原子ビーム法による
低速不安定核ビーム生成に向けた
開発研究

理研・旭応用原子核物理研究室
亀田大輔

発表の流れ:
1、中性子過剰核のモーメント測定
2、低速不安定核ビームR＆D
- 減速材の開発
- ABR、ABLS

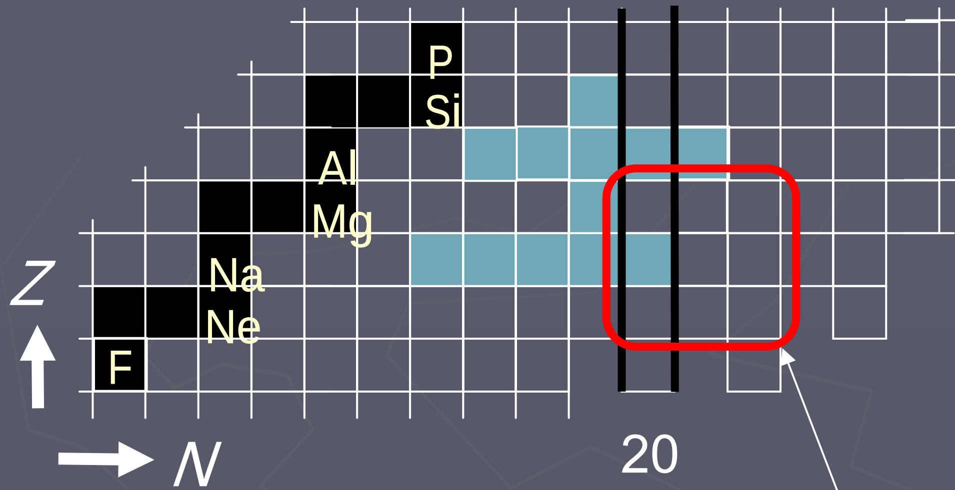
3、まとめ

RIKEN Nishina center for Accelerator based science
上野秀樹, 吉見彰洋, 杉本崇, 旭耕一郎

Department of Physics, Tokyo Institute of Technology
島田健司, 長江大輔

Rikkyo University
村田次郎, 川村広和

Nuclear moment studies around the island of inversion

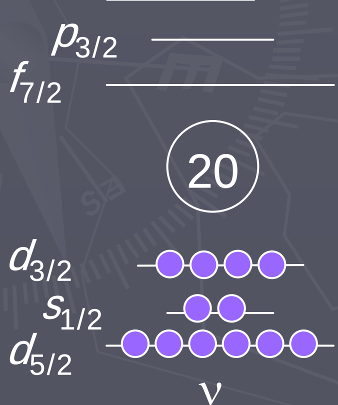


Island of Inversion

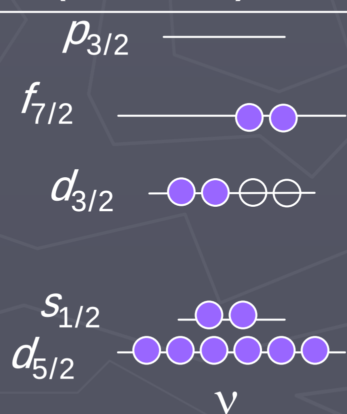
E.K. Warburton, J. A. Becker and B. A. Brown, PRC**41**(1990)1147.

Normal *sd*-shell configuration

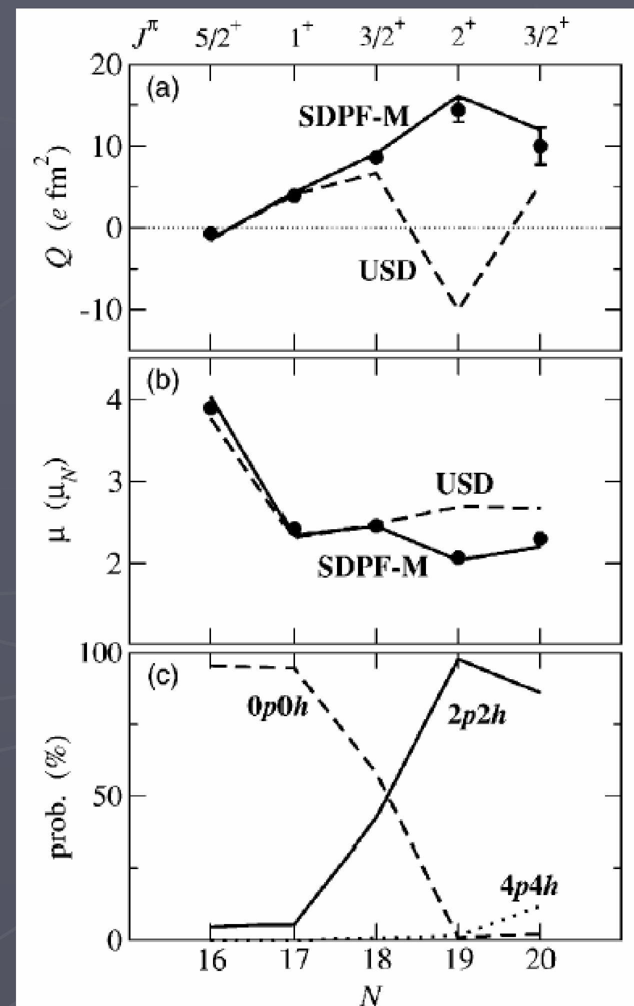
0p0h



2p2h (intruder), deformed

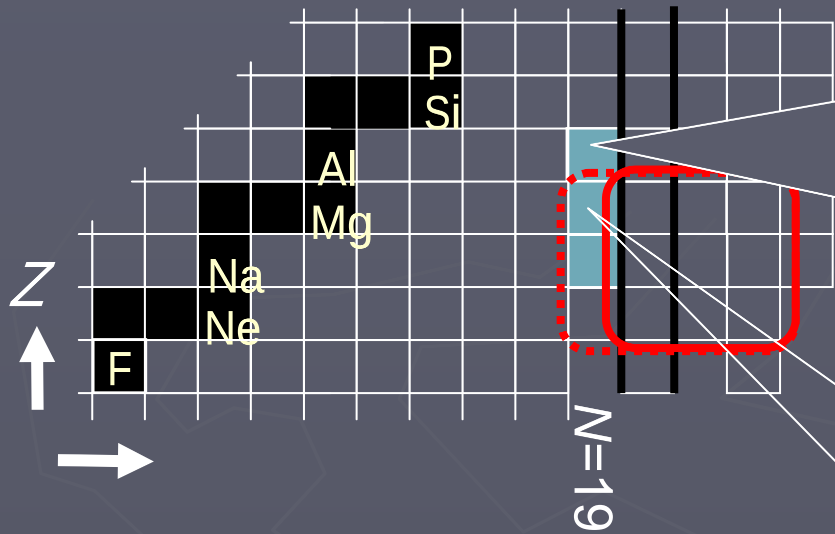


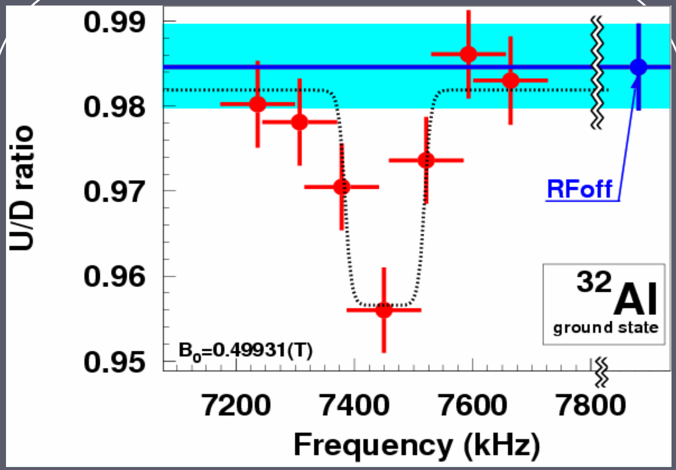
Nuclear moments of Na isotope chain:



Monte Carlo shell model with *sdpf* model space:
Y. Utsuno, *et al.*, Phys. Rev. C**70**(2004) 044307.

Magnetic moment studies on neutron-rich *N*=19 isotones





| μ ($^{32}Al_{gs}$;1^+) |= 1.959(9) μ_N

… well reproduced by *sd* (*0p0h*) shell models

H. Ueno et al, PLB**615** (2005)186.

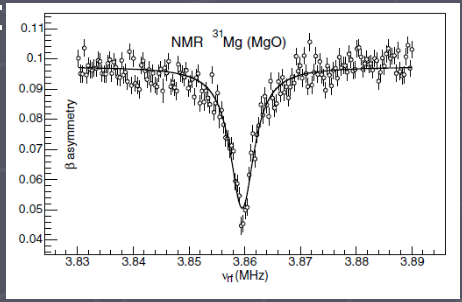
$^{32}Al_{g.s.}$:

1. ~~dominated by a 2p2h state~~
2. ~50% mixing of a 2p2h state to a 0p0h state
3. dominated by a 0p0h state

μ (^{31}Mg, I^{π}=1/2$^+$) :

→***2p2h*, deformed**

G. Neyens *et al.*, Phys. Rev. Lett. **94** (2005) 022501.



The *Q*-moment for the ground state of ^{32}Al is expected to provide the conclusive answer.

