Bunched beams from RFQ traps for laser spectroscopy studies

Marc Nantel Physics Department McGill University, Montreal

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ABSTRACT

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A fast-beam collinear laser spectroscopy apparatus has been designed and tested with the ^{23}Na D_2 line (wavelength = 589 nm) on continuous atomic beams.

A radio-frequency quadrupole ion trap and its associated electronics have been assembled and successfully operated, trapping ${}^{23}Na^+$ ions from an external source built for the purposes of this work. The bunched ions were extracted and detected; the effect of several injection, bunching and extraction parameters on the extracted bunches' size were studied. A simple model of the ion bunching and losses in the trap is proposed.

From the sensitivity limit of the collinear laser spectroscopy apparatus and the maximum bunched current output from the trap, the possibility of performing fast-beam collinear laser spectroscopy measurements on bunched atomic beams is examined.

RESUME

Un appareil de spectroscopie laser collinéaire sur faisceaux rapides a été conçu et testé avec la transition D_2 du ²³Na (longueur d'onde = 589 nm) sur faisceaux continus.

Un piège à ions quadrupolaire à fréquence radio et les appareils électroniques associés à son fontionnement ont été assemblé et testé avec succès, piègeant des ${}^{23}Na^+$ provenant d'une source externe construite à cet effet. Les paquets d'ions ainsi formés sont extraits et détectés; la variation de plusieurs paramètres d'injection, de piégeage et d'extraction et leur effet sur la grosseur des paquets extraits ont été etudié. Un modèle simplifié des processus de piégeage et de pertes d'ions dans le piège est proposé.

A partir de la limite de sensibilité de l'appareil de spectroscopie laser collinéaire et du courant maximal de paquets extraits du piège, la possibilité d'effectuer des mesures de spectroscopie laser collinéaire sur des faisceaux de paquets rapides est examinée.

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Laser spectroscopy and its limitations

Through the measurement of hyperfine structures and isotopic shifts of atomic states, important information about the nucleus can be derived: its spin, its magnetic and quadrupole moments, and its change of nean square charge radius relative to a reference isotope are some of them. Laser spectroscopy has been used through the years to probe the ground state properties of the atomic nucleus. Clean and elegant techniques have proven flexible enough to adapt to the needs and availability of the installations required to create the samples to be studied. By using mass-separated beams of different radioactive elements like those available from the ISOLDE mass separator at CERN, it is possible to survey a whole series of exotic nuclei and to test the principal models put forward by the theoreticians to explain the ground state behaviour of unstable nuclei. Several techniques of laser spectroscopy are available to perform these measurements. However, in many cases, the study of short-lived isotopes is somewhat limited by the need to prepare samples by depositing the atoms on a substrate, later evaporated in the presence of the laser. This also leads to loss in resolution because of the Dop pler width of the observed lines arising from the thermal energy spread resulting from the evaporating process, and to loss in sensitivity by the small amount of material available. The inability of using the short-lived radio-isotopes because of this intermediary step also throws a shadow on the universality of the technique.

Collinear fast-beam laser spectroscopy is one technique that offers high reso-

lution, and avoids the troublesome sample reheating, by using the mass-separated beam directly, in a geometry where the laser beam is superposed in collinear geometry to a beam of fast ions or atoms. It has become a standard technique for investigations of ground state properties at on-line mass separator and is being used extensively since it first appeared in 1976 (Ka76, Wi76).

The intensities of the beams of the more exotic nuclei aren't high enough to be directly usable by collinear laser spectroscopy. A solution to the low abundance of the beam is to "bunch" the beam into higher density packets and to look at those bunches with the collinear method. One way to bunch the beams available at ISOL facilities is to used a radio-frequency quadrupole trap.

RFQ traps and their use for laser spectroscopy

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Radio-frequency quadrupole (RFQ) traps have been used to contain small samples of ions ($\approx 10^6$) in a controlled environment for long times. They have been used extensively in mass spectrometry and in laser spectroscopy with record precisions. The use of the RFQ trap was still limited until recently by the fact that the ions to be trapped had to be created inside the trap. Trapping of ions coming from outside the trap has been achieved recently with minimal loss in beam intensity by R.B. Moore et al. working at the Foster Radiation Lab (Mo88). This has opened up the field to several new usages of the RFQ trap, one of which is the bunching of external beams for later experiments.

In-flight bunching of ISOL beams through the use of RFQ traps might be the answer for spectroscopy on low abundant beams of exotic nuclei. Bunched ion

beams, which also can be neutralized in flight with the use of a charge exchange cell, can be used to improve the sensitivity of collinear fast-beam laser spectroscopy. It is the purpose of this work to assess the feasibility of a new technique of laser spectroscopy combining the bunched beams available from RFQ traps and the parallel geometry of collinear spectroscopy. A reduction in the signal-to-background ratio for the spectra are expected from gating the photomultiplier tube detector to collect photons only when bunches are in the detector region. During the course of this work, a collinear laser spectroscopy set-up has been built and tested by the author at McGill's Foster Radiation Laboratory on 5000 eV²³Na beams in order to evaluate its sensitivity limit. Sodium was chosen as a test candidate because Sodium ions are easily produced, and later charge-exchanged, and excited by the continuous wave dye lasers available at the Foster Radiation Lab. Work on a RFQ trap was then undertaken to study systematically the bunching process and prepare laser spectroscopy experiments on bunched beams. The systematic study of the parameters that influence the quantity and quality of the ion bunches extracted from the trap led to a better understanding of the complex interactions between the trapped ions and these parameters.

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CHAPTER II — LASER SPECTROSCOPY

A. Hyperfine Structure

As part of this thesis, laser spectroscopy on atomic Sodium beams (A=23, I=3/2) was carried out for the determination of the sensitivity limit of the fast beam collinear laser spectroscopy apparatus. In order to explain the observed signals, a brief review of the hyperfine structure (h.f.s.) of atomic spectra is given in the following.

Because atoms consist of a nucleus — positively charged and hence producing an electromagnetic field — and the orbiting electrons — negatively charged and behaving like a charge-current — the energy of interaction between the nucleus and the electrons can be written as a multipole expansion (Ja62)

$$H = q\phi_0 - \vec{P} \cdot \vec{E}_0 - \vec{M} \cdot \vec{H}_0 - \frac{1}{6} \sum_{ij} Q_{ij} \left(\frac{\delta E_j}{\delta x_i}\right)_0 + \text{higher multipole terms.} \quad (II - 1)$$

The first term is the monopole term and gives rise to the general level structure of the electron orbitals. ϕ_0 is the potential produced by the electrons at the origin, located at the center of gravity of the nuclear charge distribution, and q is the total charge of the nucleus.

