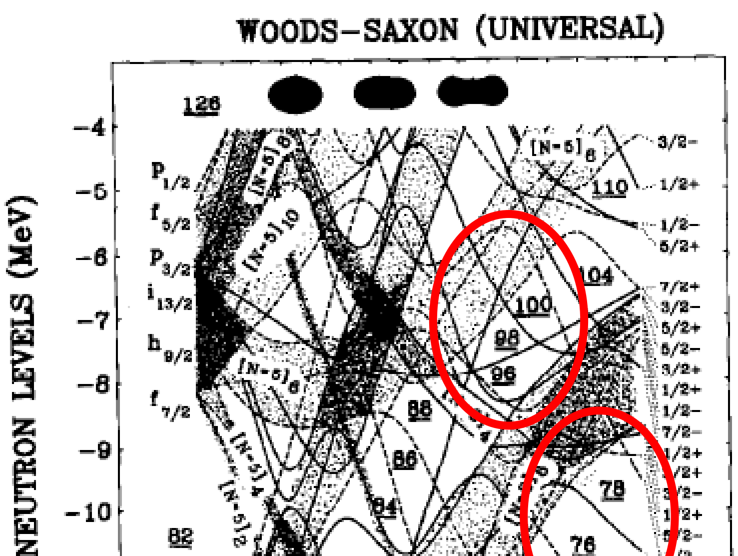


Population of high-spin state will be possible.

PHYSICAL REVIEW C **68**, 044606 (2003)

Exploratory studies towards fusion with the 16^+ isomer of ^{178}Hf

. Hinde,[1] N. Rowley,[2] M. Dasgupta,[1] R. D. Butt,[1] C. R. Morton,[1] and A. Mukherjee[1,*]



^{194}Hg(Z=80, 114)

J. Dudek et al.,
PLB211, 252 ('88)

Fm(Z=100), Cm(Z=98), Pu(Z=96)

Production of $^{178}Hf^{m2}$ target at Dubna

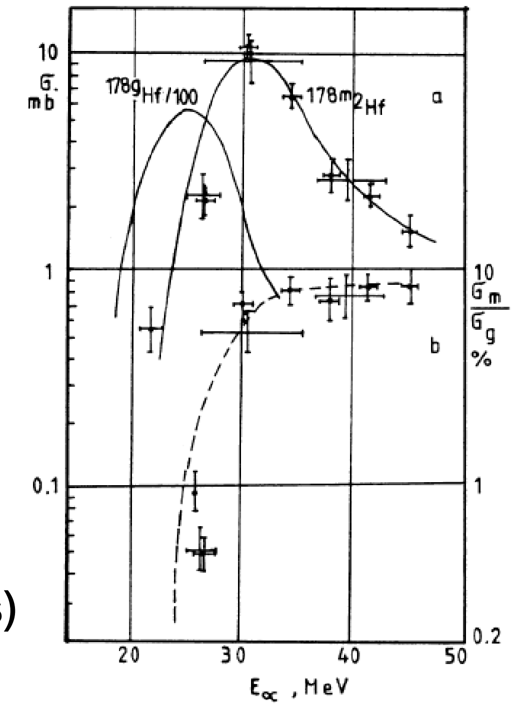
- $^{176}Yb(^{4}He,2n)^{178m2}Hf$

Hyperfine Interactions 107 (1997) 129-139

Yu. Oganessian et al.,

Table 2
^{178}Hf isomer accumulation runs at the U-200 Dubna cyclotron

Target no.	^{176}Yb enrichment (%)	Date of the run	He integral no. of ions	^{178m2}Hf produced atoms
1	93	1989	2.6×10^{19}	1.4×10^{13} Alma-Ata
2	96	jun. 1990	1.5×10^{18}	0.4×10^{13} Alma-Ata
3	96	jul. 1990	6.2×10^{18}	1.6×10^{13}
4	96	nov. 1990	1.3×10^{20}	1.2×10^{14}
5	96	dec. 1990	2.1×10^{20}	1.6×10^{14}
6	96	dec. 1991	0.6×10^{20}	0.6×10^{14}
7	99.998	dec. 1991	4.5×10^{20}	3.5×10^{14}
8	96	dec. 1992	0.7×10^{20}	0.8×10^{14}
9	99.998	febr. 1993	3.4×10^{20}	4.8×10^{14}
10	99.998	nov.1993	2.4×10^{20}	3.4×10^{14}
11	99.998	nov.1994	3.2×10^{20}	4.6×10^{14}