^{32}AlのＱモーメント測定

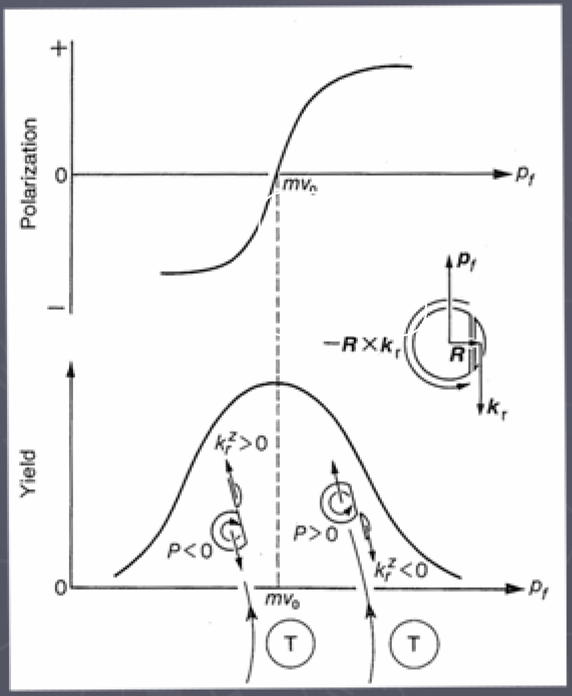
入射核破砕反応による
スピン偏極不安定核ビームの生成

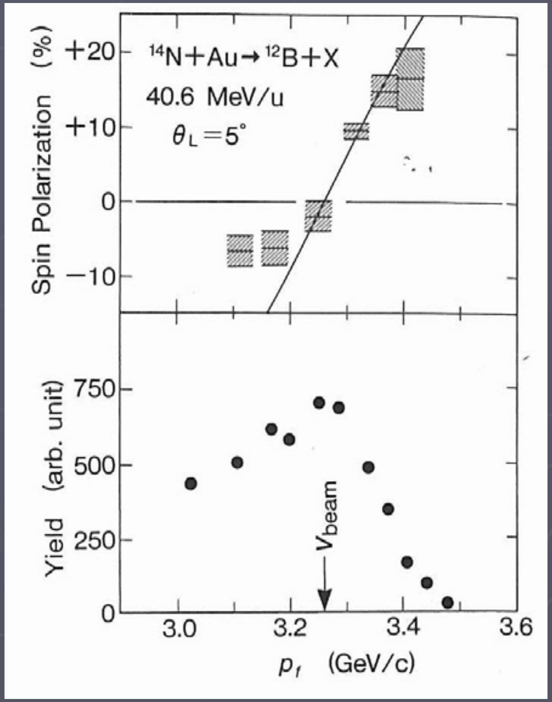
Kinematical model

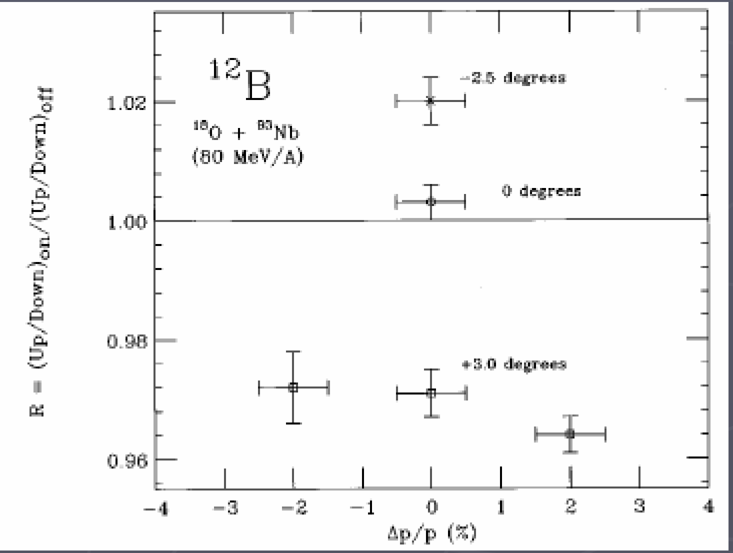
Experiment

^{18}O (80 MeV/A) + ^{93}Nb → ^{12}B:

6-nucleon removals





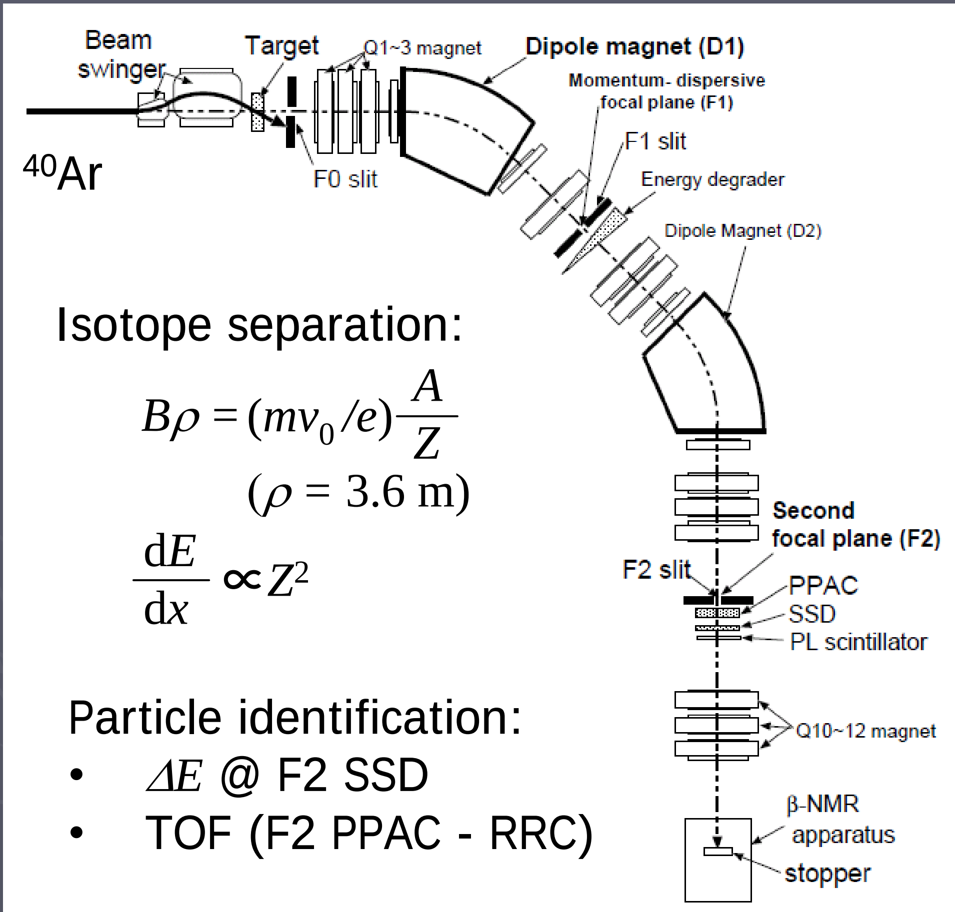


K. Asahi *et al.*,
Phys. Lett. ***B251*** (1990) 488

P.F. Mantica et al.,
Phys. Rev. C55 (1997) 2501

Production of spin-polarized ^{32}Al beam

RIKEN Projectile fragment separator (RIPS):



Isotope separation:

$$B\rho = (mv_0/e)\frac{A}{Z}$$

$$(\rho = 3.6\ \mathrm{m})$$

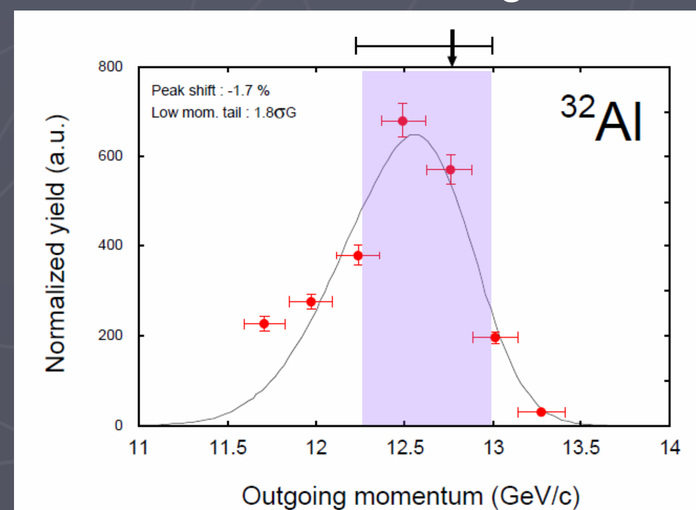
$$\frac{\mathrm{d}E}{\mathrm{d}x} \propto Z^2$$

Particle identification:

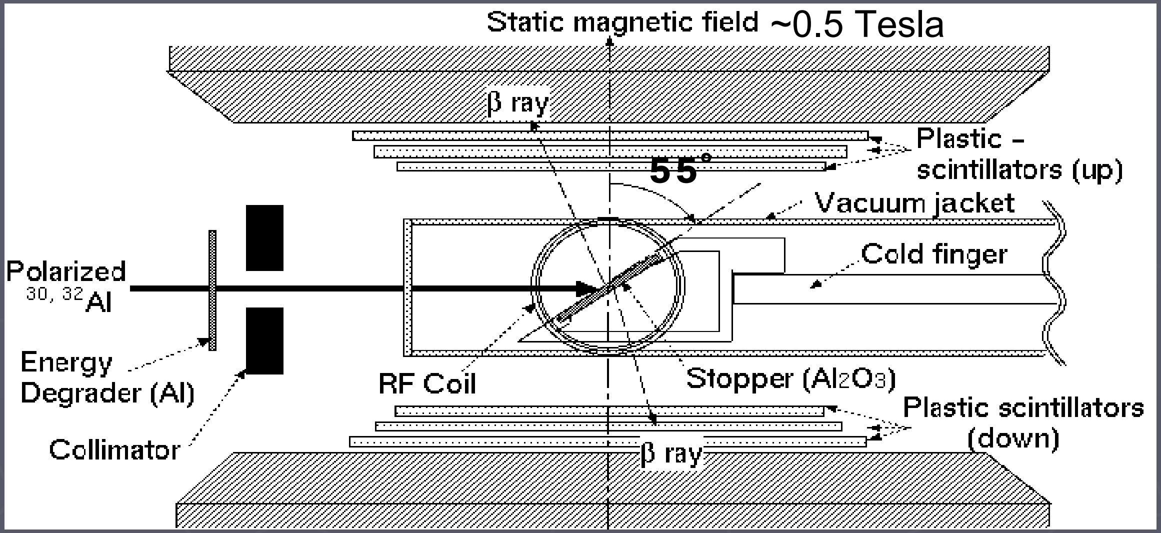
- ΔE @ F2 SSD
- TOF (F2 PPAC - RRC)

Primary beam	^{40}Ar 95 AMeV, 40pnA
Nb target	Nb, 0.37 g/cm^2
Secondary beam	^{32}Al
Emission angle	1.3 – 5.2 deg.
Momentum	12.6 GeV/c ±3 %
Intensity@F2	5 x 10^3 particle/sec.
Purity	85%
Polarization	~ 0.7 %

Selected momentum region:



β-NMR apparatus:

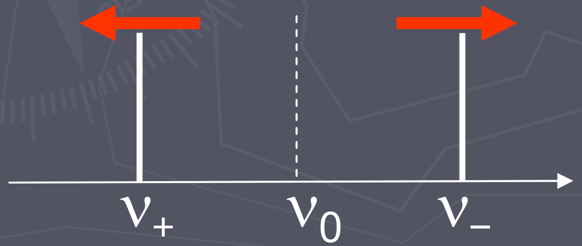


The resonance frequencies of ^{32}Al(I=1) in a stopper of single-crystal α-Al_2O_3:

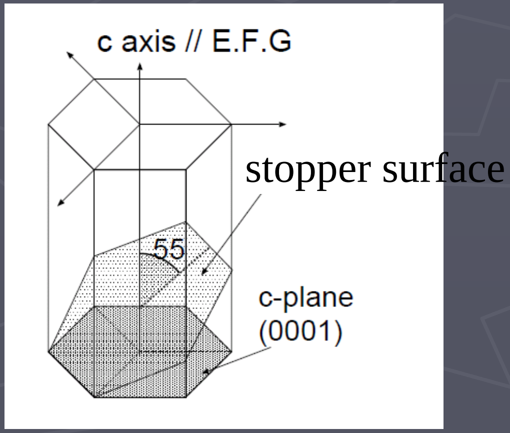
$$\nu_{\pm} = \nu_0 \mp \frac{3\nu_Q}{4} \frac{3\cos^2\theta_c - 1}{2}$$

$\nu_0 = g\mu_N B_0/h$ (Larmor frequency)

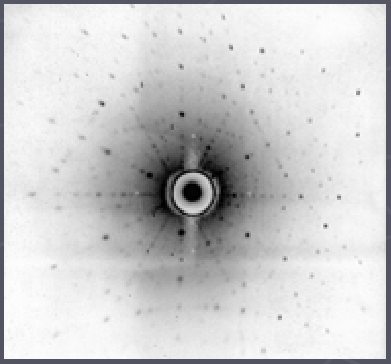
$\nu_Q = e^2qQ/h$ (Quadrupole coup. const.)