A fine structure of atomic levels arises from the interaction of the electrons' orbital angular momentum \vec{L} and their spin angular momentum \vec{S} , combining to make up the total angular momentum of the electron

$$\vec{J} = \vec{L} + \vec{S}. \tag{II-2}$$

The energy associated with the fine structure levels, measured from the ionization limit as an arbitrary reference, will be designated by W_0 .

The second term is the electric dipole term. \vec{E}_0 is the electric field produced by the electrons at the origin and \vec{P} is the electric dipole vector of the nucleus. This term is identically zero since all odd electric multipole moments of the nucleus vanish (B152).

The third term is called the magnetic dipole term and it gives rise to the hyperfine structure of the atom. $\vec{H_0}$ is the magnetic field at the nucleus produced by the electrons and \vec{M} is the magnetic dipole vector of the nucleus. The total angular momentum of the electrons, \vec{J} , couples with the nuclear spin, \vec{I} , to produce the total angular momentum of the atom

$$\vec{F} = \vec{I} + \vec{J}. \tag{II-3}$$

The energy of the interaction relative to W_0 is (Ko58)

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$$\Delta W_{mag} = A \frac{F(F+1) - I(I+1) - J(J+1)}{2} = A \frac{C}{2}$$
 (II-4)

where $A = \frac{\mu_I \overline{H}_0}{IJ}$, μ_I is the nuclear magnetic moment and \overline{H}_0 is the time average of the magnetic field \vec{H} produced by the electrons at the site of the nucleus.

The fourth term in equation (II-1) is the electric quadrupole term and also contributes to the hyperfine structure for atoms with nuclear spin $I > \frac{1}{2}$ and total electron angular momentum $J > \frac{1}{2}$ (Ko58). Q_{ij} is the electric quadrupole tensor and $(\frac{\delta E_i}{\delta x_i})_0$ are derivatives of the electric field at the nucleus. The energy of the electric quadrupole interaction is (Ca36)

$$\Delta W_Q = B \frac{\frac{3}{2}C(C+1) - 2I(I+1)J(J+1)}{2I(2I-1)2J(J-1)}$$
(II-5)

where $B = Q_s \frac{\overline{\delta E}}{\delta z}$, Q_s is the spectroscopic quadrupole moment (which can be related to Q_{ij} (Pr75)) and $\frac{\overline{\delta E}}{\delta z}$ is the averaged electronic field gradient (using the z-axis as the symmetry axis).

By combining the above results, the hyperfine structure energy of an atomic state with total angular momentum $\vec{F} = \vec{I} + \vec{J}$ can be expressed as

$$W_F = W_0 + \frac{1}{2}AC + B\frac{\frac{3}{4}C(C+1) - I(I+1)J(J+1)}{2I(2I-1)J(2J-1)}.$$
 (II-6)

The nuclear magnetic dipole moment μ_I and electric quadrupole moment Q_s can be extracted from A and B in equation (II-6) using empirical or theoretical values for the magnetic hyperfine field $\overline{H_0}$ and the electric field gradient $\frac{\overline{\delta E}}{\delta z}$ at the nucleus. Figure II-1 shows the h.f.s. splitting of the ${}^2S_{\frac{1}{2}}$ and ${}^2P_{\frac{3}{2}}$ levels in ${}^{23}Na$ $(I = \frac{3}{2})$ studied in this work.

The case of ^{23}Na

Laser spectroscopy was carried out in the present work in the atomic $3s^2S_{\frac{1}{2}} \rightarrow 3p^2P_{\frac{3}{2}}$ (D_2) transition $(\lambda = 589 \ nm)$ of ²³Na. The transitions allowed by the selection rule $\Delta F = \pm 1$ are indicated in figure II-1. Also indicated are the expected splitting between h.f.s. components calculated with the help of equation (II-6) and the experimental values for the constants given by Anton et al. (An78) and Touchard (To81)

$${}^{2}S_{\frac{1}{2}}: A = 885.8131 MHz$$

 ${}^{2}P_{\frac{3}{2}}: A = 18.6614 MHz$ (II - 7)

B = 3.03 MHz

The spectrum expected when exciting the h.f.s. transitions of ^{23}Na (D_2) by light with variable frequency is sketched in figure II-2. The relative intensities for



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Figure II-2 Spectrum of the transitions (with corresponding groups I and II) in figure II-1.

the h.f.s. components are based on the values given by Kopfermann (Ko58). Due to hyperfine pumping in laser excitation with $\Delta F = +1$ or $\Delta F = -1$ and deexcitation by $\Delta F = +1$ and $\Delta F = -1$, deviations from the calculated intensity ratios are expected in practice for strong light sources, as the lasers used in this project. Optical hyperfine pumping effects have no influence on the $(F' \rightarrow F) = (1 \rightarrow 0)$ and $(2 \rightarrow 3)$ transitions since deexcitation leads exclusively back to the initial state.

B. Laser Spectroscopy

High resolution and sensitivity are, in general, required to measure the h.f.s. of both, stable and unstable nuclides. High resolution is desirable since h.f.s. splittings are, as in the case of the ^{23}Na investigated here, small compared to the excitation frequency of the optical transition. In the case of unstable nuclei, high sensitivity is needed because of the often minute quantity of material available. One way of achieving the required resolution and sensitivity is using lasers as light sources since they offer the high photon fluxes needed. Since the goal of this thesis is the study of a new, more sensitive technique for laser spectroscopy on minute samples, a brief overview of the principles of laser spectroscopy and of the most successful methods applied for systematic measurements of low abundance isotopes is given thereafter.

Principles of laser spectroscopy

Laser spectroscopy is done in most cases by populating an excited electronic level and detecting the fluorescence light arising from their decay to the original level. Figure II-3 helps to illustrate the basic principles. An electron in level 1 is excited into level 2 by laser photons at a rate Γ_{12} . It subsequently deexcites directly back to level 1 with rate Γ_{21} , or indirectly through level 3 with rates Γ_{23} and Γ_{31} (if such a third level exist). The photoabsorption cross-section offered by an atom of lab-frame resonance frequency of ν' to a photon of frequency ν is (Ot88)

$$\sigma(\nu - \nu') = \frac{\lambda^2}{2\pi} \cdot \frac{\Gamma_{21}/\Gamma_{2total}}{1 + (4\pi(\nu - \nu')/\Gamma_2)^2}$$
(II - 8)

where λ is the photon's wavelength and Γ_2 is the total decay rate of level 2 (both branches 21 and 23-31 combined). Assuming that Γ_2 is of the same order as Γ_{21} , the cross-section for the optical photons at the resonance point ($\nu = \nu'$) is of the order $10^{-9} \ cm^2$ (Ot88).

