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journal or publication title	CYRIC annual report
volume	1988
page range	94-98
year	1988
URL	http://hdl.handle.net/10097/49466

I. 20. Construction of an Ion Trap for Nuclear Spectroscopy Using a Laser-Microwave Double-Resonance Method

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Electrons and ions have been stored or "trapped" in a small spatial region of an apparatus to measure fundamental physical quantities as well as for various applications.[1,2]. Such an apparatus for trapping ions is called an "ion trap" in comparison with a "storage ring". Recently the ion traps have been used to trap radioactive ions for nuclear spectroscopy.[3,4]

Ion traps are classified into two types; one is the Penning trap having an external static homogeneous magnetic field superimposed to a static electric quadrupole field, and the other is the Paul trap or the RF (radio-frequency) trap having a static and an alternating electric quadrupole fields without a magnetic field.

We constructed an RF ion trap for nuclear spectroscopy in terms of hyperfine interactions of trapped ions, e.g., for measuring nuclear moments using a laser fluorescence method and for measuring hyperfine anomalies using a laser-microwave double-resonance method[4]; see Fig. 1. For the first target we chose strontium isotopes, for which laser light of $\lambda = 421$ nm is required for exciting the $^2S_{1/2} \rightarrow {}^2p_{1/2}$ transition.

As the first steps we tried to detect the trapped ions through the collective resonant motion excited by the probe RF voltage. Fig. 2 shows the electrical circuit of this detection.[5] When there is no trapped ions the voltage V_i over the admittance G_0 due to L_0, C_0 (capacitance of the trap) and R_0 (not shown) gives a broad resonance peak at $f = f_0 = 1/[2\pi(L_0\ C_0)^{1/2}]$; when ions are trapped the collective motion of the ions in the z-direction resonates with the RF voltage at f_z^{res}. Therefore, if f_0 is adjusted to be near f_z^{res} this motion induces a narrow resonance dip on the broad peak of G_0.

Figure 3 shows the detection of trapped N_2^+ ions. Table 1 summarizes the experimental conditions, measured and deduced quantities of the trapped ions of N_2^+ as well as Kr^+; the mass number of the latter (A~84) is near that of Sr^+ (A~88). These ions were produced by electron bombardment of the gases introduced into the trap region at 200 V and 2 μA. The trapping time of the ions was estimated from the behavior of the detected signal when the bombardment current was switched off. The effective density of the trapped ions n_{eff} was calculated from the difference of the measured resonance frequency f_z^{res} and the theoretical value f_z neglecting the space-change effect; the total number N and the attenuation coefficient γ_2 of the trapped ions were calculated from the height and width of the dip.2,5) Here it is noted that the collision cross sections of the ions σ derived from γ_2 are much larger than that obtained from the ion swarm experiment6) for N_2^+ in N^+; from the collision coefficient $k_c = 8.0\times10^{-10}$ cm^3s^{-1} we have $\sigma = k_c/v_{12} = 1.5\times10^{-15}$ cm^2, indicating that the observed width of the dip should have been contributed mainly from other sources.

Our laser system consists of a Spectra Physics Model 380 A ring dye laser (styryl 9 operation) and Model 007-0008 argon pump laser (4W), and it is difficult to obtain 421 nm light directly from the laser. Therefore, we tested the generation of 421 nm light by the method of SHG (Second Harmonics Generation) with a non-linear optical element of $KNbO_3$.7) The experimental conditions as well as the results are shown in Table 2 and Fig. 4. It is noted that the conversion efficiency from 842 nm to 421 nm of 0.7 % is a considerable value.7) Therefore, we will be able to obtain the 421 nm light from our laser system by the same SHG method.

Presently we are constructing the optical detection part of the system, and anticipate the detection of trapped ions by resonant scattering of the tuned laser light in a near future.

We acknowledge Dr. Yoda J.of National Research Laboratory of Metrology, Dr. Murata K. of Asahigarasu Co. Ltd., Mr. Niikura S. of Spectra Physics Co. Ltd., Profs. Fukuda S. and Itoh H. of Tohoku University for cooperations.

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Table 1. Parameters of ion trapping.