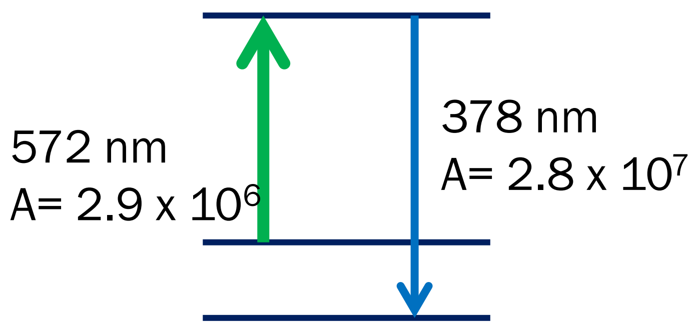
cf1.) for 5x10^{14} ^{178}Hf, 30 uA 36MeV X 500 h (20 days)
cf2.) RIKEN AVF 5uA 50 MeV

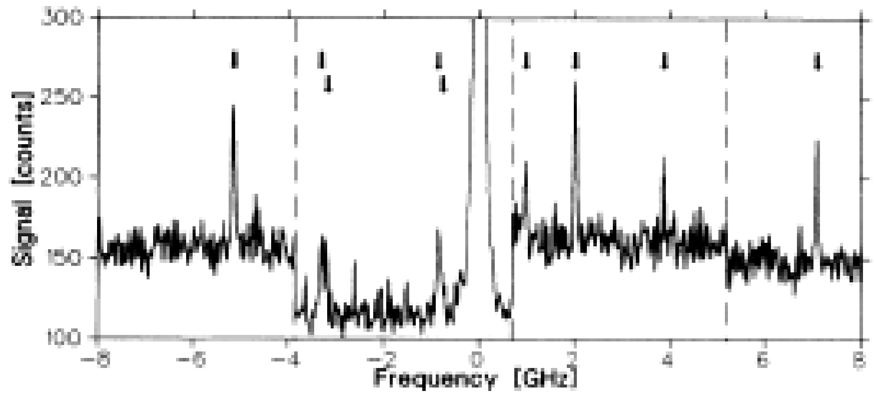
Collinear laser spec. with $^{178}Hf^{m2}$

Isomer/gs. of ^{178}Hf were well separated.

PRL72, 2689 ('92)

