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トラップされた不安定Be同位体のアイソトープシフト測定

中村貴志＠理研原子物理

T.Nakamura *et al.*, Phys. Rev. A, accepted for publication

PHYSICAL REVIEW A **74**, 1 (2006)

Laser spectroscopy of $^{7,10}\mathrm{Be}^+$ in an online ion trap

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Radioactive beryllium isotope ions ($^{7}\mathrm{Be}^+$ and $^{10}\mathrm{Be}^+$) that are provided by a projectile fragment separator with $\approx$1 GeV beams, as well as stable isotope ions ($^{9}\mathrm{Be}^+$) are stored and laser cooled in an online ion trap. Their absolute transition energies of the $2s\ {}^2S_{1/2} \rightarrow 2p\ {}^2P_{3/2}$ transition were measured with an accuracy of $\sim 10^{-8}$. In this way isotope shifts of beryllium ions were obtained and the differential mass polarization parameter $\kappa = -0.286\,41(70)$ a.u. as well as the $2s\ {}^2S \rightarrow 2p\ {}^2P$ transition energy of an infinitely heavy beryllium ion $h\nu^{\infty} = 0.145\,524\,290(42)$ a.u. were determined for the first time.

概要

RFイオンガイドから引き出された不安定$^{10,7}\mathrm{Be}^+$イオンのon-lineトラップ

($^{9}\mathrm{Be}^+$についてはoff-lineでトラップ)

$2\ ^2S_{1/2}$-$2\ ^2P_{3/2}$遷移のレーザー分光

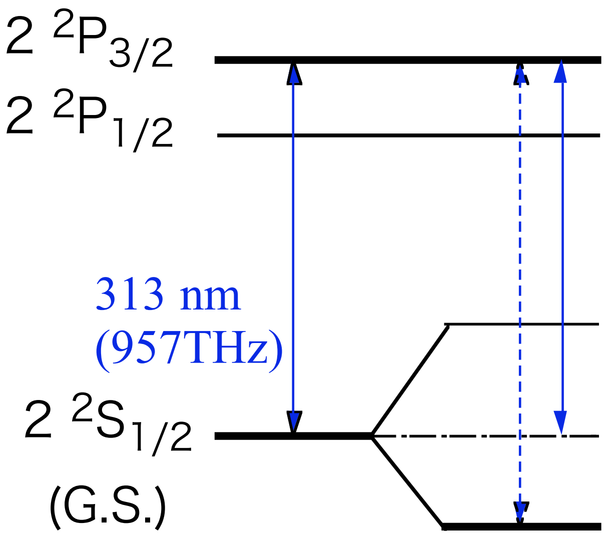
遷移周波数の絶対値測定＝アイソトープシフト(IS)測定

ISの理論計算との比較

・Be同位体：9=NA100%→Be初のアイソトープシフト測定

・$^{9}\mathrm{Be}^+$ $2\ ^2S_{1/2}$-$2\ ^2P_{3/2}$: 弱磁場(~0.54 mT)では初精密分光データ

→　過去の強磁場(~1.1 T)でのデータとの比較



Be^+ atomic energy levels

Isotope Shift (IS)

isotope shift = 同位体間にみられる遷移周波数（原子エネルギー準位）のシフト

type		origin	effective region	order @Be$^+$ $2^2S_{1/2}$ - $2^2P_{3/2}$
field shift (FS)		nuclear charge distribution	Z ≥ 58	effect ~100 MHz difference ~ 10 MHz (negligible here)
mass shift (MS)	normal MS (NMS)	reduced mass	Z ≤ 30	effect ~ 100 GHz difference ~ 10 GHz (comparable)
	specific MS (SMS)	mass polarization (multi-electronic)	2 ≤ Z ≤ 30 (0 for H-like)	

エネルギー準位のMS: 核の質量→∞の準位ϵ^∞に対する有限核質量M_nの準位

$$\epsilon(M_\mathrm{n}) = \frac{\mu}{m_e}\left(\epsilon^\infty + \frac{1}{M_\mathrm{n}}\left\langle \sum_{i<j}^{N} \mathbf{p}_i \cdot \mathbf{p}_j \right\rangle\right) = \epsilon^\infty - \frac{\mu}{M_\mathrm{n}}\epsilon^\infty + \frac{\mu}{M_\mathrm{n}}K$$

mass polarization NMS SMS

$$\mu = \frac{M_\mathrm{n} m_e}{M_\mathrm{n} + m_e}$$

$\mathbf{p}_\mathrm{k}$:束縛電子の運動量

mass polarization parameter $K = \left\langle \sum_{i<j}^{N} \mathbf{p}_i \cdot \mathbf{p}_j \right\rangle / m_e$ 計算難しい，いくつかの理論計算

遷移周波数のisotope shift (実験で測定可能)

state a,b間遷移 $h\nu_{\mathrm{obs}} = \epsilon_{\mathrm{a}} - \epsilon_{\mathrm{b}} = h\nu^{\infty} - \frac{\mu}{M_{\mathrm{n}}} h\nu^{\infty} + \frac{\mu}{M_{\mathrm{n}}} \kappa$

NMS SMS

transition energy of an infinite mass $h\nu^{\infty} = \epsilon_{\mathrm{a}}^{\infty} - \epsilon_{\mathrm{b}}^{\infty}$

differential mass polarization parameter $\kappa = K_{\mathrm{a}} - K_{\mathrm{b}}$

同位体間での遷移周波数の差(一般にはこの形で評価)

$$h\nu_{2-1} = h\nu(M_2) - h\nu(M_1) = \left(\frac{\mu_1}{M_1} - \frac{\mu_2}{M_2}\right)(h\nu^{\infty} - \kappa)$$ difference