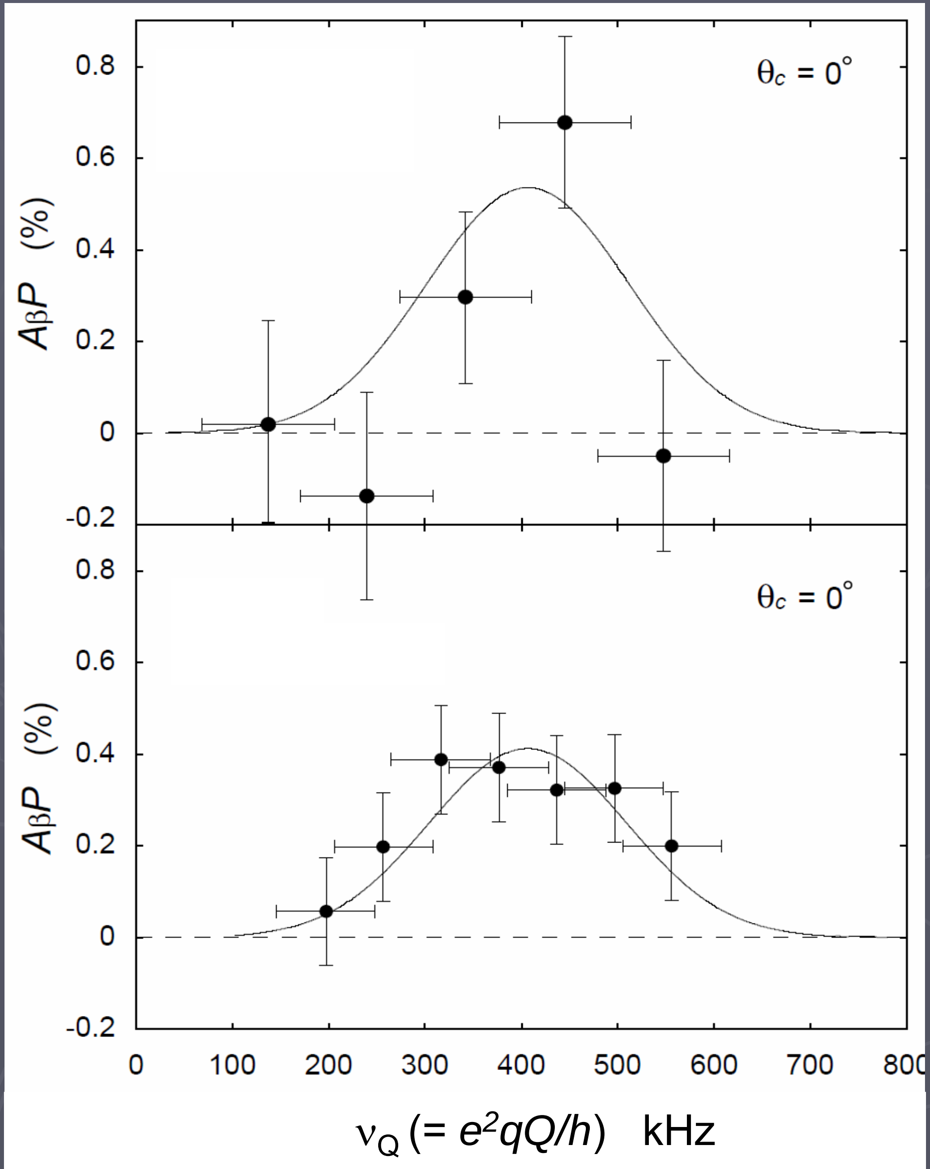
Crystal structure of α-Al_2O_3: h.c.p.



X-ray analysis



Quadrupole resonance spectra with α-Al_2O_3 stopper



Stopper conditions:

- Crystal c-axis // B_0
- Temperature ~80 K

Analysis :

- Fitting: gaussian including AFP effect
- Chemical shift correction: 0.00188(3) %

J. Magn. Reson. 128 (1997) 135.

Result : $\nu_Q(^{32}\mathrm{Al})$ = 407(34) kHz

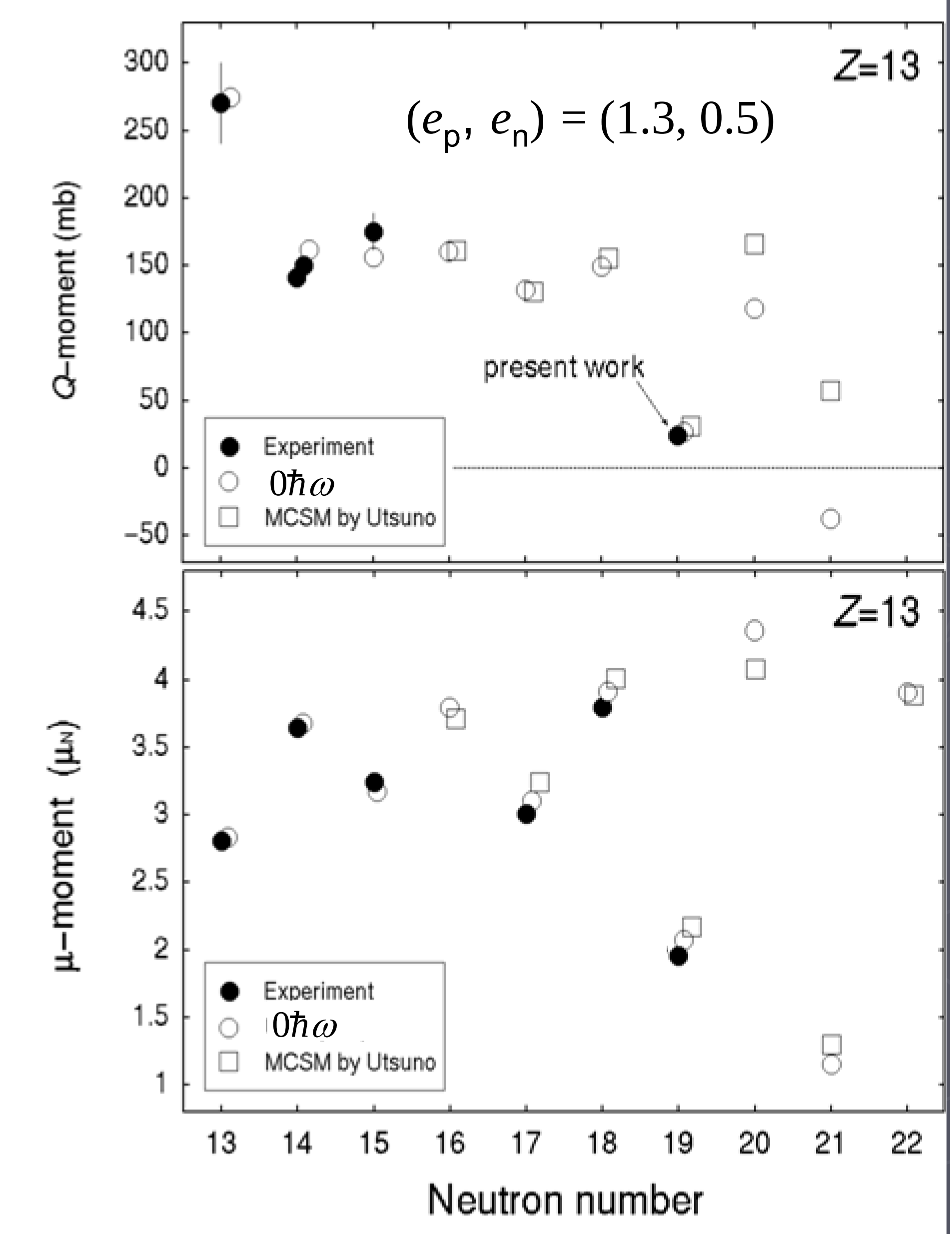
$$\frac{|Q(^{32}\mathrm{Al})|}{\nu_Q(^{32}\mathrm{Al})} = \frac{|Q(^{27}\mathrm{Al})|}{\nu_Q(^{27}\mathrm{Al})} = \frac{140.2(10)\ \mathrm{mb}}{2389(2)\ \mathrm{kHz}}$$

ref. $\nu_Q(^{27}\mathrm{Al})$ in α-Al2O3:
J. Magn. Reson. **89** (1990) 515.
$Q(^{27}\mathrm{Al})$: Phys. Rev. Lett. **68** (1992) 927.

$|Q(^{32}\mathrm{Al})|$ = 24(2) mb

D. Kameda et al., Phys. Lett. B, in press.

Systematic comparison : μ and Q for Al isotopes



0hw shell model calculations:

- USD effective interaction
- effective operators

B.Wildenthal, Prog. Part. Nucl. Phys. **11** (1984) 5

B.A. Brown and B.H. Wildenthal, Nucl. Phys.A**474** (1987) 290

sd wave function for $^{32}Al_{g.s.}$:

$$|^{32}Al_{g.s}(I^\pi=1^+)\rangle = \alpha|\pi d^{-1}_{5/2}\ \nu d^{-1}_{3/2}\rangle^{J=1+} + \beta|\pi(d^3_{5/2}d^2_{3/2})\ \nu d^{-1}_{3/2}\rangle^{J=1+} + \ldots$$

$$\alpha^2 = 79\ \%, \quad \beta^2 < 3.8\ \%$$

Large-scale shell model calculations by Utsuno in private comm.