cf.) IP of Hf = 6.825 eV





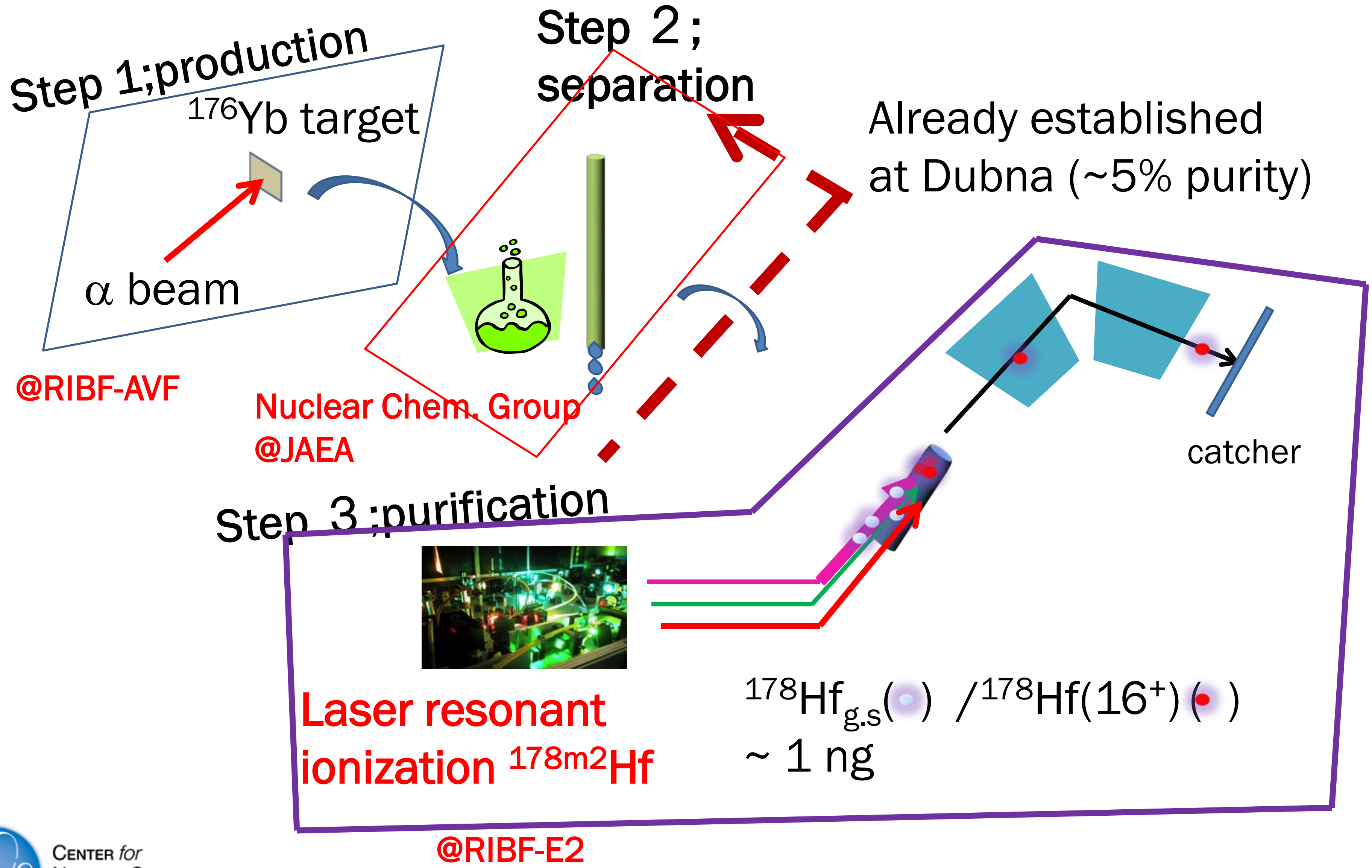
This means removing ^{178}Hf(0) is possible !

What are new ?