A continuous wave (CW) laser beam with a power of $10 \ mW/cm^2$, corresponds to a photon beam intensity of about $10^{17}/cm^2s$. Multiplying the photoabsorption cross-section at resonance by the photon beam intensity calculated above, one reaches an induced transition rate Γ_{12} of $10^8/s$ which is comparable to the spontaneous decay rate Γ_{21} . A signal of 10^8 de-excitations per second per atom can be achieved whenever saturation conditions are met ($\Gamma_{12} > \Gamma_{21}$).

The above result of 10^8 fluorescence photon per second for individual atoms is applicable in the absence of branching to a third level or group of levels. When there is branching, optical pumping to level 3 — which is often metastable — occurs



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Figure II-3 Example of three-level system. Electron in (1) is excited to (2) and deexcites back to (1) directly, or through level (3) in two steps. $\int_{\frac{1}{2}}$ are the transition rates.

and therefore the deexcitation emissions stop after a number of photon per atom of $(1 + \Gamma_{21}/\Gamma_{23})$ on average. This last number is usually not much larger than 1 (Ot88) which advantages optical spectroscopy in unbranched excitation schemes.

Laser spectroscopy: Two variations

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The following illustrates two of the most successful variations on laser spectroscopy used in recent years. The first method is laser fluorescence in resonance cells, which has been used on Hg isotopes (Ku77) and later on Cd (isotopes $102 \le A \le 120$) (Bu81, Bu87).

Figure II-4 shows the experimental set-up. Mass-separated isotopes are collected on a foil inside a quartz vessel at 500 C and are then reheated in the presence of He buffer gas. This permits keeping the Cd in gaseous phase for about 1 minute before it condenses. During that time, a pulsed dye laser tuned to the resonance frequency excites the atoms in the vessel. The fluorescent light is detected by a photomultiplier. The principal reason for using a pulsed laser here is that to reach the atomic resonance lines, situated for Hg and Cd in the far ultra-violet, frequency-doubling has to be used. Only pulsed laser display the power density of several kW/cm^2 necessary for efficient frequency-doubling. Unfortunately, Doppler broadening (1.7 GHz), laser bandwidth after doubling (1.2 GHz) and collision effects with the He buffer gas (1.3 GHz) combine to give a total linewidth of 3.9 GHz, which is comparable to h.f.s. splitting of the odd isotopes and the h.f.s. pattern is barely resolved (Figure II-5). The major drawback of this solution besides the low resolution of the spectra is that pulsed lasers have a duty cycle of the order



Figure II-4 Experimental set-up for on-line laser spectroscopy of Cd isotopes. Upper part: Schematic view. (GR: grating, E: etalon, T: telescope, DC: dye cell, P: polarizer, M: mirror, L: lens, FD: frequency doubling crystal, PM: photomultiplier, F: colour filter, BS: ion beam stop, MO: laser intensity monitor, O: oven). Lower part: resonance vessel and oven system. (Reproduced from Bu87)



Signal of ¹⁰³Cd from apparatus in figure II-4. The hyperfine components are indicated by arrows. (Reproduced from Bu87)



of 10^{-6} and thus the number of atoms in the vessel has to be of the order of 10^{9} for significant fluorescence photon yields to be obtained. Experiments on elements with lower lying excitation energies can be done using CW lasers, but they usually have high chemical affinity and stick to the walls of the vessel too quickly.

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Laser fluorescence from collimated beam solves the problem of resolution. Figure II-6 shows the set-up for this experimental technique schematically. Atomic beams produced in a heated crucible are collimated into a beam of typically 25 mrad divergence. This leads to a reduction in Doppler width when the beams are excited under right angles by laser light, but at the cost of collimation losses (figure II-7). Still, when CW lasers are used, the full duty cycle compensates largely for the appreciable amount of atoms lost through collimation. For the data in figure II-7 for example, $6 \times 10^{10} \ ^{126}Ba$ atoms were used in a 6 min measurement, for a sensitivity of $\approx 2 \times 10^8 \ atoms/s$. This method was used extensively at Foster Radiation Lab for measurements on $^{84-90}Sr$ (Bu85) and elsewhere to study ground state properties of $^{40-48}Ca$ (Be80, An82), $^{124-138}Ba$ (No78, Be79) and $^{196-214}Pb$ (Th83, An86).



Figure II-6 Principle of laser spectroscopy from a collimated atomic beam. The beam emerges from an oven with orifice A, goes through a collimating orifice which gives it divergence . At a distance r, the laser excites the atoms in the overlaping volume V. (Reproduced from Ot88)



Figure II-7 Fluorescence spectrum of the 553.5 nm line taken from a sample of Barium 126 (Be79). (Reproduced from Ot88)

Collinear fast-beam laser spectroscopy

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The examples of laser spectroscopy given in the preceding section had several limitations. The principal one is that low abundance isotopes delivered as ions by on-line mass separators are not used directly. The idea of doing on-line spectroscopy on mass-separated beams to avoid the deposition and reheating of the sample for offline experiments led to a new method of Doppler-free spectroscopy: collinear fastbeam laser spectroscopy. This method was used extensively at CERN's *(SOLDE for measurements of l.f.s. and isotopic shifts of radioactive isotopes. Figure II-8 shows the experimental set-up. A beam of ions delivered by the mass separator is neutralized in flight in a charge exchange cell and is superposed collinearly with a laser beam tuned to the resonance. The atoms are excited by the laser photons and the deexcitation is detected by the photomultiplier.*

It was Kaufman (Ka76) and, independently, Wing et al. (Wi76) who noticed that exciting the fast ion beams available at mass separators by laser light in the collinear geometry actually reduces the Doppler broadening in the observed spectra by a large factor: the kinetic energy spread δE of a sample of ions, as for instance found in the ion source of a mass separator, is unchanged under electrostatic acceleration (due to phase-space considerations) since

$$\delta E = \delta(mv^2/2) = mv\delta v = constant. \qquad (II - 9)$$

 δE here is in the direction of the beam and v is the velocity of the ions. Hence by making v large, one proportionally reduce δv which determines the magnitude of



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Figure II-8 Set-up for on-line fast-beam collinear laser spectroscopy. (Reproduced from Ne85)

the Doppler broadening $\delta \nu_D(0)$ through (De81)

$$\delta \nu_D(0) \approx \nu_0 \frac{\delta v}{c}$$
 (II - 10)

where ν_0 is the frequency of the transition and c is the speed of light, and creates a Doppler shift $\Delta \nu_D$

$$\Delta \nu_D \approx -\nu_0 \frac{v}{c} \tag{II-11}$$

with the negative sign indicating a red shift when the laser and ion beams propagate in the same direction.