BeではISが大きいので困難, $h\nu^{\infty}$と$\varkappa$の独立導出困難

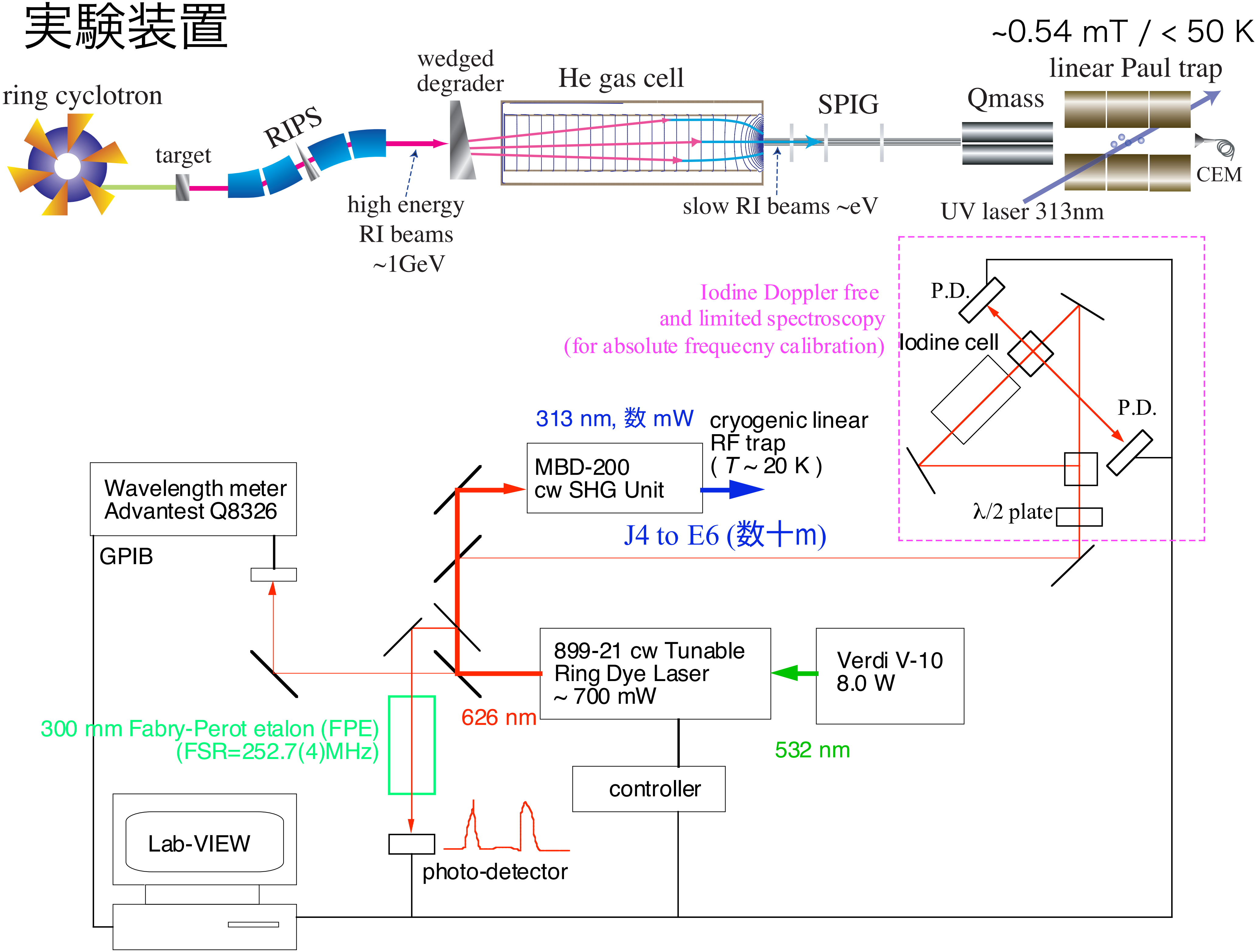
ここでは,

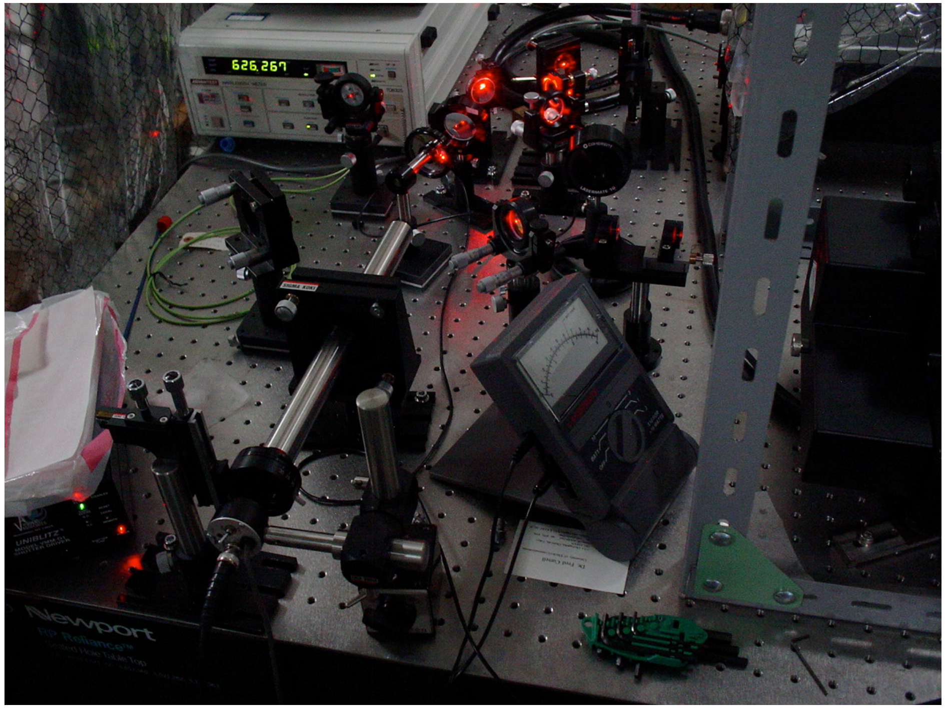
各同位体の遷移周波数の絶対値測定

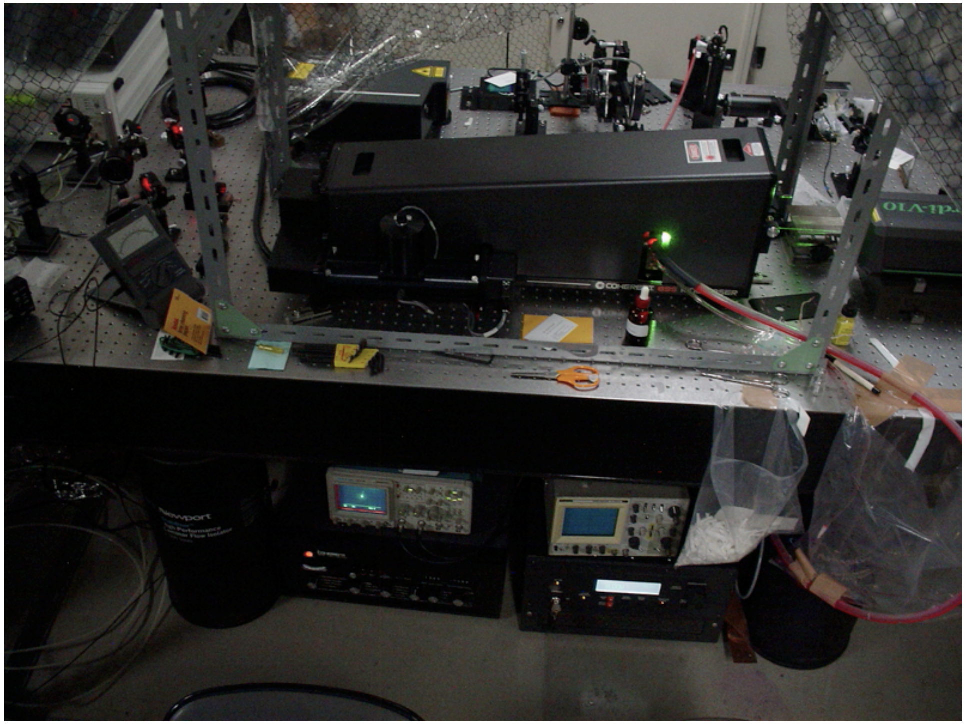
↓

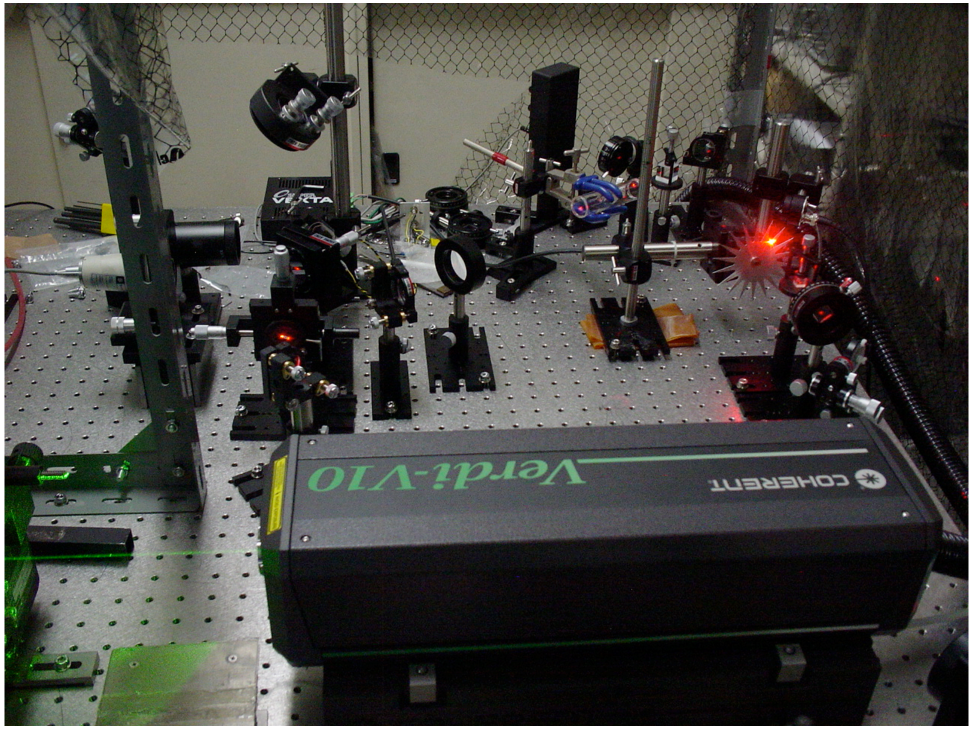
isotope shiftを特徴付ける量として$h\nu^{\infty}$と$\varkappa$を**導出, 理論計算と比較**

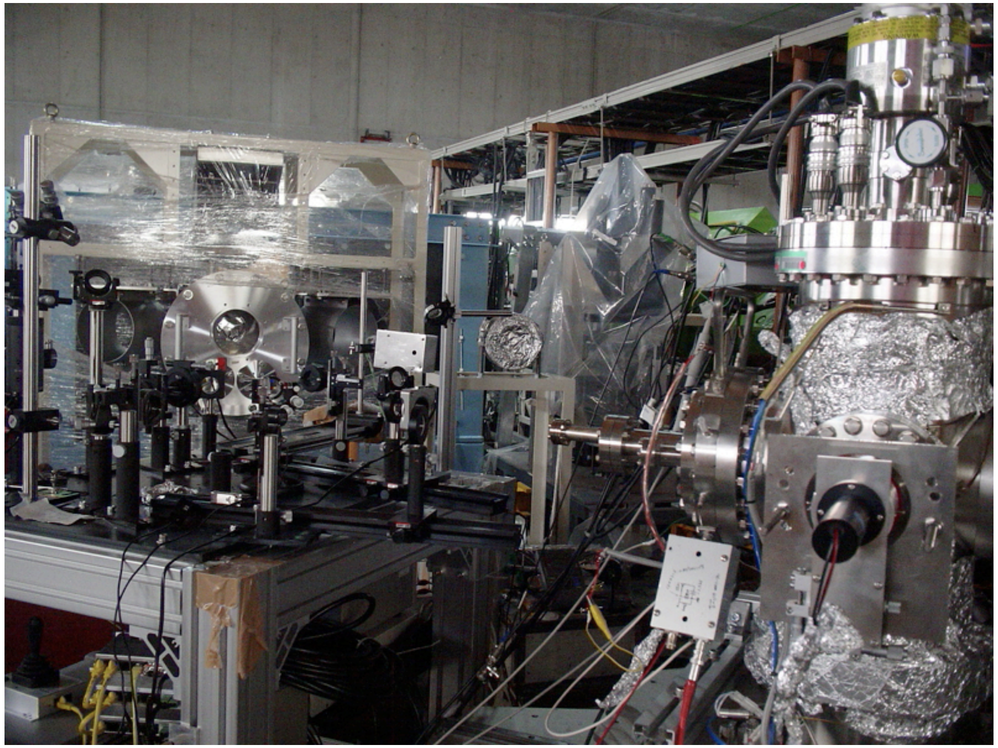
実験装置

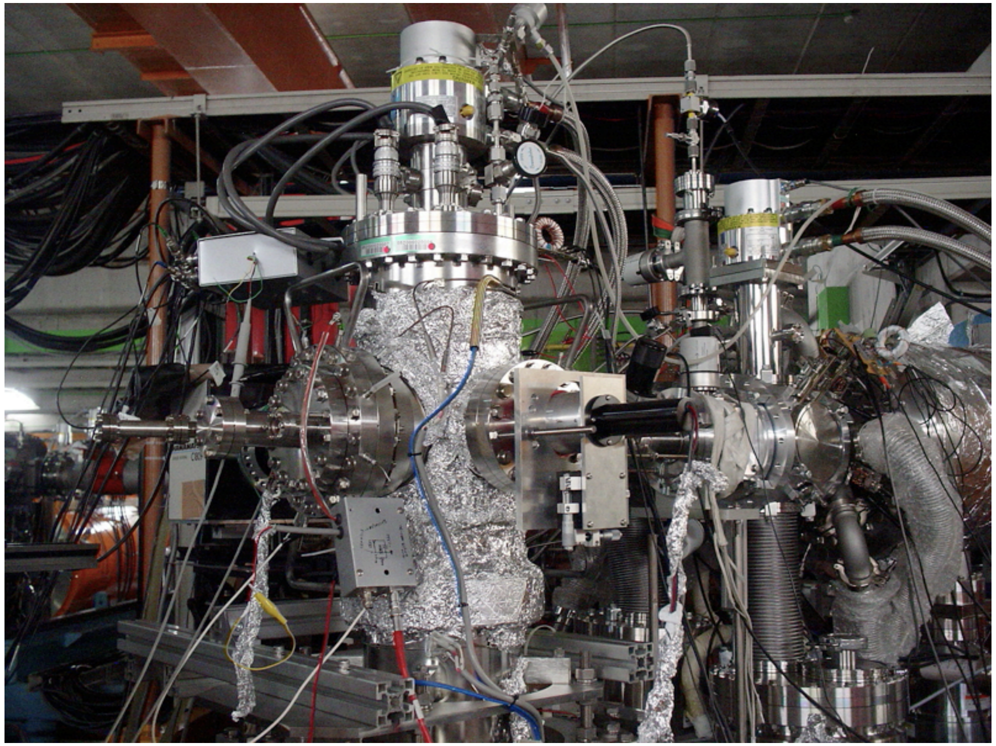

~0.54 mT / < 50 K
ring cyclotron
target
RIPS
wedged degrader
He gas cell
SPIG
Qmass
linear Paul trap
CEM
high energy RI beams ~1GeV
slow RI beams ~eV
UV laser 313nm
Iodine Doppler free
and limited spectroscopy
(for absolute frequecny calibration)
P.D.
Iodine cell
P.D.
λ/2 plate
313 nm, 数 mW
cryogenic linear RF trap (T ~ 20 K)
MBD-200
cw SHG Unit
J4 to E6 (数十m)
Wavelength meter
Advantest Q8326
GPIB
899-21 cw Tunable
Ring Dye Laser
~ 700 mW
Verdi V-10
8.0 W
626 nm
532 nm
300 mm Fabry-Perot etalon (FPE)
(FSR=252.7(4)MHz)
controller
Lab-VIEW
photo-detector