1. $^{178}Hf_{g.s.}$ separation by lasers

2. $^{178}Hf(16^{+})$ acceleration

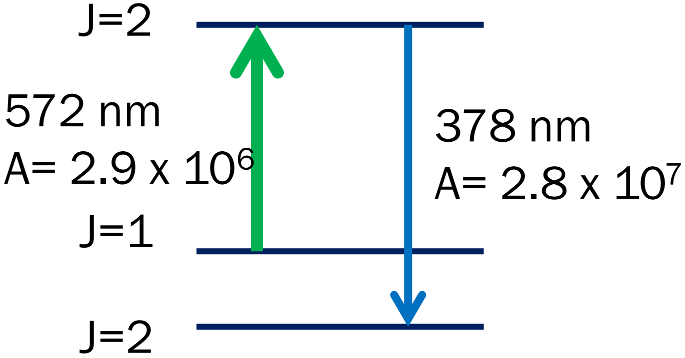
Procedure

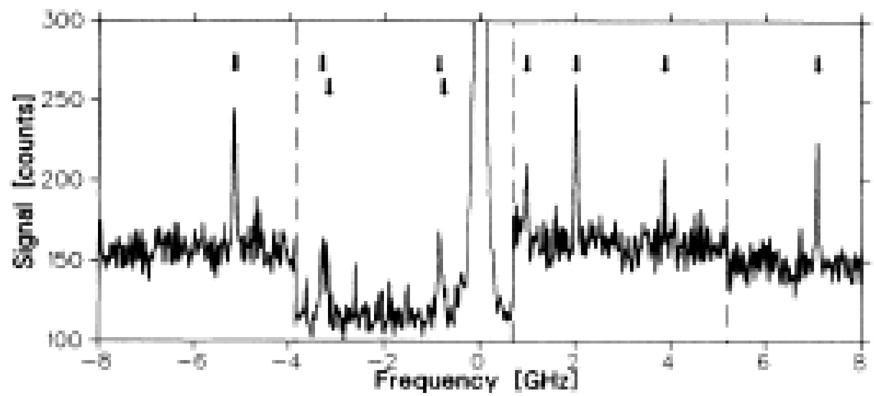

Step 1;production
^{176}Yb target
α beam
@RIBF-AVF
Step 2;
separation
Nuclear Chem. Group
@JAEA
Already established
at Dubna (~5% purity)
catcher
Step 3 ;purification
Laser resonant
ionization ^{178m2}Hf
^{178}Hf$_{g.s}$( ) /^{178}Hf(16^{+}) ( )
~ 1 ng
@RIBF-E2

Resonant laser ionization

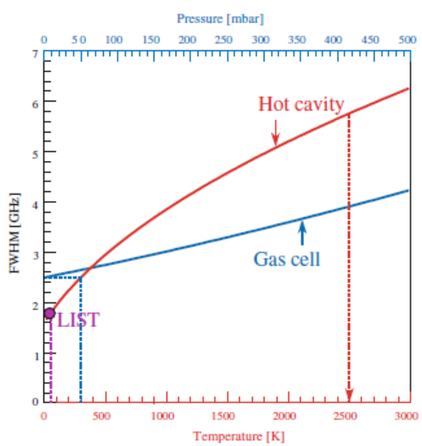
Hyperfine interaction makes isomer/g.s. of ^{178}Hf well separated.

cf.) I.P. of Hf = 6.825 eV





N. Boes et al., PRL72, 2689 ('92)



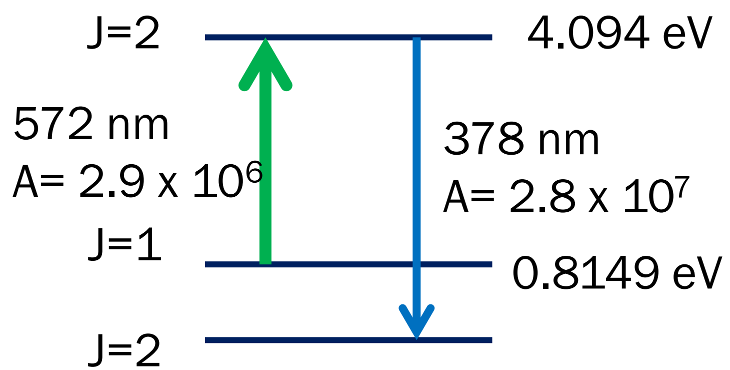
Doppler broadening ~ 4 GHz (FWHM)@ 1500 K
Line width of laser ~ 1 GHz

ionize only the ^{178m2}Hf

T. Sonoda et al., NIMB 267, 2918('09)

Center for Nuclear Study
Univ. of Tokyo

Search for new scheme(s)



Transition from the ground state to a state of *J=1* and of a large A coefficient

Excitation energy (eV)	Atomic spin *J*	Population (%) @2000 K
0	2	74
0.29211	3	19
0.5663	4	5
0.6846	0	0.278
0.8149	1	0.4

λ1 (nm)	(eV)	A coefficient (s^{-1})
270.5611	4.58	$1.01e^8$
288.9621	4.29	$6.68e^7$
301.6815	4.11	$3.07e^7$
377.7655	3.28	$2.32e^7$

Confirmation of hyperfine splitting is needed.