If one considers a sample of singly ionized ions with ideal thermal distribution in the ion source at temperature T, there remains, after acceleration through a potential difference U, a reduced Doppler width of (De81)

$$\delta\nu_D = \left(\frac{kT}{4eU}\right)^{\frac{1}{2}} \delta\nu_D(0). \qquad (II-12)$$

A reduction factor of approximately 10^3 in the linewidth of the observed signal for a thermal ion source at T = 2000 K and an acceleration voltage of V = 60 kV (typical voltage used at the ISOLDE facility, at CERN) is obtained using equation (II-12). This gives, for example, for the barium resonance line at $\lambda = 535 nm$, a residual Doppler width of 1 *MHz* which is well under the natural linewidth of 19 *MHz* (Ot88). In reality, the performance of the ion source, the stability of the acceleration voltage and the beam optics' quality limits this improvement of linewidths between 10 and 50 *MHz* (Ot88).

This method is universally applicable to all elements which can be delivered as ion beams, not only allowing spectroscopy from the ground state but also from

metastable states populated in the neutralizing charge transfer reaction (Bu82). Its sensitivity limit is 10^4 to 10^7 particles/s delivered as beam, with the lower number applying to the simpler spectra (Ot88). Its versatility, sensitivity, high resolution and universality makes it the most successful technique for on-line investigations of nuclear ground state properties.

C. The collinear spectroscopy set-up

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The quest for an enhancement of the sensitivity, in order to exploit new physics phenomena in elements which are not available with high beam intensities, has led to several variations of fast-beam spectroscopy which were successfully applied for measurements of h.f.s. and isotope shifts (Ne86, Si87, Ea86). The methods developed so far are largely element specific (Ne86, Si87) or have to rely on very pure isotope beams (Ea86), a condition which is not easily met for most elements since isobaric contamination in mass separated beams is not easily avoidable. The methods applied lead automatically to a loss in universality in fast beam spectroscopy.

One way to obtain better sensitivity without giving up universality is to reduce in a straightforward way the background and the noise in the detected spectra. As pointed before, this can be done by bunching the ion beam with the help of RFQ traps and by using gating techniques for the detection. In what follows, the fastbeam collinear laser spectroscopy experimental set-up used to study the feasibility of this novel technique is described.

The apparatus built for that purpose is shown schematically in figure II-9. Ions are produced by an ion gun (G) positioned right in front of the RFQ trap. They





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are bunched by the trap's radio-frequency field and the ion bunches are extracted by a negative pulse applied on the far endcap (FE), the ion beam transport system ensure that the bunched beam stays well defined. After passing through the charge exchange cell (CEC) where they are neutralized, the atoms in the bunches are excited by the laser photons in the interaction region and detection of the deexcitation light is done using a photomultiplier tube (PMT). Residual ions are deflected onto a Faraday plate (P3) for detection. A brief description of the main components follows; discussion on the RFQ trap itself will be left until chapter III which deals exclusively with the trap's working and experimental results.

(i) The vacuum system

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The bulk of the vacuum system consisted of 5, 10 and 15 cm HVE Dependex vacuum tubes sealed with nitrile rubber O-rings. The system is pumped with two 10 cm CVC High Vacuum diffusion pumps (DP1, DP2 in figure II-9) with appropriate fore-vacuum mechanical pump and high-vacuum tubing. The diffusion pumps have a net pumping rate of 250 *liters/s*. On average, pressures inside the apparatus are 2×10^{-5} Torr in the interaction region (where the pump is equiped with a water-cooled baffle) and 5×10^{-6} Torr in the RFQ trap region (where the pump is equiped with a liquid nitrogen trap). Three major sliding valves (V1, V2, V3) were included to isolate different parts of the vacuum line: one for each diffusion pump and one to separate the RFQ trap region from the interaction region. Three bleed valves were also installed: two for nitrogen gas bleeding when breaking the vacuum was necessary (one in each region), and one high-precision needle-valve in the RFQ

trap region to introduce Helium buffer gas which is, as explained later, needed when trapping ions. Two Penning vacuum gauges (G1, G2) are used to monitor the line's pressure (one in each region) and two thermocouple gauges monitor the back pressure of the diffusion pumps. A retractable bellow (B) inserted in the beam line in front of the charge exchange cell (CEC) permits the experimenters to reach the inside when needed.

(ii) Ion source and electronics

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An ion source (G on figure II-9) was built to provide the experiment with a beam of thermally ionized $^{23}Na^+$, it is schematically shown in figure II-10. A small tube filled with Na_2CO_3 is heated by a current flowing through a Kanthal wire filament (resistance $\approx 10 \Omega$). The filament also heats the ionizing surface, closely packed rods of tungsten wire situated at the opening of the tube. The currents in the filament is controlled by a 15 V/5 A power supply. A heat shield prevents over-heating of the source by providing a path for the excess heat to flow out to the flange on which the gun was mounted.

The working principle of the thermal ion source relies on the Saha-Langmuir equation which states that for atoms with ionization potential ϕ impinging on a hot metal with work function W, the fraction of ions to atoms resulting is

$$\frac{n_{\downarrow}}{n_0} = Ae^{\frac{W-\phi}{kT}} \qquad (II-13)$$

where n_+ is the number of ions, n_0 the number of atoms, k is the Boltzmann constant and T is the temperature of the metal in Kelvin. A is a constant involving the ratio of statistical weight of ion and atom, and has a value of $\approx \frac{1}{2}$ (Re68). ²³Na



Figure II-10 Sodium ion source used in this work.

has $\phi = 5.1 \ eV$ and Tungsten (the ionization surface used for the ion source in this work) has $W = 4.5 \ eV$ (ToS1). At the estimated temperature of 1000 K for the ion source used here, equation (II-13) gives approximately 0.05% of ions.

The gun is mounted on the same support as the trap so as to fit into the near endcap (NE in figure II-9) which was hollowed for that purpose. Typically, the source gives up to 50 nA of ion current as measured at the ion collector P1, 70 cm from the trap, for between 10 to 20 W of heating power.

(iii) Ion beam transport

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The trap and its support are biased to 5000 V by a Fluke model 410B 0-10 kV high voltage power supply and the ion gun is biased an additional 40 V by an HP model 6209B 0-320 V bias supply. The ions from the gun, they enter and exit the trap through small holes (8 mm) in the near and far endcaps (see chapter III, section (i)). When the trap is not operating, as is the case for the spectroscopy runs on continuous beams which establish the sensitivity limit of the apparatus, it merely acts as a collimator for the continuous ion beam. The ions emerge from the trap and drift into the extraction region (EX in figure II-9, see figure III-11 for more detailed view) which is held at a typical bias of 4900 V by a 0-5000 V EG&G Ortec model 459 bias supply; the ions acquire their final acceleration between the extraction clectrode and a plate (GR in figure II-9) which is kept at ground potential. The ion gun bias and the extraction electrode bias are set to maximize the ion current out of the gun.