$^{32}Al_{g.s}$: *sd*-normal configurations : 87 %
fp-intruder configurations : 13 %

$^{32}Al_{g.s}$:

1. ~~*dominated by a 2p2h state*~~
2. ~~*~50% mixing of a 2p2h state to a 0p0h state*~~
3. ***dominated by the 0h0p state***

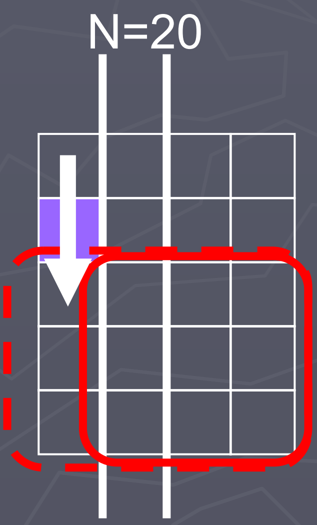
Studies on the neutron-rich N=19 isotones:

^{33}Si (Z=14) → sd shell structure (normal)

Reaction study	L.K. Fifield et al., Nucl. Phys. A453, 497 (1986).
	B. Fornal et al., Phys. Rev. C 49, 2413 (1994).
	B.V. Pritychenko et al., Phys. Rev. C 62, 051601(R) (2000).
	J. Enders et al., Phys. Rev. C 65, 034318 (2002).
$\beta-\gamma$ spectroscopy	A.C. Morton et al., Phys. Lett. B 544, 274 (2002).

^{32}Al (Z=13) → normal sd-shell or pf-intruder ?

Reaction	B. Fornal et al., Phys. Rev. C 55, 762 (1996).
$\beta-\gamma$	G. Klotz et al., Phys. Rev. C 47, 2502 (1993).
	S. Grevy et al., Nucl. Phys. A 734, 369 (2004).
$\beta-n$	M. Langevin et al., Nucl. Phys. A 414, 151 (1984).
Isomer production via PF	M. Robinson et al., Phys. Rev. C 52, R1465 (1996).
$\mu-$moment for g.s.	H. Ueno et al., Phys. Lett. B 615, 186 (2005).
Q-moment for g.s	D. Kameda et al., Phys. Lett. B, accepted (2007).



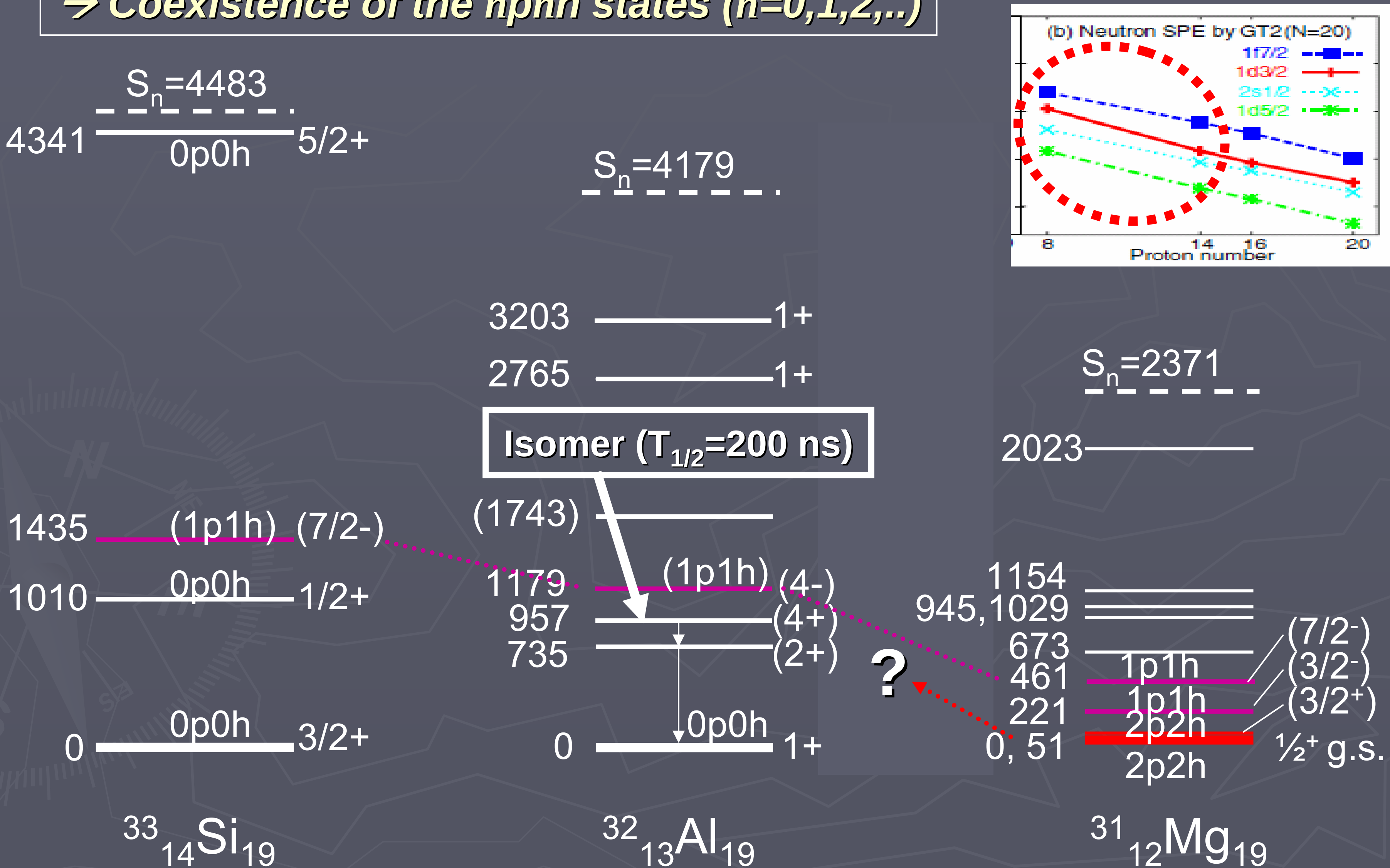
^{31}Mg (Z=12) → deformed pf-intruder structure

Reaction	H. Mach et al., Eur. Phys. J. A 25, 105 (2005).
$\beta-\gamma$	G. Klotz et al., Phys. Rev. C 47, 2502 (1993).
	F. Marechal et al., Phys. Rev. C 72, 044313 (2005).
μ-moment & spin	G. Neyens et al., Phys. Rev. Lett 94, 022501 (2005).

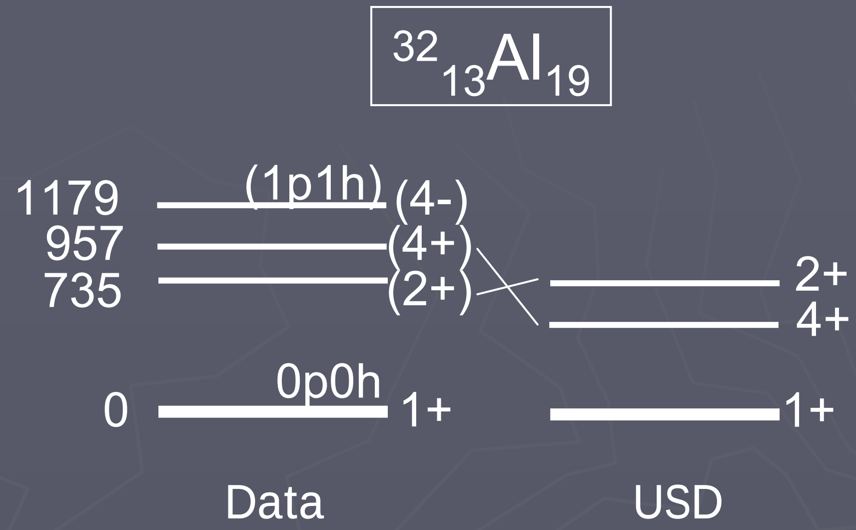
What happens in the *N*=19 low-lying levels ?

Gradual reduction of the sd-pf shell gap
→ Coexistence of the npnh states (n=0,1,2,..)

T. Otsuka et al.,
PRL97(2006)162501



Nuclear moments of ^{32m}Al



Approach I:

Measurement of the isomeric μ- and *Q*- moments of ^{32}Al by the Time Differential Perturbed Angular Distribution (TDPAD) method:

→ *The spin/parity of the isomeric state*
→ *The (mixing) amplitudes of the np-nh (n=0,2) configurations*

Approach II:

^{32}Mg β-delayed γ spectroscopy:

→ *β branching ratios, in particular, for the ground state of ^{32}Al*
→ *Construct the level scheme*

Submitted to RIBF proposal

^{32}Al	USD	EXP.
$g(4^+)$	1.330	To be measu.
$g(2^+)$	1.628	
$Q(4^+)$	163 mb	To be measu.
$Q(2^+)$	14.8 mb	
$Q(1^+_{g.s.})$	26.8 mb	24(2) mb
$g(1^+_{g.s.})$	2.065	1.959(9)
$T_{1/2}(4^+ \rightarrow 2^+)$	122 ns	200(20) ns
$T_{1/2}(2^+ \rightarrow 1^+)$	0.31 ps	

今後の目標･課題

今後の目標:

- 不安定核の系統的な核モーメントデータを得る
  (基底状態、及び励起状態の核モーメントデータ)
  → 殻構造変容の解明

課題:

- Spin orientation (polarization, alignment)
  - Projectile fragmentation…?
- Stopper to preserve the orientation
- SN ratio in the radiation detection