What's to do

- Isotope shift/hyperfine splitting of atomic transitions with stable Hf isotopes.

  → off-line TOF mass spectrometer

- Hot cavity-Laser ion source at E2

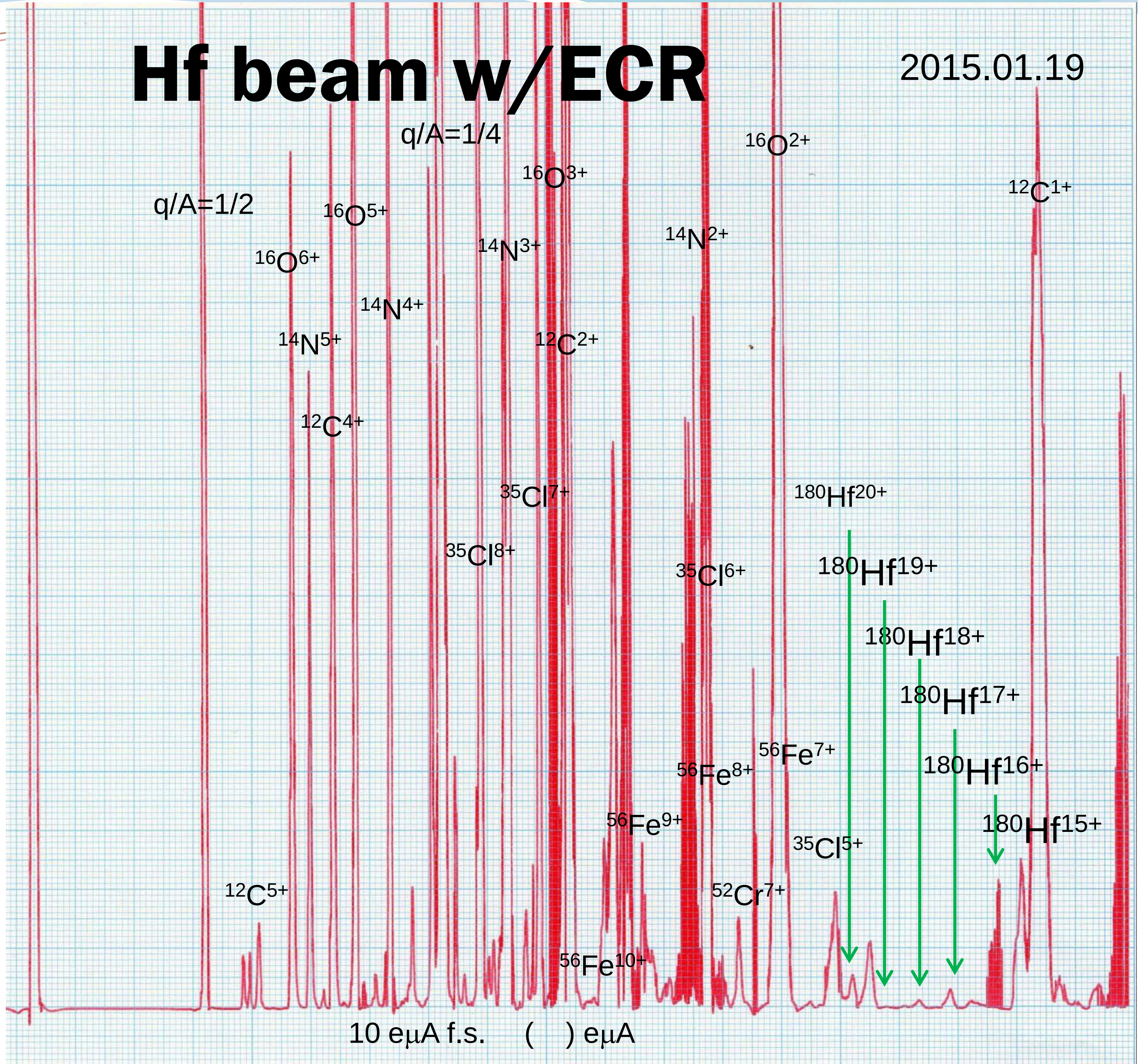
  modification of PA at E2

- Production of multi-charged ion of Hf w/ECR