The ions are then focused by an Einzel lens (EL) situated 50 cm from the ground

plate and biased typically at 6200 V by a 0-7 kV LeCroy HV4032A high voltage power supply. A set of horizontal and vertical deflecting plates (HD, VD) directly following the Einzel lens guides the beam to the interaction region through the charge exchange cell (CEC). A last set of vertical deflecting plates (VD) installed after the interaction region deviates the ions which are not neutralized onto ion collector P3 for measurement of the charge exchange efficiency. The ion beam has usually a full width at half-maximum (FWHM) of 1-1.5 cm and a divergenge of 3.4 mrad. These measurements are taken by sliding P1 and P3 in and out of the beam line and recording the ion current read on pico-ammeters.

(iv) Charge exchange cell

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To perform spectroscopy on an atomic Na beam, it is required to neutralize the Sodium ions after their acceleration and before the interaction region. This is done using a charge exchange cell (CEC in figure II-9).

The charge exchange in the cell relies on charge transfer collisions between the ions in the beam and a cloud of vaporized Na metal. The cross-section for charge exchange $(10^{-15}-10^{-14} \ cm^2)$ is two orders of magnitude larger than the kinetic cross-section and the physical properties of the beam, thus its velocity spread and its divergence, are unaffected. Neutral Na is chosen as the charge-exchange alkali because of the high resonant charge exchange cross-section it brings.

Figure II-11 shows a diagram of the charge exchange cell used for this work. It features a small sodium reservoir around which fits a cylindrical block of aluminium containing two 350 W and two 150 W heaters. The block heaters melt the Sodium



Figure II-11 Charge exchange cell. Temperature reading are taken at points marked "T".

Charge exchange vs heating temperature



Figure II-12

A.

Graph of the charge exchange percentage as a function of the temperature (measured on the outside of the main heating block). "% while heating" shows the onset of the charge exchange as the cell is heated and "% while cooling" shows the diminution of charge exchange as the temperature drops when the heaters are turned off. (melting point of 97.5 C) in the reservoir and evaporate the liquid. A 300 W heating tape coiled around the central area of the cell keeps the Sodium in the gas phase for the charge exchange. The reservoir and central area temperatures are controlled independently by two 0-120 V AC power supplies. Temperature readings come from three thermocouple wires connected to a meter (see figure II-11). Fine wire meshing covers the inside walls of the cell to ensure, through capillary action, that the condensed Sodium flows back to the reservoir. Cooling on each side of the cell is provided by two heat sinks. Charge exchange efficiency is calculated from ion current measurements on P1 and P3. Figure II-12 shows a graph of the charge exchange efficiency as a function of the temperature read on the aluminium block's exterior surface.

(v) Lasers and optics

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To populate the $3p^2 P_{\frac{3}{2}}$ level from the $3s^2 S_{\frac{1}{2}}$ ground state of the Sodium atoms (figure II-1), a Coherent CR-600 tunable dye laser in standing wave configuration, pumped by a Spectra Physics model 171 Argon ion laser is used. The Argon laser is tuned on the green ($\lambda = 514 nm$) line and has an output of typically 3 W. The dye laser uses rhodamine 6G as the lasing medium. Typically, the dye laser's output is 50 mW, single mode. A Burleigh wavemeter and Fabry-Perot interferometer provide the experimenters with a wavenumber measurement and a feedback on the stability in the frequency of the laser output. The dye laser is tuned approximately to the Doppler-shifted resonant wavelength of 589.6 nm (wavenumber of $\approx 16961.7 cm^{-1}$) corresponding to the resonance frequency of Na atoms accelerated to $\approx 5000 eV$. It can be scanned over a range of 3 GHz around that point.

Since the lasers are in a different room as the rest of the apparatus, provisions are made for both light and laser control signals transportation to the apparatus (see figure II-13). Signals were transmitted via BNC cables: the etalon signal, and the wavenumber with a television camera and receiver. The laser beam itself is passed through a beam expander telescope to reduce the effects of vibrations of the laser tables, fluctuations in density of the air and dilation and contraction of the mirror mounts with changing temperature. This expanded beam of about 2.5 cm in diameter is then directed by 6 mirrors (M1 \rightarrow M6) before being brought back to a focus in the interaction region by another beam expander telescope including a 12.5 μ m pinhole to purify the laser beam and two other mirrors (M7, M8). An elliptic polarizer prism in combination with a polarizing filter allows adjustment of




the intensity of the light to the desired level and sets the polarization of the light so as to minimize stray light from the surface of a Brewster window (BW on figure II-9) through which the laser light enters the apparatus. The total length of the light path from the laser to the apparatus is about 40 m and the total final laser power available at the interaction region focus is typically 1 mW.

Mirrors M7 and M8 are used to center the laser beam along the axis of the apparatus. Aligning the beam is made relatively easy by a window near the RFQ trap (W1 in figure II-9). The window gives a visual feedback on the beam position in the trap. Four conical apertures — the three first ones (A1, A2, A3) of 1 cm in diameter and the one just after the interaction region (A4) of 0.5 cm in diameter — and the two charge-exchange cell's end apertures (1 cm in diameter) ensured good alignment. A1, A2, A3 and A4 served to reduce the stray light as much as possible. Once this preliminary alignment is performed, the signal from the photomultiplier can be used to minimize the background stray light.

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(vi) Detectors and associated electronics

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To detect the Sodium deexcitation light in the interaction region, a RCA 8850 photomultiplier tube (PMT in figure II-9), with quantum efficiency of 1% at the required wavelength, is used. It is biased positively on the photocathode in the range 1800 V to 2000 V by a HP model 6516A 0-3 kV power supply. The output of the PMT is put through a EG&G Ortec model 9301 fast pre-amplifier, a model 584 constant fraction discriminator and a model 449 ratemeter. The analog output of the ratemeter is fed to a Nicolet model 3091 storage oscilloscope to record the spectra. The spectra can be transferred to a recorder for hard copies. The photomultiplier tube is housed in a cylinder that protrudes into the interaction region and has a 2.5 cm diameter window (see figure II-14). The window is positioned 1.5 cm from the center axis of the interaction region and the solid angle seen by the detector is 10% of 4π . Most parts of the apparatus in the interaction region are blackened with soot to reduce the stray light background and when the photomultiplier is not in use, a sliding obturator (SO in figure II-9) is pushed in and pressed on the window to protect the photomultiplier tube from light.

The ion collectors P1 and P3 are used to detect the ion current of the gun transmitted through the vacuum line. They are retractable Faraday plates connected to pico-ammeters. They allow to monitor the total current in the ion beam, its stability, and collect data for the evaluation of the ion beam's width and the charge exchange efficiency. They are also used to help align the laser and atomic beams in collinear geometry.

Use is made of a set of chevron multichannel plates but mostly in the detection



Figure II-14 A top view of the interaction region.

of the bunched ion beam and it will be described in chapter III.