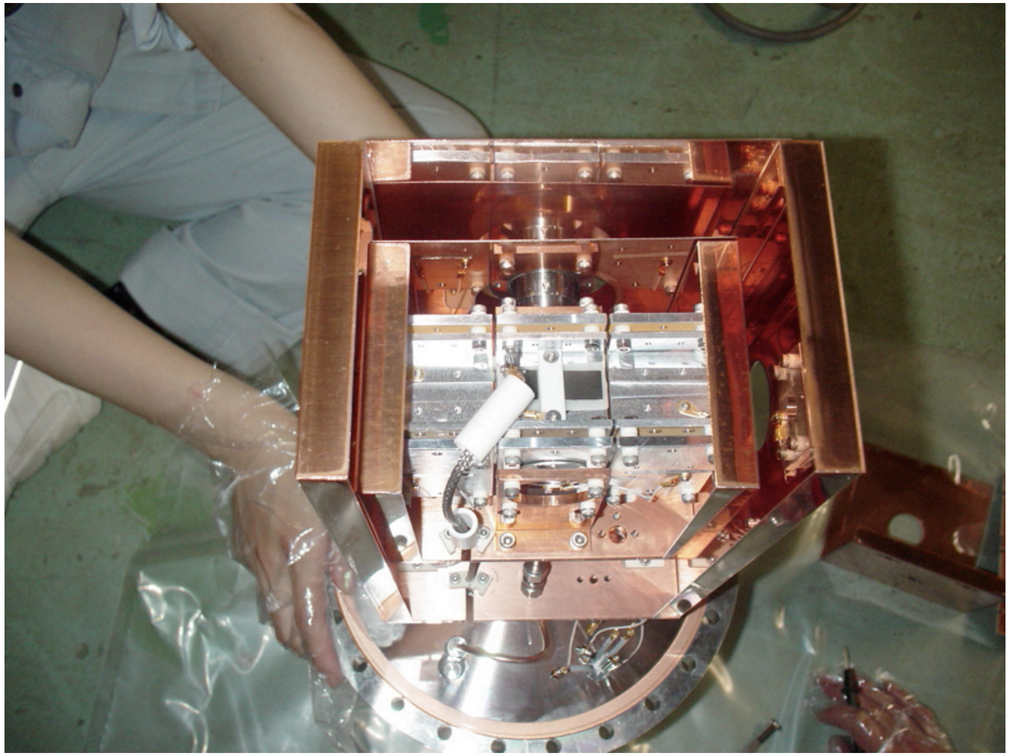

626.267
Newport
UNIBLITZ

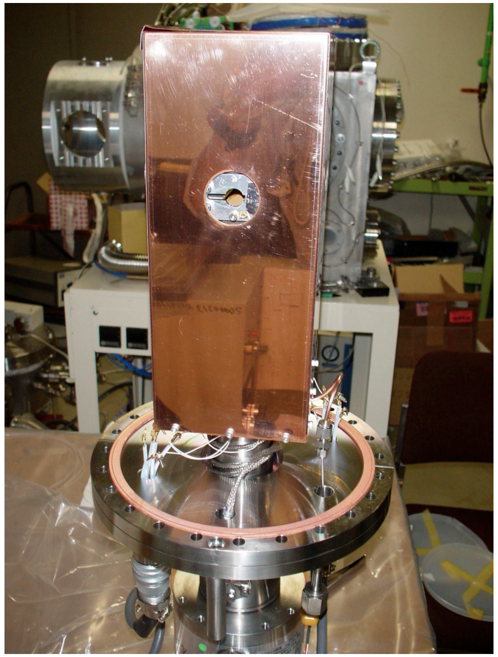

COHERENT
Newport

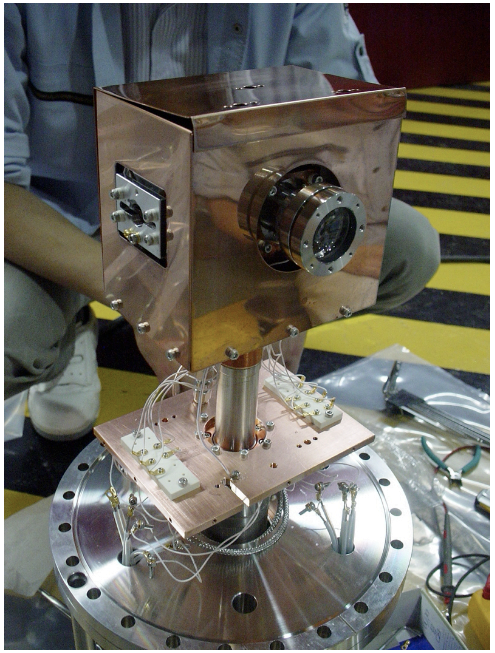

Verdi-V10
COHERENT

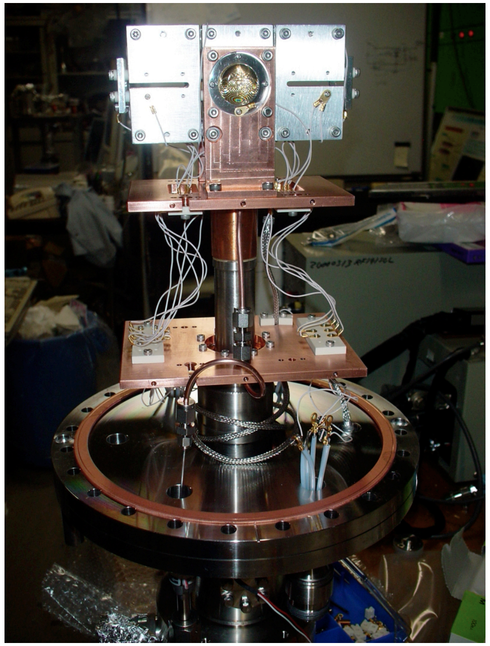


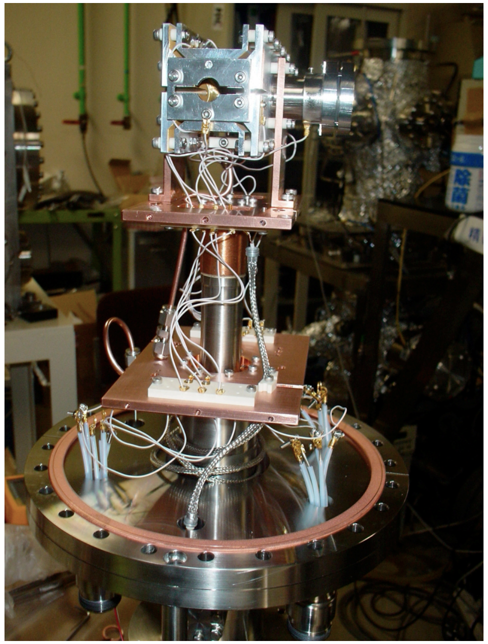