Quantity		N_2^+	Kr^+
Trap dimension	r_0	15 mm	same
	z_0	$r_0/\sqrt{2}$	same
Static voltage	V_{dc}	5.52 $V_{0\text{-}p}$	2.71 $V_{0\text{-}p}$
RF voltage	V_{ac}	172 $V_{0\text{-}p}$	170 $V_{0\text{-}p}$
frequency	$f_{ac}(=2\pi\Omega)$	755 kHz	514.5 kHz
Admittance (inv.)	$1/G_0$	1.5 MΩ	same
Load resistance	R_f	2.0 MΩ	same
Res. gas pressure	p_{res}	---	4×10^{-9} mbar
Gas press. (N_2, Kr)	p	1×10^{-7} mbar	1×10^{-7} mbar
Parameters of	a_z, q_z	-0.0301, 0.468	-0.0106, 0.332
eq. of motion[a]	a_r, q_r	0.0150, -0.234	0.0053, -0.166
β value	β_z, β_r	0.276, 0.207	0.210, 0.138
Global freq.[b]	f_z, f_r	104 kHz, 78.1 kHz	54.0 kHz, 35.5 kHz
Max. trap density[c]	n_{max}	1.46×10^{7} cm^{-3}	1.03×10^{7} cm^{-3}
Res. frequency	f_z^{res}	60.8 kHz	46.2 kHz
width	Δf_z^{res}	0.3 kHz	0.24 kHz
dip	Y_{max}	83.3 %	50.0 %
Trapping time	t_{trap}	~ several s	~ several s
Atten. coeff.[d]	γ_2	460 s^{-1}	890 s^{-1}
Collision time[d]	τ_c	4.4 ms	2.2 ms
Mean free path[d]	λ	2.3 m	1.1 m
Cross section[d]	σ	1.7×10^{-12} cm^2	3.3×10^{-12} cm^2
No. of trapped ions	N	3.0×10^{6}	3.5×10^{6}
Effective density	n_{eff}	1.36×10^{7} cm^{-3}	4.4×10^{6} cm^{-3}
Effective volume	V_{eff}	0.22 cm^3	0.80 cm^3

a) Parameters of Mathieu eq. of motion a, q (in the stable region): $u_i''+(a_i-2q_i\cos 2\pi f_{ac}\tau)u_i = 0$, where, i=z, r; " is 2nd deriv. in τ.

b) Fundamental frequency of the global motion of the ions when the space charge effect is negligible (f_{ac} is the freq. of trapping RF.): z-direction; $f_z = \beta_z f_{ac}/2$, r-direction; $f_r = \beta_r f_{ac}/2$.

c) Maximum density of trapped ions due to the space-charge effect.

d) Attenuation coefficient and collision time of ions, γ_2 and τ_c. From these mean free path λ and cross section σ are derived; $\lambda \sim \tau_c \cdot v_{ion}$ and $\sigma \sim v_{ion} \cdot \tau_c \cdot n_{atom}$ ($v_{thermal}$ = 520 m/s is used).

Table 2. SHG by $KNbO_3$[a)]

Nonlinear element	Chem. form (s.c.)	$KNbO_3$[b)]
	Dimension	2×2×10 mm^3
	Direction	along a-axis
	Temperature	-30°C
Primary light	Incident direction	along a-axis
	Source	Model 3900[c)]
	Wave length	842 nm
	Power	450 mW
Secondary light	Wave length	421 nm
	Power	3 mW
Conversion efficiency		0.7 %

a) Our light source will be Spectra Physics Model 380 A ring dye laser (styryl 9 operation) plus Model 007-008 4W argon pump laser.
b) JTT Crystal Company, 730 Willow Run Lane, Winter Springs, FL.
c) Spectra Physics Model 2040 Ti-sapphire tunable laser pumped by Model 2045-25 argon laser at 7 W.