D. Spectroscopy results and analysis

This section examines the results that were obtained on a continuous beam of ²³Na with the fast-beam collinear laser spectroscopy apparatus described earlier. The experiment was carried out in order to determine and optimize the sensitivity limit of the apparatus. This is important since space charge effects in the RFQ trap used for bunching limits the total current to $\approx 10^7 \cdot 10^8 \ ions/s$ as will be seen later. Thus for carrying out laser spectroscopy on bunched beams, it is necessary to ensure that the sensitivity limit matches the available beam current.

The spectroscopic results

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Laser spectroscopy on continuous ²³Na beams followed the typical procedures: the ion gun is switched on. Then, when a stable ion current is established ($\approx 3 nA$ at P1), the charge-exchange cell (CEC) is warmed up slowly as acceleration, gun bias, extraction, Einzel lens and deflection voltages are selected so as to maximize transmission of the beam through the line. Meanwhile, the lasers are also turned on and adjusted to the Doppler-shifted wavelength and the tunable laser is scanned (this supposes that some laser beam alignments had been done beforehand). As the CEC continues to heat up and charge exchange gradually takes place, the final adjustments are made on the laser beam alignment, minimizing the stray light background by looking at the output current of the photomultiplier. The laser focus in the interaction region is typically 1 mm in diameter.

Figure II-15 shows a typical spectrum obtained along with a drawing of the

transitions and the expected positions and intensities of the peaks from as seen earlier in figure II-2. The ions in this particular run had an energy of $5\,040\,eV$. The spectrum was recorded at a current (measured at P1) of approximately 20 nA in a single scan at a laser power of 0.6 mW in the interaction region. The transmission of the ion beam was 50% and the charge exchange rate was 40% at the time of spectrum acquisition. The time constant of the ratemeter is 30 ms.

The two hyperfine groups $(F = 3, 2, 1 \rightarrow F' = 2)$ and $(F = 2, 1, 0 \rightarrow F' = 1)$ are readily identifiable. The individual transition peaks are harder to identify, partly the fact that the intensity ratios are changed due to optical pumping. Using the distance of 1772 *MHz* (corresponding to the h.f.s. splitting of the ground state) between the two groups (figure II-15), a linewidth of 30 *MHz* was evaluated for the largest peak ($F = 3 \rightarrow F' = 2$). This linewidth is explained by equations (II-10) and (II-12) as follov The natural linewidth is calculated to be 10 *MHz* using the $3p^2 P_{\frac{3}{2}}$ lifetime of 16.36 *ns* given in Carlsson (Ca88). The original velocity spread for a beam of ions of mass *m* at temperature T = 1000 K accelerated through a potential *U* is found through

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$$E = eU = \frac{1}{2}mv^2 \Rightarrow v = \sqrt{\frac{2eU}{m}} \quad \text{and}$$

$$\delta E = kT = mv\delta v \Rightarrow \delta v = \frac{kT}{mv} = \sqrt{\frac{kT}{2m}}$$

(II - 14)

gives $\delta v = 425 \text{ m/s}$ which, using equation (II-10) corresponds to a Doppler broadening of $\delta v_D(0) = 0.7 \text{ GHz}$. The residual Doppler width of the line is calculated with equation (II-12) to be $\delta v_D = 15 \text{ MHz}$. The sum of the natural width and the residual Doppler width of 25 MHz is in good agreement with the experimental linewidth of 30 MHz obtained from figure II-15.

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Fluorescence spectrum for the 589.0 nm line of Sodium from fast-beam collinear laser spectroscopy on a DC beam. The height of the large peak (F=3 to F'=2) is 90 000 counts/s, the background is16 000 counts/s (measured from the zero in the center) and the noise is 6 000 counts/s. An identification of the peaks is drawn below the spectra with group numbers I and II corresponding to those in figure II-2. The additional peak is identified as a 3p excitation (see text). The spectrum exhibits an additional peak at the high frequency side of the $(F = 3 \rightarrow F' = 2)$ peak. It can be attributed to a 3*p* excitation of the Na atoms arising during the charge exchange collisions. The energy of the 3*p* excitation is 2.1 eV above ground state (Mo71) and we can write

$$Na(3s) + Na^{+} \longrightarrow Na(3p) + Na^{+} - 2.1 \ eV. \qquad (II - 15)$$

2.1 eV corresponds to 72.4 MHz (at the Doppler-shifted frequency of 5.085×10^{14} Hz) which is the distance of that additional peak from the center of the $(F=3 \rightarrow F'=2)$ peak.

For the main peak, the counting rate from the ratemeter was 90000 counts/s with a background count rate of 16000 counts/s. This translates into a S/B of 5.6.

Sensitivity limit of the spectroscopy apparatus

From these measurements, the sensitivity limit of the apparatus can be estimated. A fluorescence of 9×10^4 counts/s in resonance for an ion current of 2×10^{11} ions/s gives a detection efficiency of 4.5×10^{-7} count/ion. This sensitivity limit can be explained by considering the following factors which influence the detection efficiency: photomultiplier tube quantum efficiency = 1%

photomultiplier tube window solid angle = 10%

spectral overlap =
$$\delta \nu_0 / \delta \nu_D = 66\%$$

spatial overlap of the laser and atomic beams
$$= 1\%$$
 (II - 16)

hyperfine level competition at charge exchange = 50%

charge exchange efficiency = 40%

atomic beam transmission efficiency = 50%.

Multiplying these factors, a detecting efficiency of 6.6×10^{-7} is obtained. This explains the sensitivity limit if each atom emits only one fluorescence photon, which is unlikely, especially for the transitions involving no optical pumping. From the 10^8 fluorescence per second derived earlier and the $\approx 0.1 \ \mu s$ flight time of the atoms in the interaction region, it is reasonable to expect 10 fluorescence photons per atom and the detecting efficiency becomes 6.6×10^{-6} . The missing factor between the sensitivity limit and the detecting efficiency can be mostly accounted for in this way: it was shown by A. Einstein (Ei17) that not all the atoms can be excited at the same time. One calculates first the spectral density of the laser beam using

$$\rho_{\nu} = \frac{P}{\delta_{\nu_{nat}} \cdot F \cdot c} \qquad (II - 17)$$

where P is the laser power, $\delta_{\nu_{nat}}$ is the natural linewidth of the transition, F is the cross-section of the laser beam and c is the velocity of light. For the data in figure II-15, this number is $3.2 \times 10^{-20} W s cm^{-3}$. Then the fraction of excited atoms is

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$$\frac{N^*}{N} = \frac{\rho_\nu}{\rho_\nu + \frac{8\pi\hbar}{\lambda^3}} \tag{II-18}$$

where N^* is the number of excited atoms, N is the number of ground state atoms, h is Planck's constant and λ is the wavelength of the transition. In this case $N^*/N = 0.28$ for a total detecting efficiency of 1.8×10^{-6} , leaving a factor of 4 between the total detecting efficiency and the sensitivity limit.