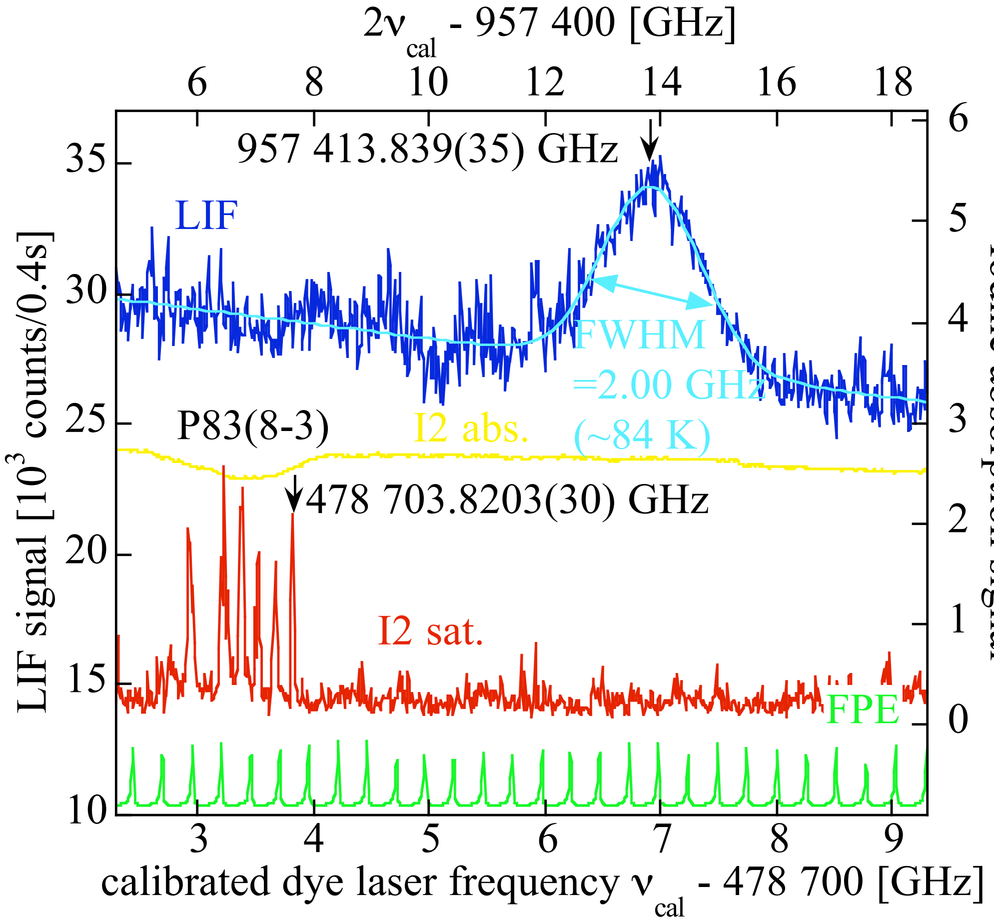


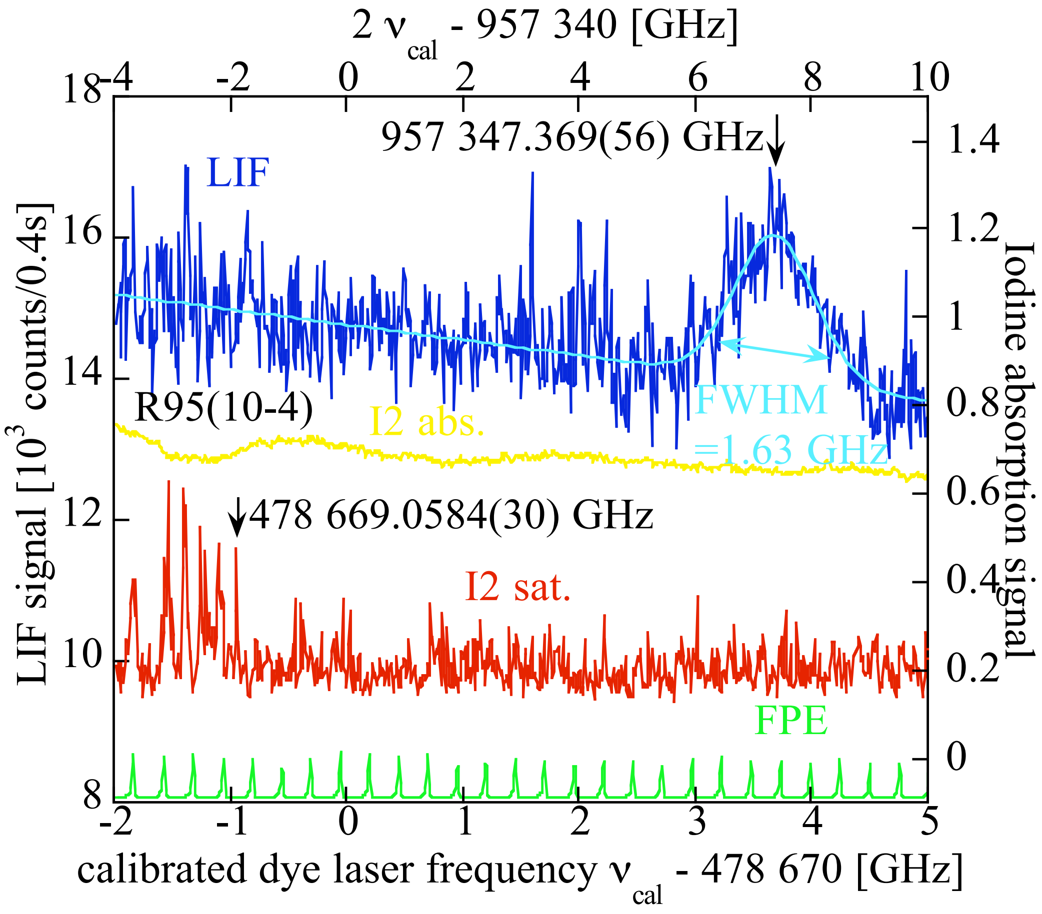
He buffer gas cooled spectra of on-line trapped ^{10,7}Be^{+}

^{10}Be^{+} (no hfs)

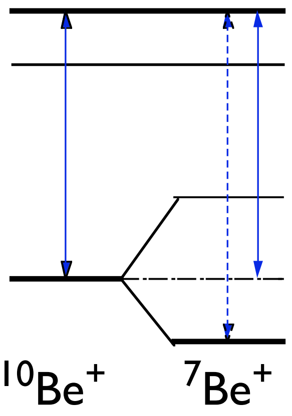
He ~ 4e-4 Torr

^{7}Be^{+} (hfs)