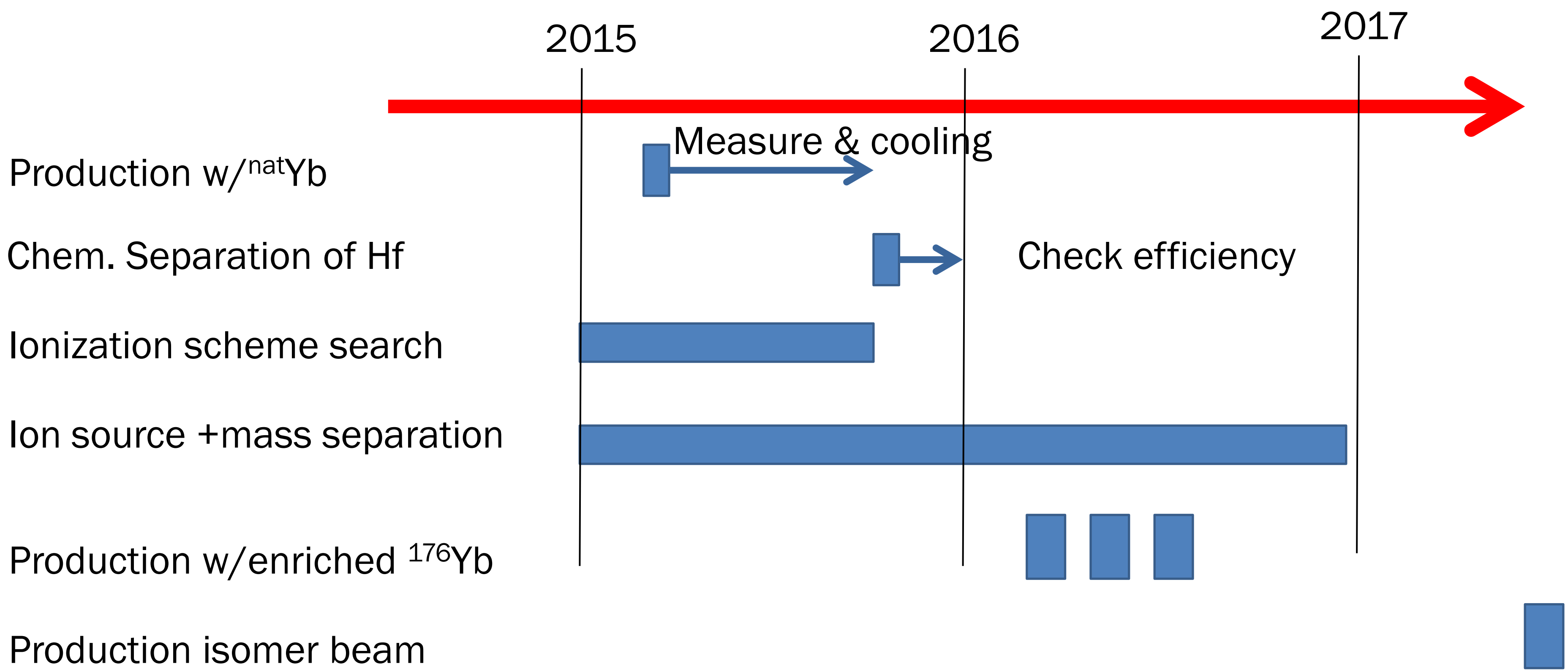
Hf beam w/ECR

2015.01.19

SUS container
CCl_4
$+HfO_2$



Time table


2015
2016
2017
Measure & cooling
Production w/natYb
Chem. Separation of Hf
Check efficiency
Ionization scheme search
Ion source +mass separation
Production w/enriched 176Yb
Production isomer beam