CHAPTER III — RADIO-FREQUENCY QUADRUPOLE ION TRAPS

A. Theory and past experiments

The radio-frequency quadrupole (RFQ) trap (see figure III-1) was invented by W. Paul and H. Steinwedel (Pa56) at the University of Bonn in 1955. They recognized the utility of the quadrupole field strong-focusing technique used to focus proton beams in accelerators and applied it to a three-dimensional device. The first formal publication on RFQ traps came in 1959 from Fisher (Fi59) and in the same year Wuerker, Shelton and Langmuir used a similar apparatus to contain charged particles (Wu59).

Since then, RFQ traps have been used mostly in mass spectrometry and in laser spectroscopy. It allows experimentalists to conduct precise measurements. Hyperfine splitting measurements with accuracies of 1 part in 10^{11} have been done on clouds of less than 10^6 ions (Mc78). Mass spectrometry has been carried out to accuracies of 1 in 10^6 on just tens of ions (Gr80, Ma80) and measurements detecting only one ion of Barium were made (Ne80). Figure III-1 shows an RFQ trap. It is composed of three electrodes: a ring and two endcaps. The ring and endcaps are complementary hyperbolae of revolution. The dimension of the trap is described by the length of the semi-axes r_0 and z_0 which have a ratio $\frac{z_0}{r_0}$ of $\sqrt{2}$. Follows a derivation of the fields and equations of motion of an ion in such a trap.

The quadrupole potential required to achieve strong focusing in three dimensions can be written (Da69)

$$\Phi = \Phi_0(\lambda x^2 + \sigma y^2 + \gamma z^2) \tag{III-1}$$

where λ , σ and γ are constants. The type of restoring force obtained from this field depends on the gradient of the potential and therefore is proportional to the displacement of the particle from the center of the field.

Assuming there is no space charge within the electrode structure that gives the field, the potential must satisfy Laplace's equation. $\nabla^2 \Phi = 0$. Taking the Laplacian of the potential gives the following constraint on the constants:

$$\lambda + \sigma + \gamma = 0. \tag{III-2}$$

Any combination of values for λ , σ and γ that satisfy condition (III-2) will give strong focusing fields. For the three-dimensional quadrupole ion trap, they are (Wu59)

$$\lambda = \sigma = \frac{1}{2r_0^2} \text{ and } \gamma = \frac{-1}{r_0^2}.$$
 (III-3)



Figure III-1 A radio-frequency quadrupole trap with ring and endcap electrodes. Also indicated are the trap's coordinate system. (Reproduced from Da69)



Using other values for λ , σ and γ , while respecting the above condition (III-2), will give quadrupole fields with different electrode configurations:

$$\lambda = -\sigma = \frac{1}{2r_0^2}$$
 and $\gamma = 0$ (III - 4)

gives the mass filter geometry (figure III-2)(Da69) The mass filter contains the ions only in two directions. When an ion beam of mixed species of ions penetrates the mass filter, only those species for which the filter is tuned will be transmitted. The mass filter is widely used as residual gas analyzer for vacuum systems.

$$\lambda = -\sigma = \frac{1}{r_0^2} \text{ and } \gamma = 0$$
 (III - 5)

gives the monopole mass filter geometry (Da69) (figure III-3). More exotic geometries include the six-electrodes structure (To75) or the cylindrical trap (Be73).

Mathieu equations and solutions

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For radio-frequency quadrupole traps, Φ_0 , the voltage between the opposing set of electrodes, is the sum of a DC component U and an AC component $V\cos\omega t$: $(U - V\cos\omega t)$ with U and V constant. Then equation (III-1) becomes

$$\Phi = (U - V\cos\omega t)(\lambda x^2 + \sigma y^2 + \gamma z^2) \qquad (III - 6)$$

or, in the case of the RFQ trap using the parameter set of equation (III-3) and making use of cylindrical coordinates,

$$\Phi = (U - V\cos\omega t) \frac{(r^2 - 2z^2)}{2r_0^2}.$$
 (III - 7)

One obtains the electric fields from the potential (III-7) by taking the gradient

$$E_r = -\frac{\partial \Phi}{\partial r} = -(U - V \cos \omega t) \frac{r}{r_0^2}$$

$$E_\theta = -\frac{1}{r} \frac{\partial \Phi}{\partial \theta} = 0 \qquad (III - 8)$$

$$E_z = -\frac{\partial \Phi}{\partial z} = (U - V \cos \omega t) \frac{z}{2r_0^2}.$$

Remembering that, for example, the kinetic energy of an ion in the r-direction is

$$-eE_r = m\frac{d^2r}{dt^2} \tag{III-9}$$

the equations of motion of a singly charged ion of mass m are

$$\frac{d^2r}{dt^2} - \frac{e}{mr_0^2} (U - V\cos\omega t)r = 0$$

$$\frac{d^2z}{dt^2} - \frac{2e}{mr_0^2} (U - V\cos\omega t)z = 0.$$
(III - 10)

The two equations (III-10) illustrate that the ion moves independently in rand z, which allows for the treatment of each coordinate separately. Equations (III-10) are differential equations of the Mathieu type (Mc47) and can be put in the canonical form of the Mathieu equation

$$\frac{d^2u}{d\xi^2} - (a_u + 2q_u \cos 2\xi)u = 0 \qquad (III - 11)$$

by using the following transformations:

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$$u = z, r$$

$$a_{z} = -2a_{r} = \frac{8eU}{mr_{0}^{2}\omega^{2}}$$

$$q_{z} = -2q_{r} = \frac{4eV}{mr_{0}^{2}\omega^{2}}$$

$$\xi = \frac{1}{2}\omega t$$
(III - 12)

where a_u and q_u are called the Mathieu parameters and relate the Mathieu equations of motion to the trap's physical operational parameters $(m, r_0, U, V \text{ and } \omega)$.

For solving the Mathieu equations of motion, a straightforward solution is found in Lawson, Todd and Bonner (La70). A similar solution, albeit more general, can be found in Abramovitz and Stegun (Bl65).

The general solution $u(\xi)$ can be expressed as the superposition of two particular solutions $u_1(\xi)$ and $u_2(\xi)$

$$u(\xi) = Au_1(\xi) + Bu_2(\xi).$$
 (III - 13)

The solutions are periodic and hence Floquet's theorem applies

$$u(\xi) = e^{\mu\xi} F(\xi) \qquad (III - 14)$$

where μ is a constant and $F(\xi)$ has a period of π . By dividing the solution in even and odd terms

$$u(\xi) = A e^{\mu\xi} F(\xi) + B e^{-\mu\xi} F(-\xi), \qquad (III - 15)$$

 $F(\xi)$ and $F(-\xi)$ can be expressed in terms of series using Fourier's theorem and

$$u(\xi) = A e^{\mu\xi} \sum_{n=-\infty}^{\infty} C_{2n} e^{2in\xi} + B e^{-\mu\xi} \sum_{n=-\infty}^{\infty} C_{2n} e^{-2in\xi}.$$
 (III - 16)

Though A and B are determined by the initial RF phase, position and velocity of the ion in the trap, the expansion coefficients C_{2n} are functions of a_u and q_u only and hence are independent of the initial position and velocity conditions.