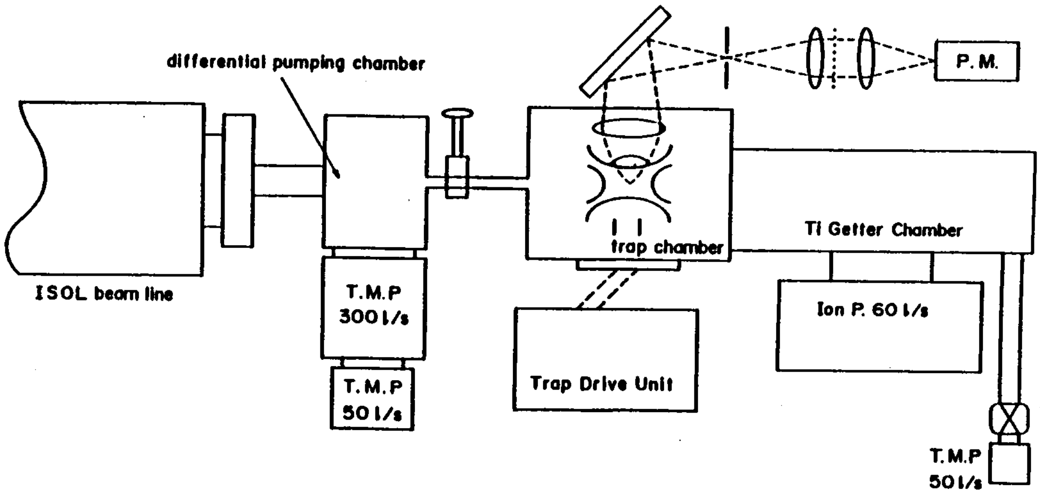

Fig. 1. Ion trap in a vacuum chamber connected to an isotope separator beam-transport end plate via a differential pumping section.

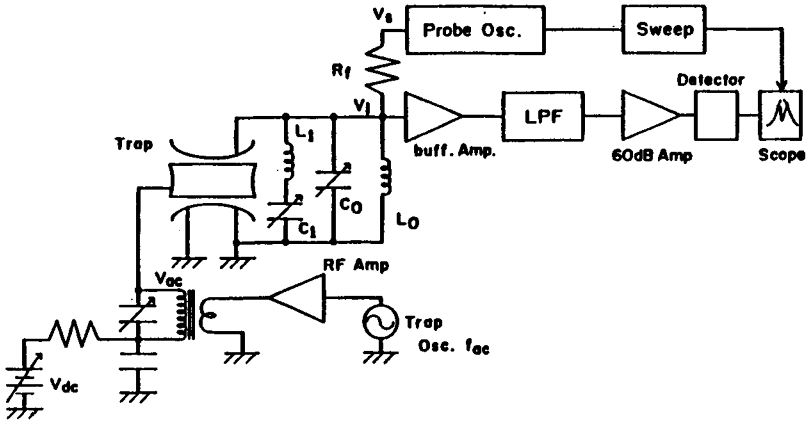

Fig. 2. Electric circuit for detecting trapped ions.

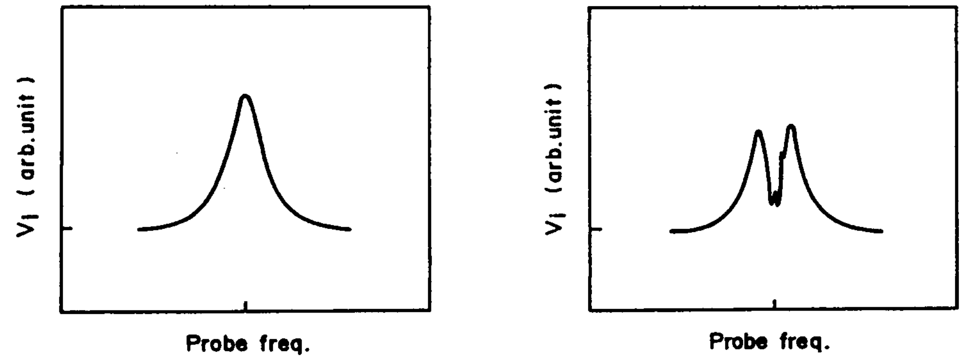

Fig. 3. Detection signal of trapped N_2^+ ions: a) when there are no ions, b) when there are ions.

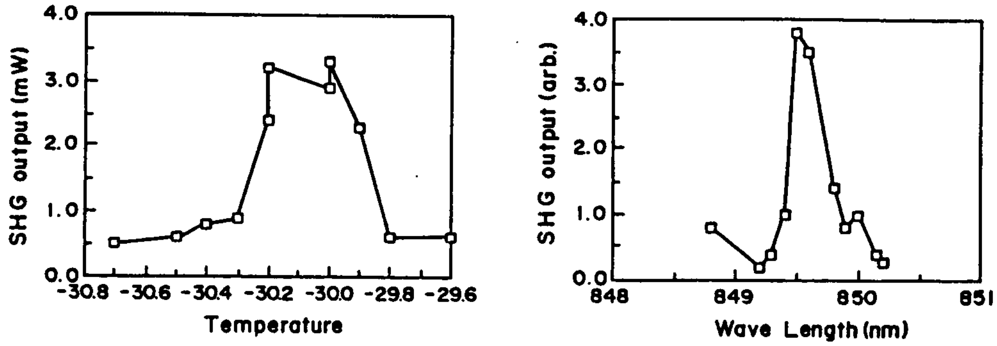

Fig. 4. Dependence of SHG output on temperature and wave length.