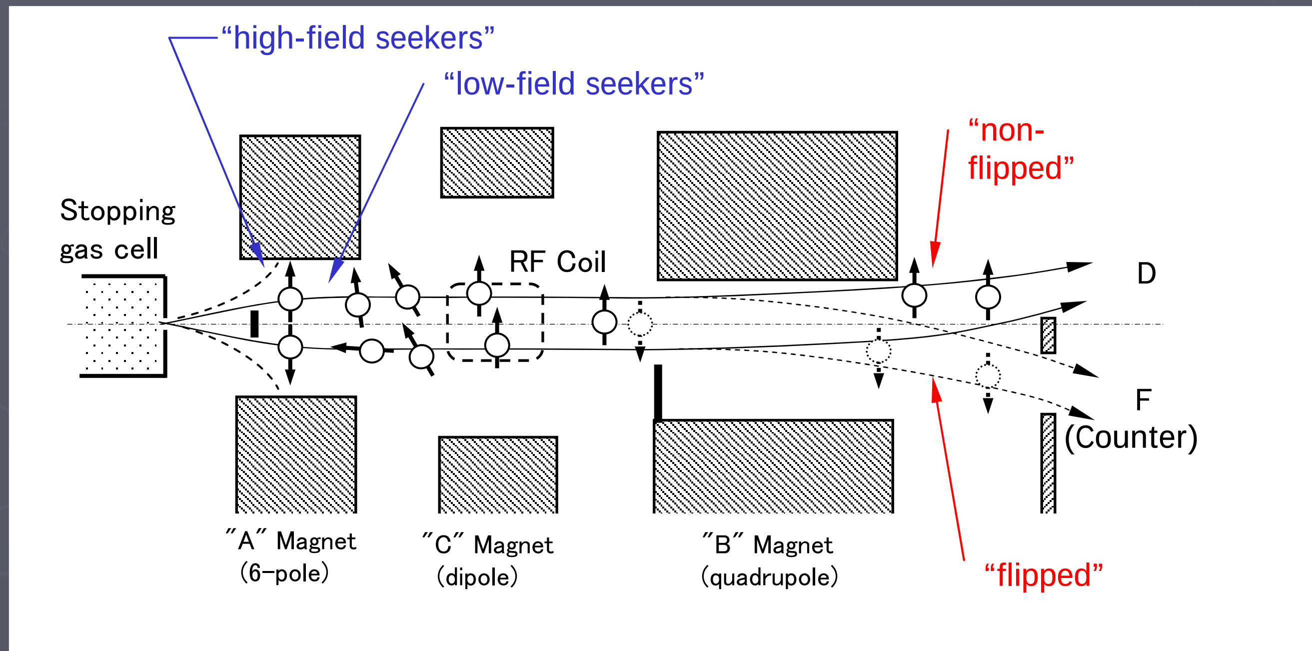
3S issues

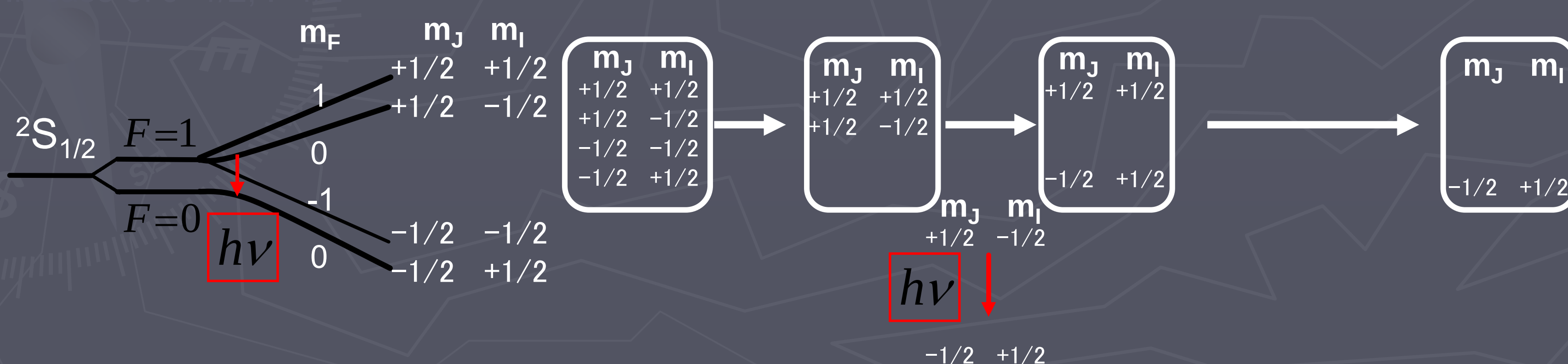
in particular,
nuclear moment measurements of ground states

低速不安定核ビームを用いた核モーメント測定

→ Free from 3S issues

原子ビーム共鳴法:

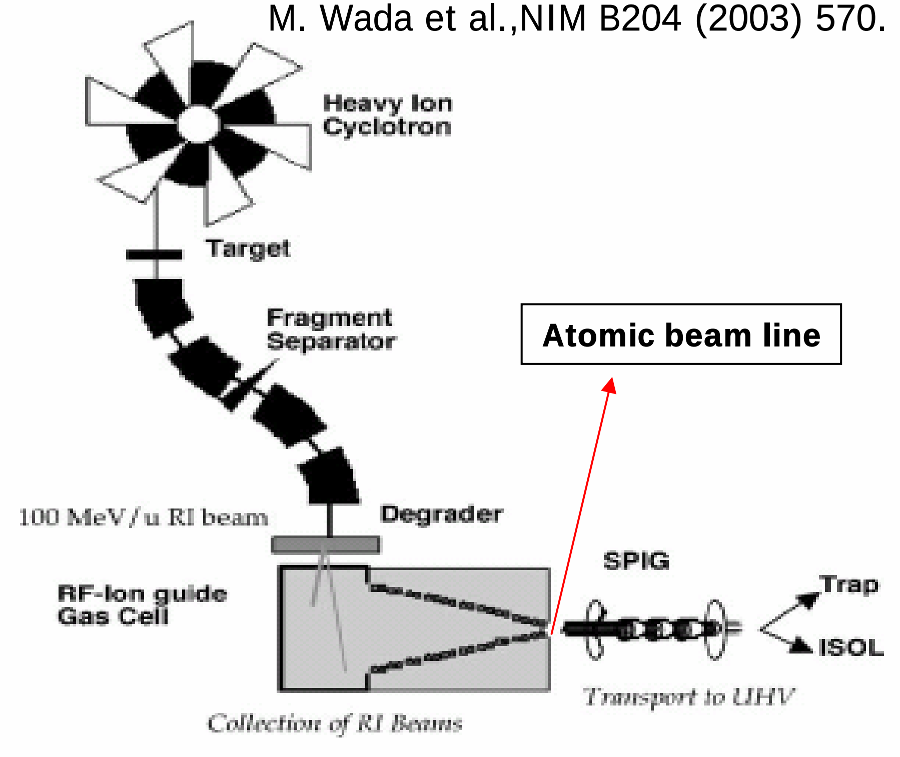




低速不安定核ビームの生成過程

1. 減速：減速材
   - くさび状のアルミ板：入射核破砕反応の運動量広がり補償
   - Arガス：圧力調整による厚さの微調整
   - 両者の組み合わせ
2. 停止 → 電場によるイオンの引き出し：停止材ガス種
   - Heガス：非中性化効率大、ストッピングパワー小
   - Neガス：ストッピングパワー大、非中性化効率…
3. 中性化
4. 原子ビーム生成
   - ラバールノズル：旧来方式

M. Wada et al.,NIM B204 (2003) 570.



Arガス減衰層の開発@CYRIC

実験セットアップ

Ar-Gas degrader　　Ne-Gas stopper

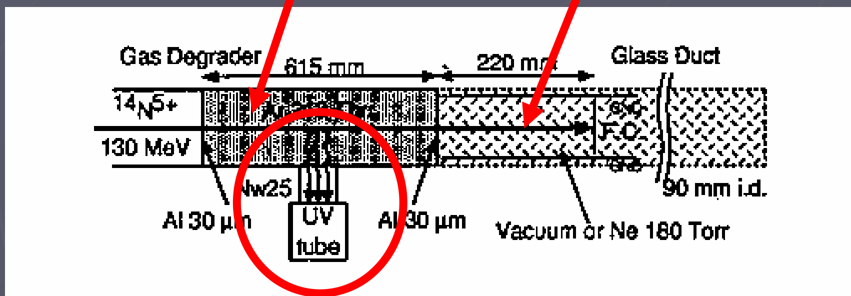
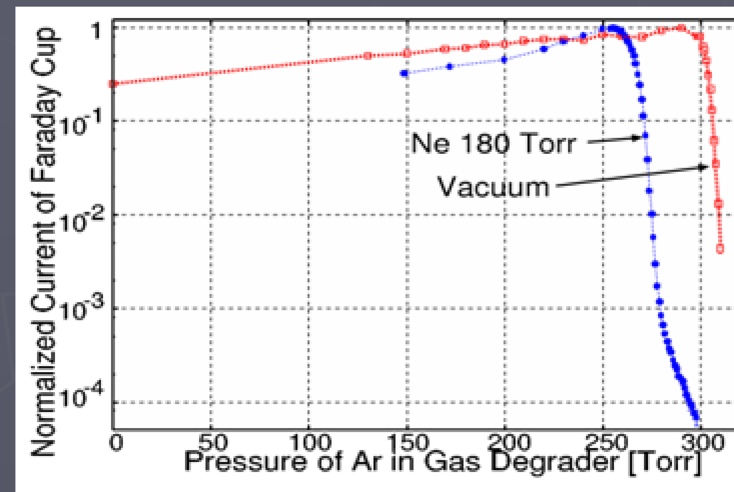


Fig. 1. Setup of the experiments.

Arガス圧調整 (F.C.固定位置):



- 入射ビーム: ^{14}N (Stable), 130MeV
- 減衰層(兼ビームモニター): Arガス
- ストッパー: Neガス

ガ

停止位置は、チャンバー内に置いた
ファラデーカップ(F. C.)の電流値より測定

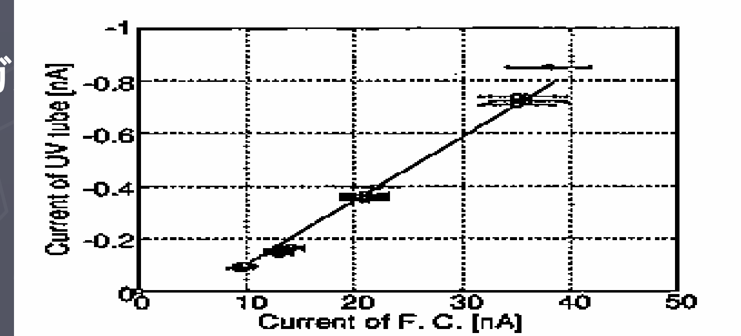


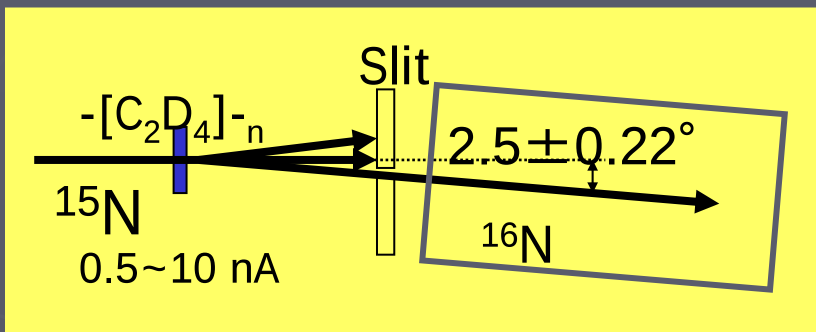
Fig. 3. Currents at the UV multiplier tube and F. C. were changing beam intensity.