測定周波数＝遷移周波数



測定周波数＝遷移周波数？

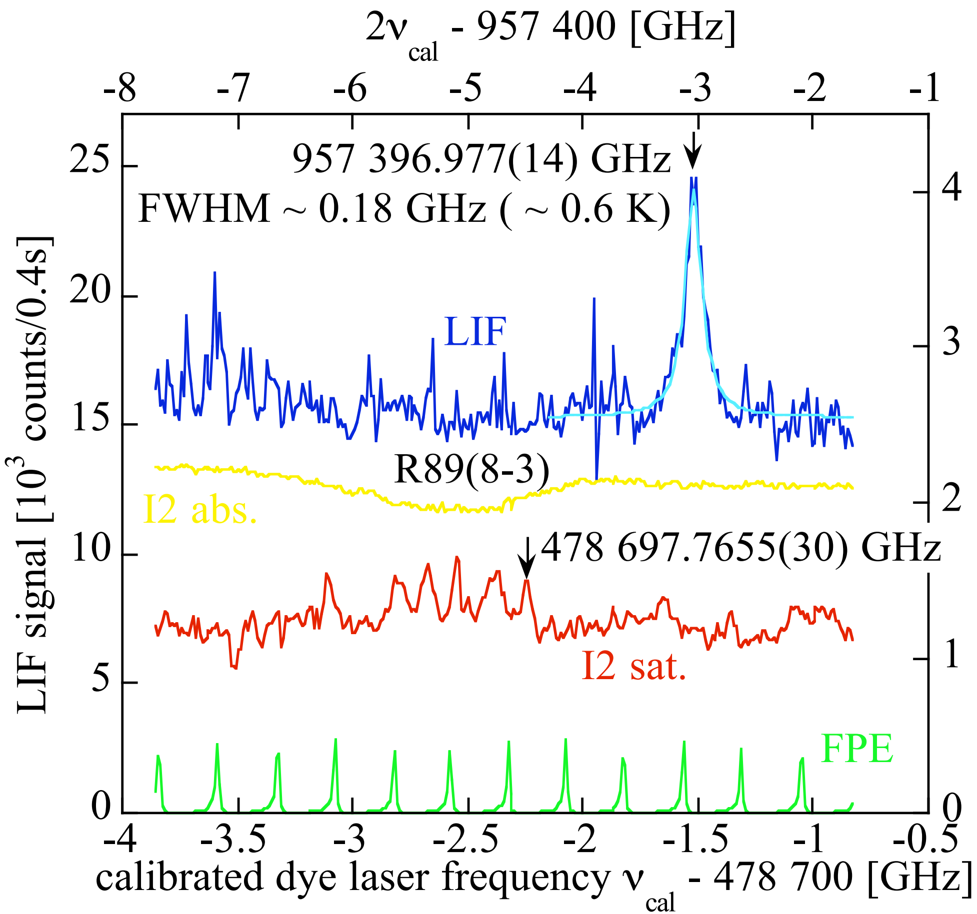
（hfsの影響を調べる必要あり）

↓

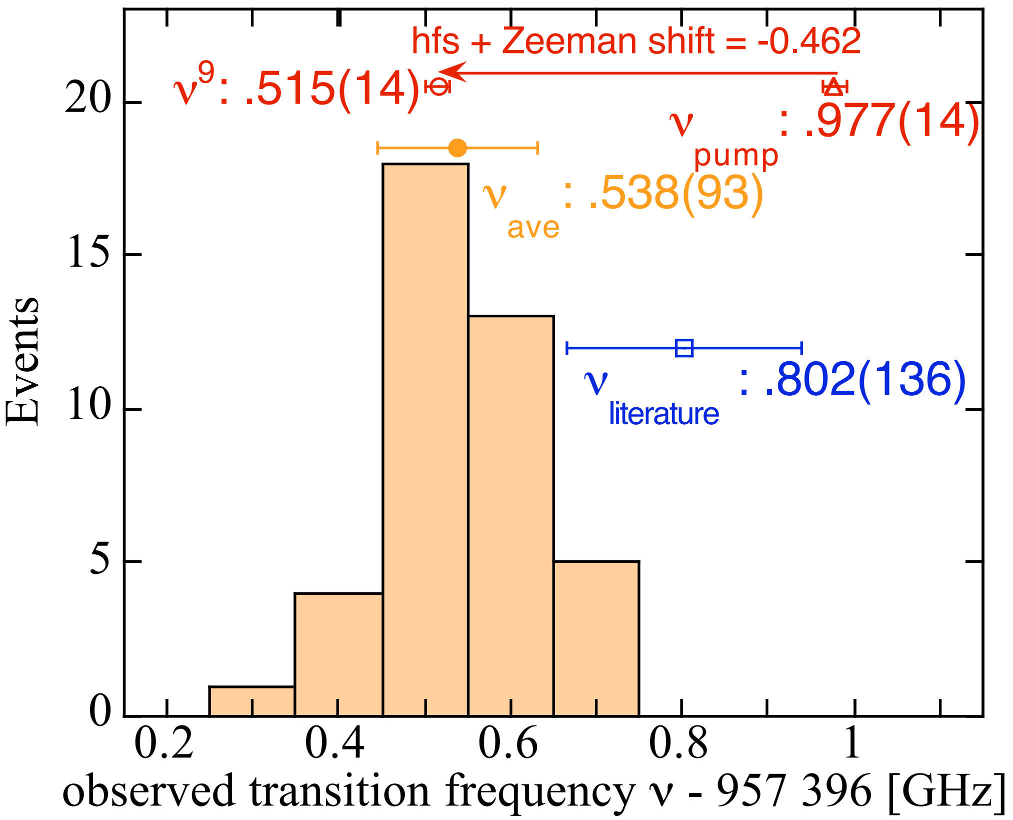
Be9 off-line実験で検証

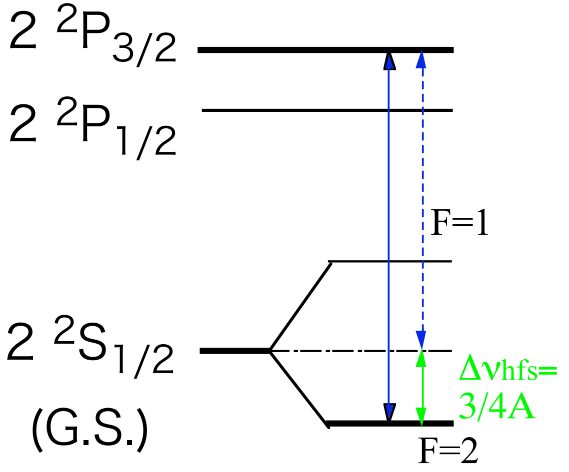
off-line ^{9}Be$^+$ experiment

laser cooled



He gas cooled (~4e-4 Torr)





laser cooled: hfs準位にoptical pumpされた周波数

gas cooled: 重心間の遷移周波数，hfsの影響による不確定性大

→^{7}Be$^+$の測定精度に補正必要

ν literature(Bollinger et al., Phys.Rev.A31, 2711(1985))