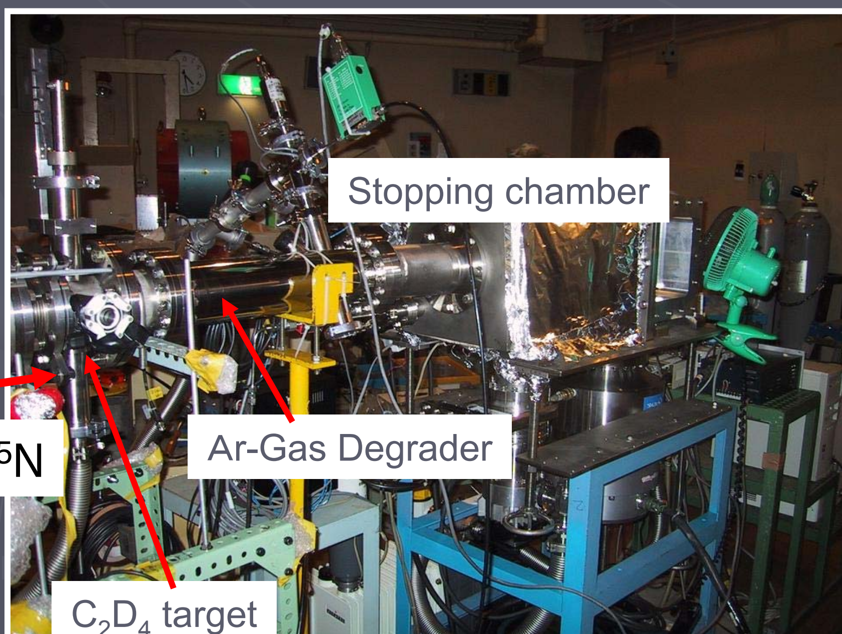
K. Shimada et al., RIKEN Accel. Rep. 39 (2006).

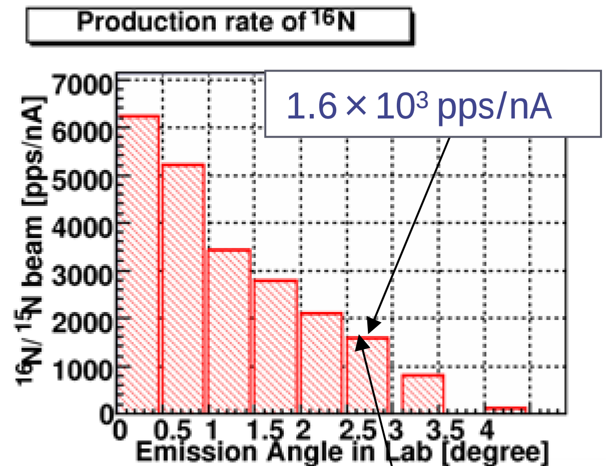
不安定核ビームを用いた停止位置の確認@CYRIC

Production of ^{16}N (I=1, $T_{1/2}$=7.1 s)

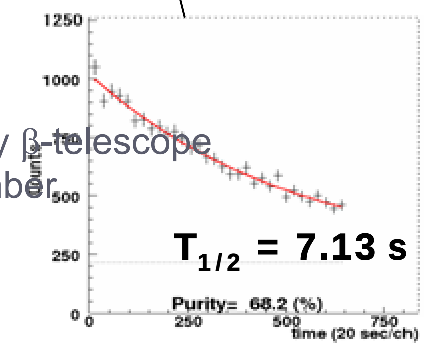
d(^{15}N, ^{16}N)p @ Cyclotron Center, Tohoku Univ.







Detected by β-telescope
in the chamber

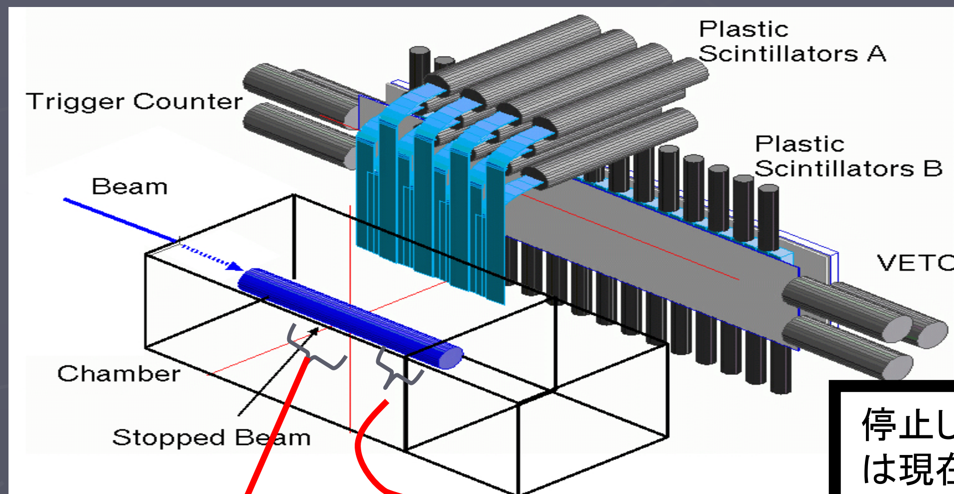


10^4 cps ^{16}N (with 10nA of 15N)
→Extraction → 10^3 cps
↓
Experiment for extraction/neutralization is possible

Arガス圧による停止位置の微調整@CYRIC

入射ビームの停止分布測定

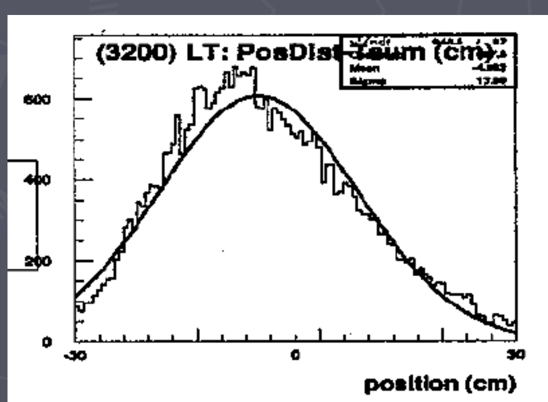
外側の β-telescope から 16N 停止位置を観測

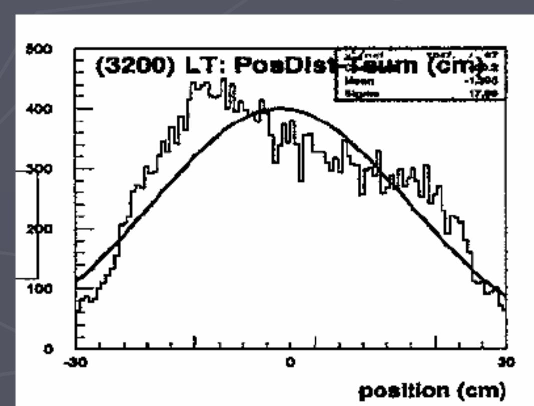


停止した^{16}N の電場によるドリフトの確認は現在進行中…

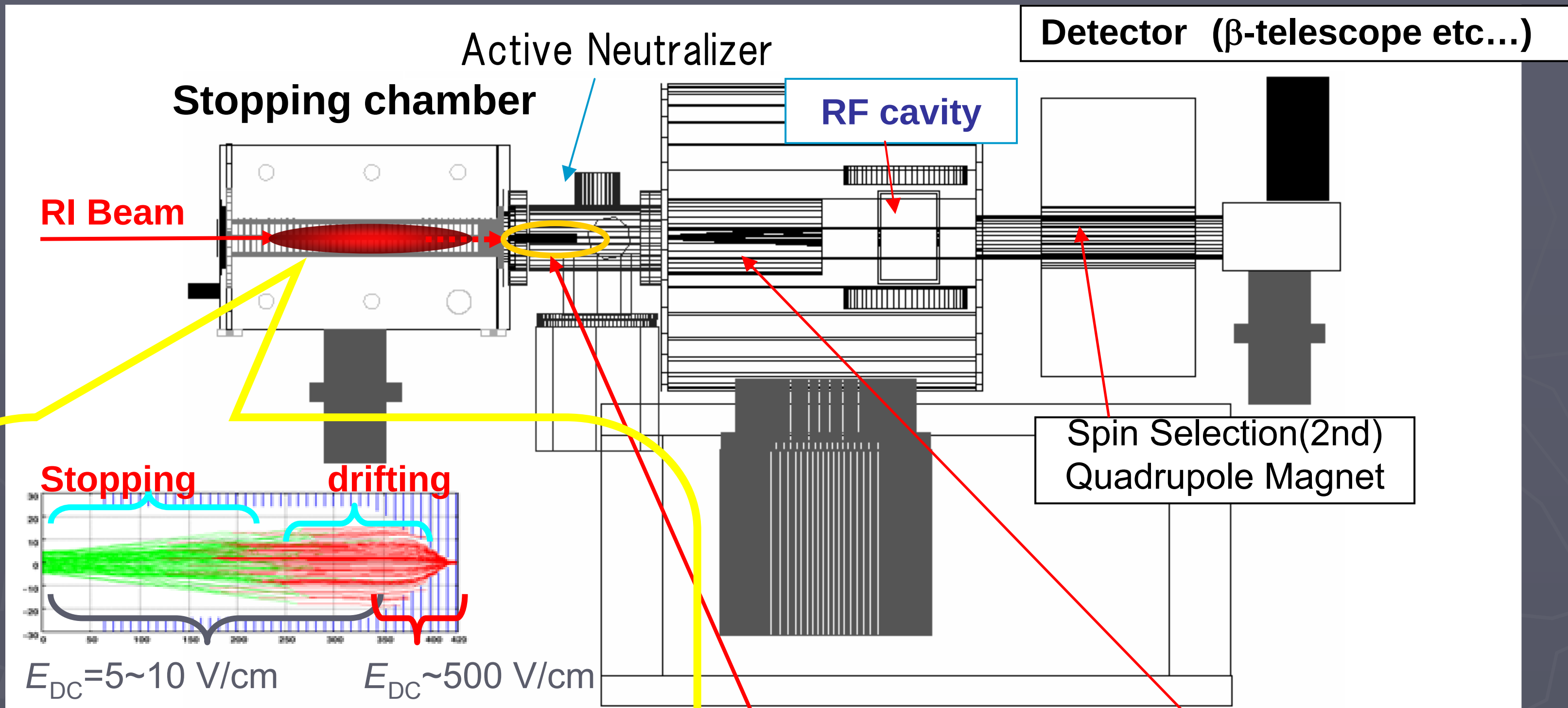
中心付近に停止

ノズル付近に停止





低速不安定核ビームの応用I:原子線共鳴法



Note:

$$v_{\mathrm{ion}} = \mu E_{\mathrm{DC}} \qquad \mu : \text{mobility}$$

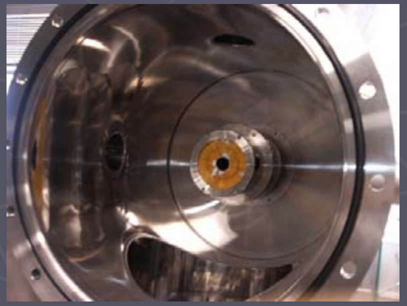
μ = 4.0 (in Ne gas)

μ =10.0 (in He gas)

120 ms for E=10V/cm, Ne 200 torr

Yttrium tube

Spin Selection(1st)
Sextupole Magnet



1.3T@pole tip

応用II: 原子線レーザー分光

オフライン開発段階:

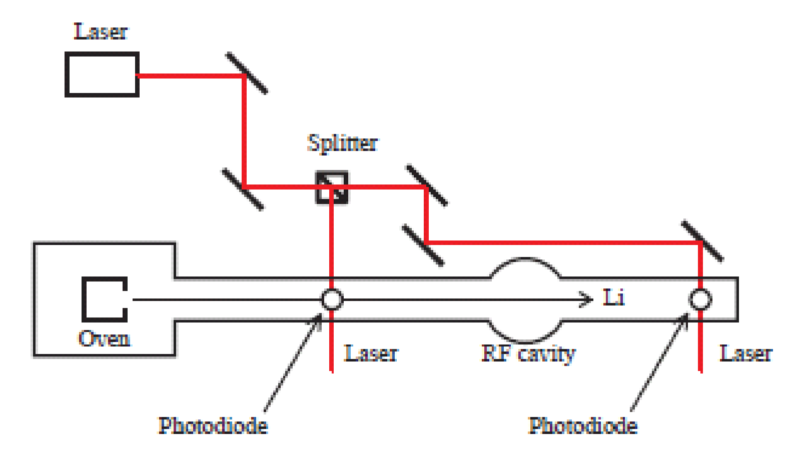


Fig. 1. Schematic view of RF test cavity.