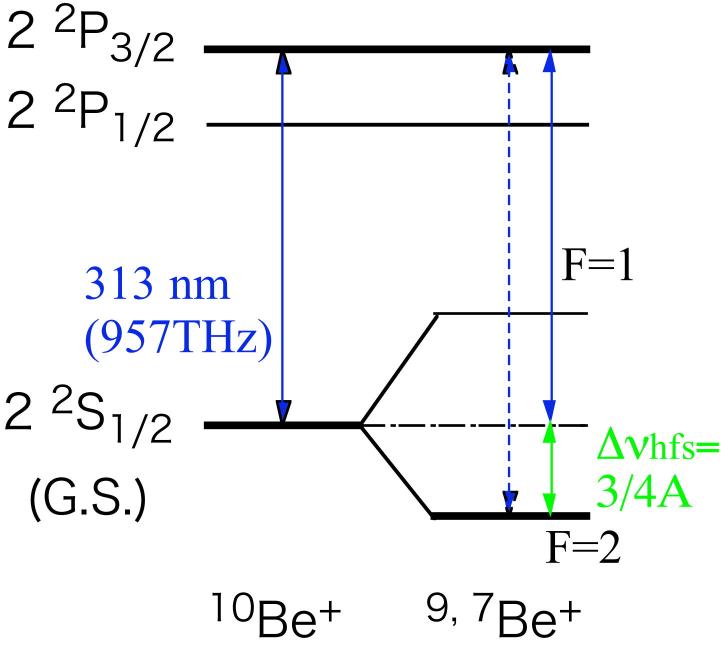
外部磁場1.1 T→0に外挿

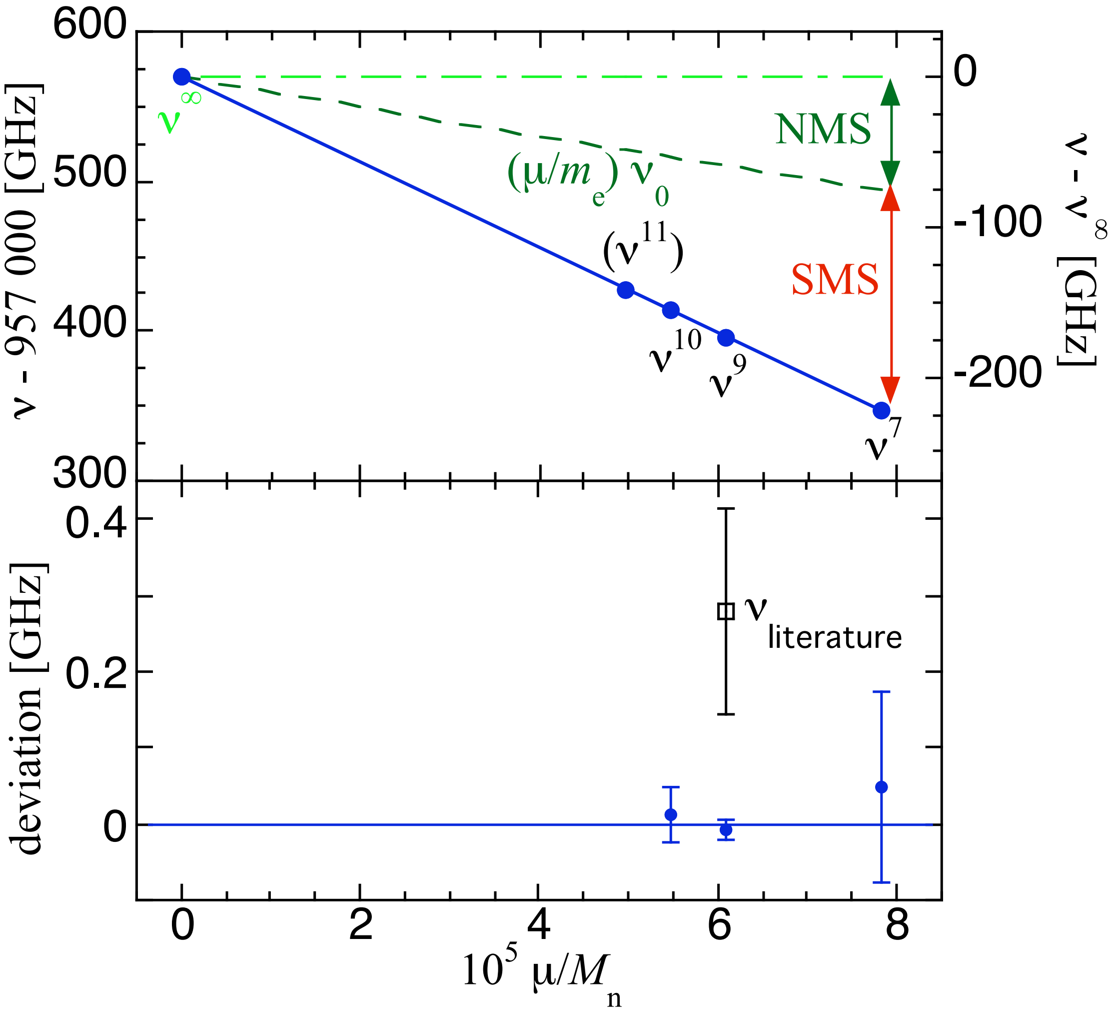
observed resonance frequencies of Be isotopes

A	ν^A [THz]	note
7	957.347 369(124)	
9(NIST)	957.396 802(135)	B=1.1T→0に外挿
9	957.396 515(14)	
10	957.413 839(35)	
11	(957.428 07(36))	計算値
∞	957.569 55(28)	infinite mass
κ/h	-1 884.5(46)	diff. mass pol. para.

$$h\nu_{\mathrm{obs}} = \epsilon_{\mathrm{a}} - \epsilon_{\mathrm{b}} = h\nu^{\infty} - \frac{\mu}{M_{\mathrm{n}}} h\nu^{\infty} + \frac{\mu}{M_{\mathrm{n}}}\kappa$$

NMS SMS

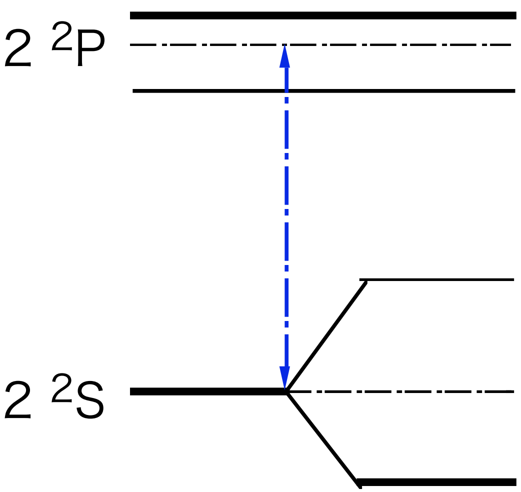




理論計算との比較

$h\nu^{\infty}$: transition frequency of an infinite mass
κ:differential mass polarization parameter

(in *atomic unit*)	this work experiment	Chung et al. FCPC, RVM (1991,1993) relativistic	Yan et al. Hylleraas (1998)	Yamanaka CI(STO) (1998)
$h\nu^{\infty}$	0.145 524 290(42)	0.145 530 6(11)	0.145 429 884	0.145 761 9
$h\nu^{\infty}{}_{\text{expt}} - h\nu^{\infty}{}_{\text{theo}}$	–	-0.000 006 3(11)	0.000 094 41(4)	-0.000 237 6
κ	-0.286 41(70)	-0.287 5	-0.286 76	0.285 26
$\kappa_{\text{expt}}-\kappa_{\text{theo}}$	–	0.001 1(7)	0.000 35(70)	-0.001 15(70)