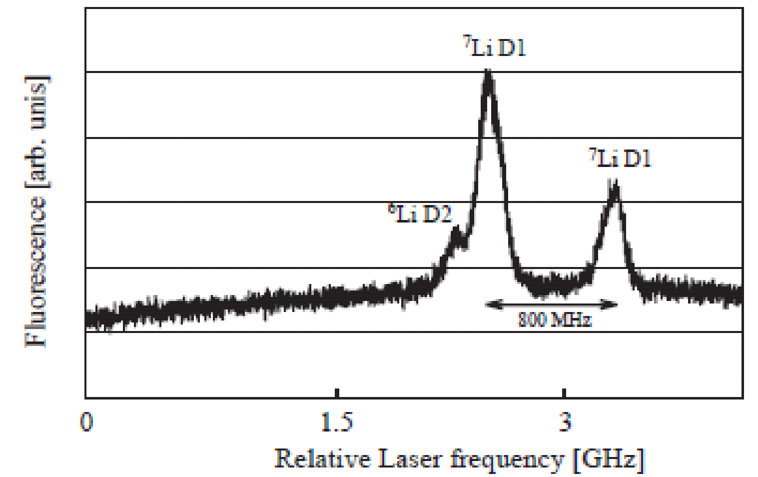


Fig. 2. Fluorescence taken during laser detuning. The first peak corresponds to the ^{6}Li D2 line and the second and third peaks to the ^{7}Li D1 lines.

^{7}Li atomic beam:

Optical pumping by a diode laser: $^2S_{1/2}$, F=1 → $^2P_{1/2}$, F=2 (D1)

D. Nagae et al., RIKEN Accel. Prog. Rep. **39** (2006)

まとめ

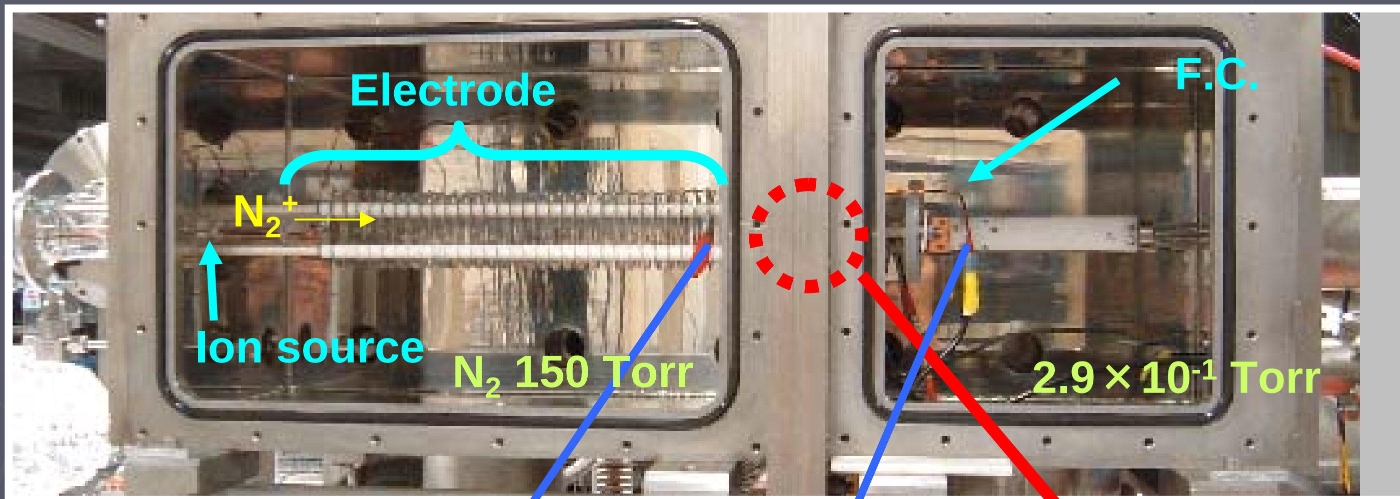
- 不安定核の系統的な電磁気モーメントデータ
  → 不安定核構造を探る上で不可欠

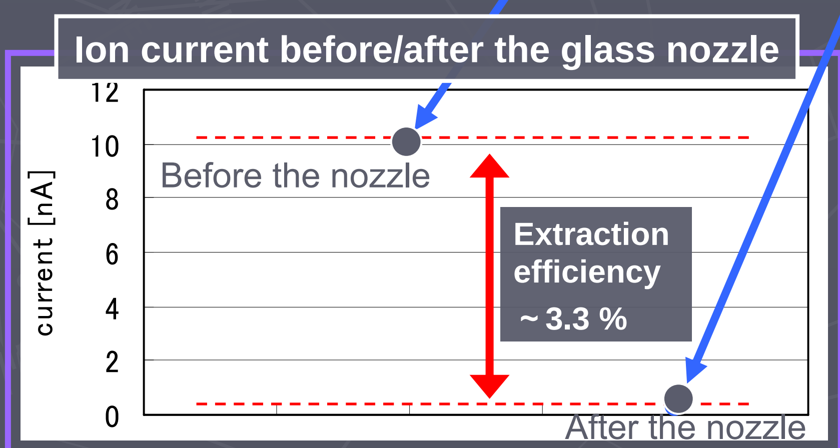
- 3S課題の克服
  → 基底状態の核モーメント測定:
  低速不安定核ビーム生成に向けた開発
  不安定核ビームを用いた開発実験の必要性

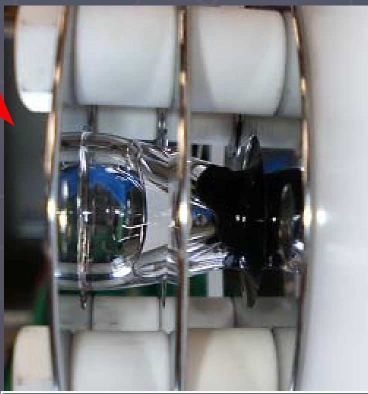
  → アイソマーの核モーメント測定:
  TDPAD, TDPAC, etc…

オフライン：イオンの引き出し

放電による生成イオンを用いて、オフライン実験を行った





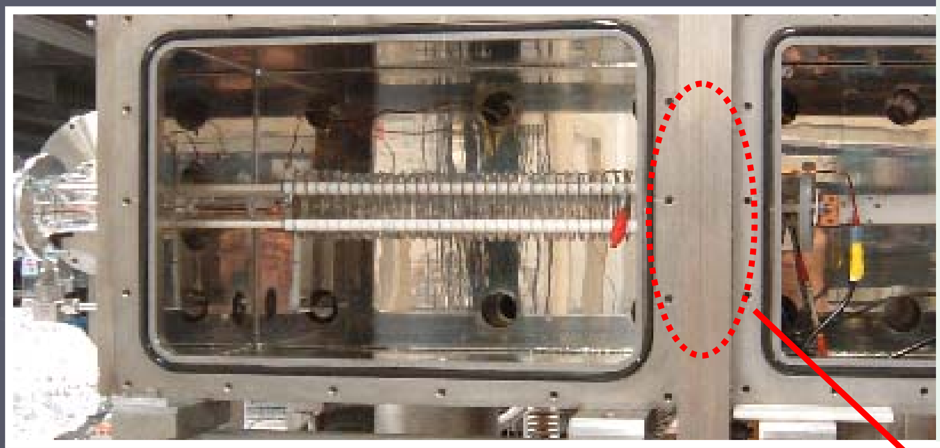


Glass nozzle Φ1 mm
(Laval-type)

オフライン：RF イオンガイド

イオンの引き出しを向上するために……

Ion-guide efficiency = 33%
Wada et al., NIMA 532(2004)40



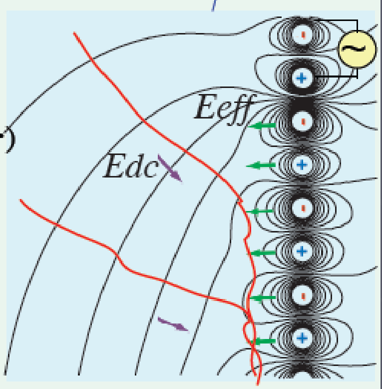
RF gradient Field: Barrier

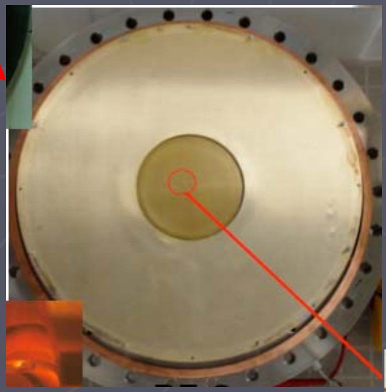
$$\overline{F} = -\frac{e^2}{4m}\frac{1}{(\Omega^2 + 1/\tau_v^2)}\nabla \mathbf{E}_{rf}^2(\mathbf{r})$$

$(\mathbf{E}(\mathbf{r},t) = \mathbf{E}_{rf}(\mathbf{r})\cos(\Omega t),\ \tau_v$: relax time)

$$E^{max}_{\text{eff in gas}} = \frac{m\mu^2 V_{rf}^2}{e r_0^3}$$

$2r_0 \approx$ electrode distance





Off-line experiments with LASER-induced ions
→ On-line experiments with 16N beam (2006/12, 2007/1-2)

Carpet is made of ring electrodes 0.28 mm interval

軽核領域の核モーメント測定

TITech / RIKEN
Osaka / RIKEN

- *g*-Factors measured at RIKEN
  - Boron isotopes : ^{14}B, ^{15}B, ^{17}B
  - Carbon isotopes : ^{9}C, ^{15}C, ^{17}C
  - Nitrogen isotopes : ^{17}N, ^{18}N, ^{19}N
  - Oxygen isotopes : ^{13}O
  - Fluorine isotopes : ^{21}F
  - Aluminum isotopes: ^{23}Al, ^{30}Al, ^{32}Al

Spin-parity assignment

Effect of neutron excess on the magnetic moment

- *Q*-moments measured at RIKEN
  - Boron isotopes : ^{14}B, ^{15}B, ^{17}B
  - Nitrogen isotopes : ^{18}N
  - Oxygen isotopes : ^{13}O
  - Magnesium isotopes : ^{23}Mg
  - Aluminum isotopes: ^{31}Al, ^{32}Al

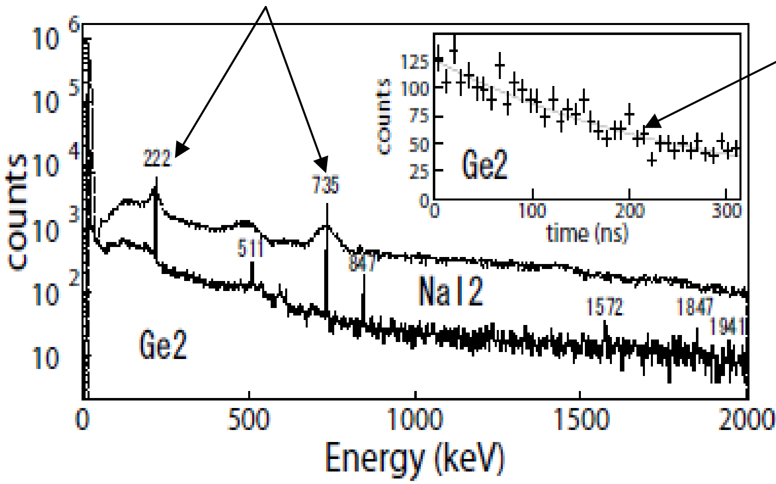
Reduction of *E*2 effective charges

I, TDPAD measurements

1. Produce spin-aligned ^{32}Al isomers
   - Projectile fragmentation of ^{40}Ar(95 MeV/u)
2. Implant the isomers in a stopper
   - g-factor: Perturbation-free material, metal(Al, Cu), MgO, Si
   - Q-moment: α-Al_2O_3 (The E.F.G. was known)
3. Detect the γ-ray decay of the isomeric state
   - Particle-γ slow coincidence technique
   - A static magnetic field with a suitable magnitude

We have already produced the ^{32m}Al beam in RIPS:

γ cascade from ^{32m}Al



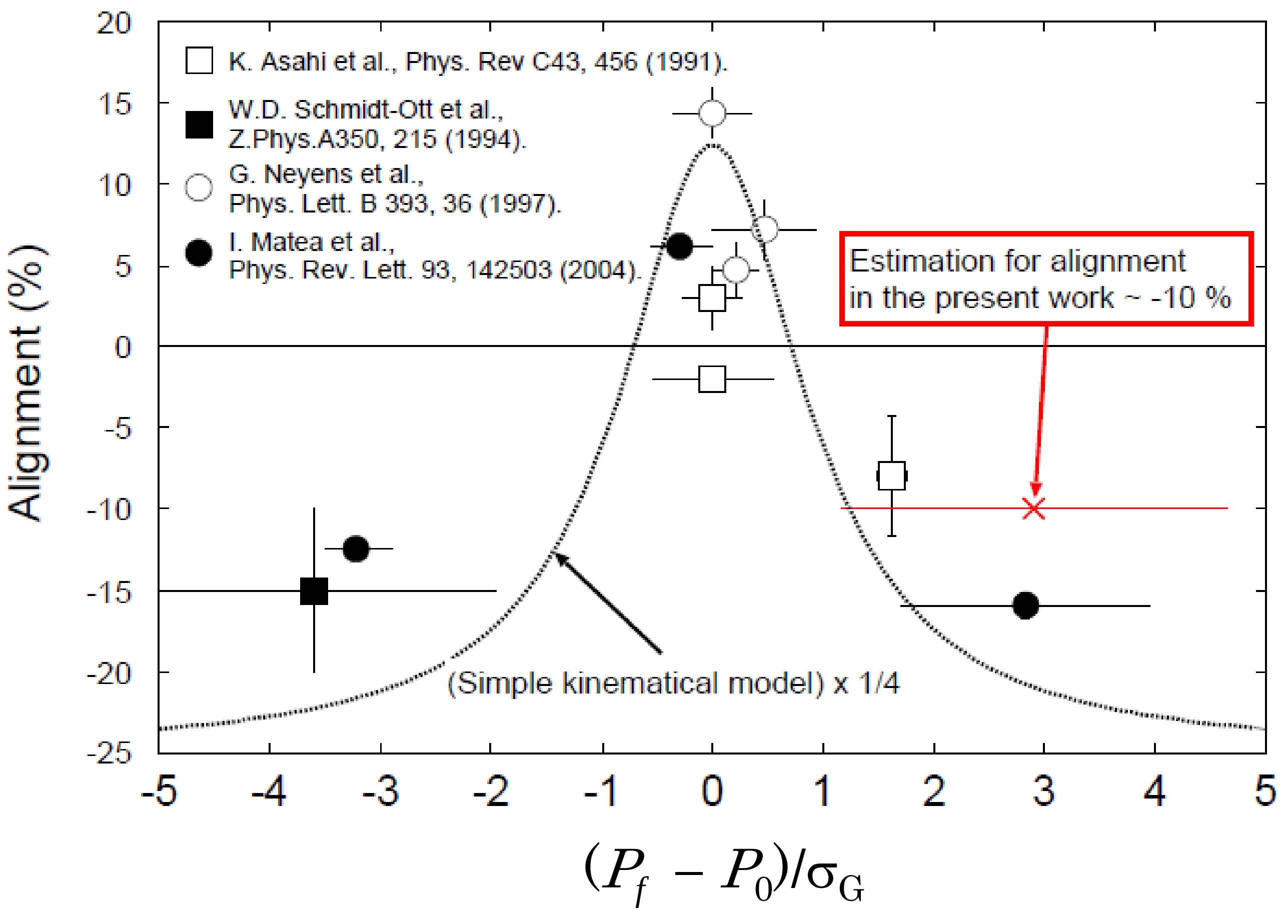
$T_{1/2}$=199(10)ns

in good agreement with the literature

Background at the low-energy peak:

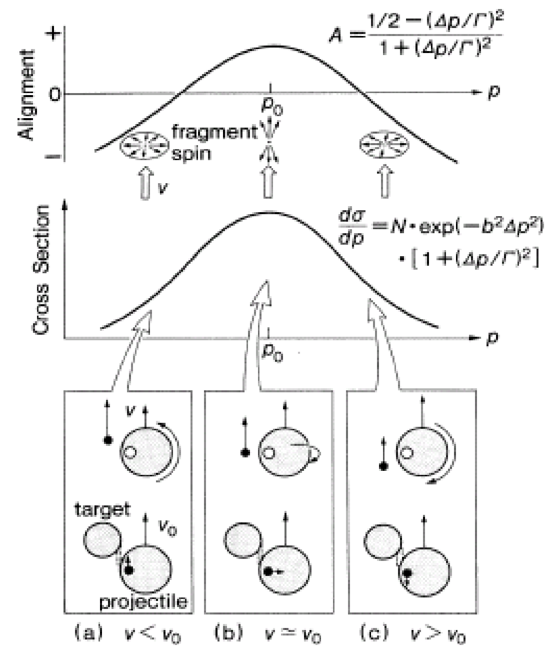
	NaI	HPGe
SN ratio @222 keV	1.3	30

Alignment via projectile fragmentation



Kinematical model:

K. Asahi et al., PRC43(1991)456.



Goldhaber distribution:

$$\sigma_G = \sigma_0 \sqrt{(Af(Ap - Af)/(Ap-1)}$$

$(\ \sigma_0 = 90$ MeV/c)

A.S. Goldhaber, PLB53 (1974) 306.

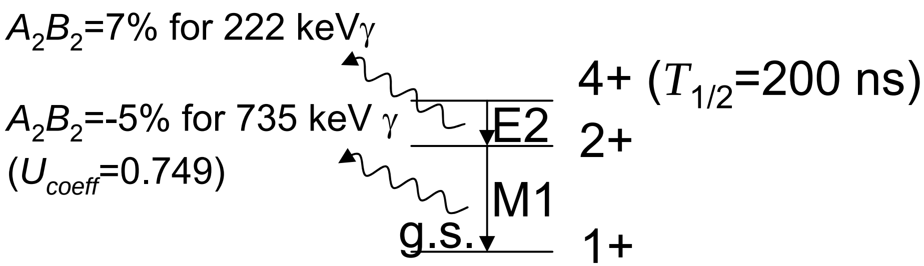
Simulation of TDPAD spectra by GEANT3

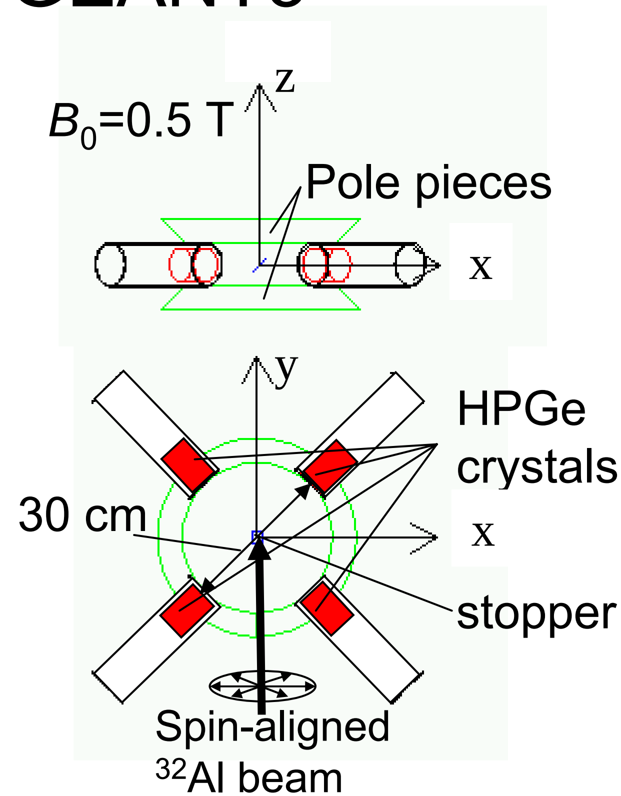
- Isomer yield = 1 kpps
- Alignment = - 10 %
- $g(^{32m}\mathrm{Al})=1.33$
- Angular distribution:

$$W(\theta) = 1 + A_2 B_2 P_2\{\cos(\theta - \nu_0 t)\}$$

A_2: Angular correlation coefficient

B_2: Orientation parameter





$$R(t, \theta, B_0) = \frac{I(t, \theta, B_0) - I(t, \pi/2 + \theta, B_0)}{I(t, \theta, B_0) + I(t, \pi/2 + \theta, B_0)} \quad (\theta = \pi/4)$$