$h\nu^{\infty}$：relativistic, etc.高次の補正必要
κ ：Yan et al.の計算が良く合う

LiではYan et al.のrelativistic, QEDその他の補正を含んだ計算と精密分光実験値よりField Shiftと荷電半径を導出
(PRL96, 033002(2006))

より高精度の測定と理論計算によりBeの荷電半径の導出を計画

PRL 96, 033002 (2006) PHYSICAL REVIEW LETTERS week ending 27 JANUARY 2006

Nuclear Charge Radii of ^{9,11}Li: The Influence of Halo Neutrons

R. Sánchez,[1] W. Nörtershäuser,[1,2] G. Ewald,[1] D. Albers,[3] J. Behr,[3] P. Bricault,[3] B. A. Bushaw,[4] A. Dax,[1,*] J. Dilling,[3]
M. Dombsky,[3] G. W. F. Drake,[5] S. Götte,[1] R. Kirchner,[1] H.-J. Kluge,[1] Th. Kühl,[1] J. Lassen,[3] C. D. P. Levy,[3] M. R. Pearson,[3]
E. J. Prime,[3] V. Ryjkov,[3] A. Wojtaszek,[1,†] Z.-C. Yan,[6] and C. Zimmermann[2]

$$\delta\nu^{A,7}_{\mathrm{IS,exp}} - \delta\nu^{A,7}_{\mathrm{IS,MS}} = \frac{Ze^2}{3\hbar}[r_c^2(^A\mathrm{Li}) - r_c^2(^7\mathrm{Li})](\langle\delta(r_i)\rangle_{3s} - \langle\delta(r_i)\rangle_{2s}) = -1.5661\,\frac{\mathrm{MHz}}{\mathrm{fm}^2}[r_c^2(^A\mathrm{Li}) - r_c^2(^7\mathrm{Li})], \tag{2}$$

$$\langle r_c^2\rangle = \langle r_{\mathrm{pp}}^2\rangle + \langle R_{\mathrm{p}}^2\rangle + \frac{N}{Z}\langle R_{\mathrm{n}}^2\rangle + \frac{3\hbar^2}{4m_{\mathrm{p}}^2c^2}, \tag{3}$$

TABLE I. Isotope shifts measured at TRIUMF (this work) and GSI [8] [avg = weighted mean] compared with theoretical mass shifts for ^{7}Li-^{A}Li in the $2s\,^2S_{1/2} \rightarrow 3s\,^2S_{1/2}$ transition. Uncertainties for r_c are dominated by uncertainty in the reference radius $r_c(^7\mathrm{Li}) = 2.39(3)$ fm [9].

Isotope		Isotope Shift, kHz	Mass Shift, kHz	r_c, fm
^{6}Li	TRIUMF	−11 453 984(20)		
	GSI	−11 453 950(130)		
	avg	−11 453 983(20)	−11 453 010(56)	2.517(30)
^{8}Li	TRIUMF	8 635 781(46)		
	GSI	8 635 790(150)		
	avg	8 635 782(44)	8 635 113(42)	2.299(32)
^{9}Li	TRIUMF	15 333 279(40)		
	GSI	15 333 140(180)		
	avg	15 333 272(39)	15 332 025(75)	2.217(35)
^{11}Li	TRIUMF	25 101 226(125)[a]	25 101 812(123)	2.467(37)

[a] 68 kHz statistical +57 kHz systematic from ac-Stark shift

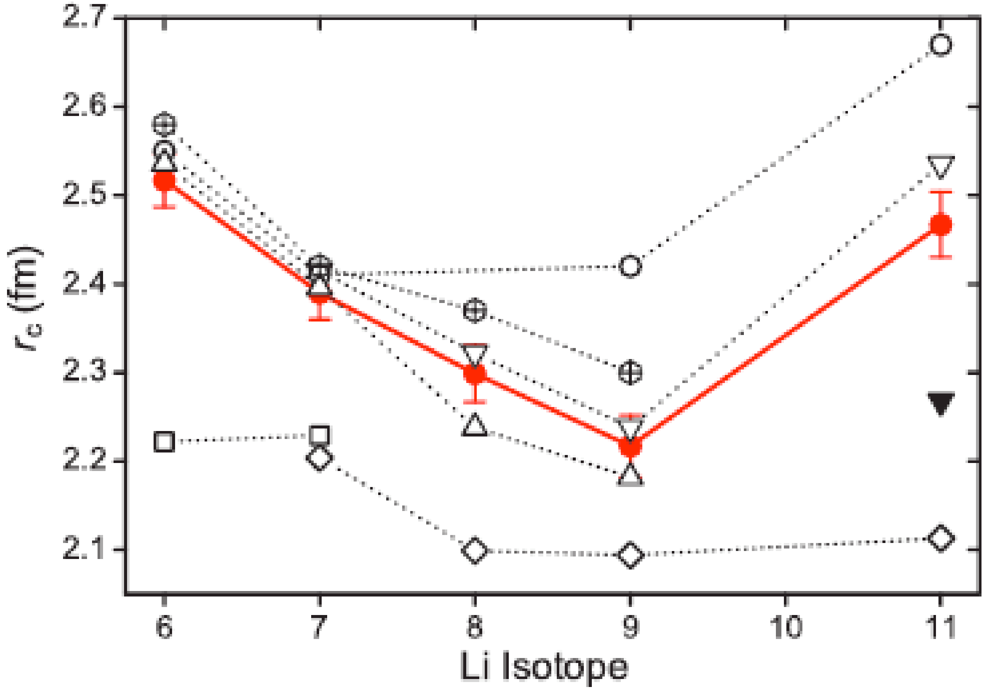


FIG. 2 (color online). Experimental charge radii of lithium isotopes (red, ●) compared with theoretical predictions: △: GFMC calculations [4,22], ▽: SVMC model [27,28] (▼: assuming a frozen ^{9}Li core), ⊕: FMD [26], ○: DCM [19], □ and ◇: *ab initio* NCSM [23,24].

Conclusion

on-line trap $^{10}\mathrm{Be}^+$, $^{7}\mathrm{Be}^+$ ＠ He gas cooled

off-line $^{9}\mathrm{Be}^+$ ＠ laser cooled/He gas cooled

・2 $^2S_{1/2}$–2 $^2P_{3/2}$遷移のレーザー分光

・ヨウ素スペクトルとの比較により絶対値測定（〜10^{-8}）

・isotope shiftの効果として以下を導出・理論と比較

differential mass polarization parameter: κ

transition energy of an infinite mass: $h\nu^{\infty}$

共鳴周波数の確認＝hfsレーザー分光への足掛かり

T.Nakamura, *et al*., Phys. Rev. A, accepted for publication

SLOWRIプロジェクト最初の物理の成果

今後の予定

・^{7}Be^{+}, ^{11}Be^{+}: 2 $^{2}S_{1/2}$のhfs測定（レーザー・マイクロ波共鳴分光）

Bohr-Weisskopf効果の導出→核内磁化分布（価中性子分布）

・2 $^{2}S_{1/2}$–2 $^{2}P_{1/2}$ のIS精密測定（レーザー・レーザー二重共鳴分光）

原理的により高精度の測定が可能

レーザーコムにより絶対周波数の高精度測定(~10^{-10}目標)

field shiftの導出→核荷電半径（陽子分布）

電磁プローブによる核物質半径測定

“^{11}Be”：中性子ハロー核構造の解明