There will be two types of solutions: "stable" and "unstable" solutions. The type of solution obtained depends on the nature of μ (Da69):

- 1) $\mu = \text{real and nonzero: the solution is unstable as } e^{\mu\xi} \to \infty \text{ if } \mu > 0 \text{ or } e^{-\mu\xi} \to \infty$ if $\mu < 0$ when $\xi \to \infty$,
- 2) $\mu = im$ is purely imaginary and m is an integer: the solutions are periodic but unstable,
- 3) μ is imaginary: the solutions are unstable,
- μ = iβ is purely imaginary and β is not an integer: the solutions are periodic and stable.

Replacing μ by $i\beta$ for stable solutions and making use of Euler's rule

$$e^{i\beta} = \cos\beta + i\sin\beta \qquad (III - 17)$$

equation (III-16) becomes

$$u(\xi) = \mathcal{A} \sum_{n=-\infty}^{\infty} C_{2n} \cos(2n+\beta)\xi + \mathcal{B} \sum_{n=-\infty}^{\infty} C_{2n} \sin(2n+\beta)\xi \qquad (III-18)$$

where $\mathcal{A} = (A + B)$ and $\mathcal{B} = i(A - B)$.

With this solution, the ion will move following periodic oscillations on a stable orbit in the RFQ device. Replacing $\xi = \frac{1}{2}\omega t$ and defining $\omega_n = (2n + \beta)\frac{\omega}{2}$ as the frequencies of possible oscillations, one obtains the frequency spectrum of the oscillations by

$$\cos(2n+\beta)\xi = \cos(2n+\beta)\frac{\omega t}{2} = \cos\omega_n t \qquad (III-19)$$

and solving for the ω_n 's

$$\omega_n = (n \pm \frac{\beta}{2})\omega$$
 for $n = 0, 1, 2...$ (III - 20)

with fundamental frequency $\omega_0 = \frac{\beta \omega}{2}$ (figure III-4).

The factor β determines the frequencies and can be expressed recursively as showed in McLachlan (Mc47) in



Computer simulation of the ion motion along the z-axis with time showing RF modulation of the collective ion motion oscillation between the endcaps. (Reproduced from Lu86)

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terms of the parameters a and q:

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$$\beta^{2} = a + \frac{q^{2}}{(2+\beta)^{2} - a - \frac{q^{2}}{(4+\beta)^{2} - a - \frac{q^{2}}{(6+\beta)^{2} \dots}}} + \frac{q^{2}}{(\beta-2)^{2} - a - \frac{q^{2}}{(\beta-4)^{2} - a - \frac{q^{2}}{(\beta-6)^{2} \dots}}}$$
(III - 21)

Mathieu stability diagram

According to conditions 2 and 4 for the stability of the orbits expressed in last section, β has to be non-integer for the ion to stay in the RFQ trap. Hence, a stability region is defined by the values of β between 0 and 1. Since β is defined by the values of a and q, one can plot the regions of stability on the a vs q plot called Mathieu stability diagram (see figure III-5 and figure III-6).

For the specific case of the RFQ ion trap, there are two Mathieu stability diagrams: one for the z-direction and one for the x-y plane or r-direction. To have stability in three dimensions, operating parameters a_x , a_r , q_x and q_r have to define a common stability region by superposing the two stability diagrams (see figure III-7). The two sets of stable regions are of inverse sign and differ by a factor of two, as can be understood in view of equations (III-12). In all areas shared by the two diagrams, the ion theoretically has stable trajectories; however most devices use only the first stable regions as the amplitudes of oscillations in the other regions tend to be too large (figure III-8). An ion with a and q values anywhere in this region can have stable trajectories as long as the physical size of the trap permits it.





Stability regions for the RFQ trap consisting in the superposition of the stability regions for the z coordinate and -2 times the stability regions for the r coordinate. (Reproduced from Da69)

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First stability region for the RFQ trap, also called "Mathieu stability diagram". (Reproduced from Da69)



Real devices

All the mathematics above describes the motion of one ion of mass m already in the trap with perfect fields created by infinite electrodes. Under these conditions, as long as they have Mathieu parameters in a stability zone, an unlimited amount of ions can be stored, for an unlimited time. However in real life, there are some complications:

- The inclusion of ions in the trap affects the validity of the basis of the derivations: ∇²Φ = 0. Space charge will change the field in the trap. Also, there is a limit on the number of ions that can fit in a given volume in space-charge phase-space,
- with more than one ion present in the trap, ion-ion collisions arise and result in ion loss,
- there might be some neutral, background gas and ion-neutral atom collisions arise also resulting in ion loss and charge exchange, leading to a contaminated ion sample,
- some ions with stable orbits larger than the trap's physical dimensions will be lost to the electrodes,
- 5) imperfections in the electrodes or the RF electronics introduce field errors that are difficult to evaluate, let alone treat analytically and
- 6) the orbits depends critically on the initial phases (with respect to the RF field), velocities and positions of the ions. This becomes a major concern if the ions are to be introduced in the trap from the outside. For extraction purposes, the RF phase at which the extraction is done is also important.

This work concentrates on points 1, 3 and 6. A discussion on ion loss through collisions is given in Dawson (Da76) and computer simulations of ion trajectories in fields generated by non-perfect electrodes were conducted by Lunney (Lu86).

Ion bunch size and density

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To find the total number of ions that can be held in a trap is a complicated manybody problem in itself. The best that can be done to evaluate this number is to make use of rather simplified theoretical models or to measure it experimentally. Two of these models will be outlined hereafter as they give more insight in the physics of RFQ traps.

The first model is due to Fisher (Fi59). Fisher assumes that the presence of a finite charge from the ions in the trap is equivalent to the addition of a DC potential $\Delta U/2$ on the electrodes. The values derived are

$$\Delta U_z = -\Delta U_r = -\frac{nr_0^2}{4\epsilon_0} \qquad (III - 22)$$

where n is the ion density in the trap and ϵ_0 is the permittivity. Since the Mathieu parameters $a_{r,z}$ are related to U, a change in ΔU in U will result in a change Δa in a:

$$\Delta a = \pm \frac{e}{\epsilon_0 m \omega^2} n. \qquad (III - 23)$$

This as for main effect of reducing the area of stability in the trap's Mathieu diagram (figure III-9). In other words, it spreads the ion cloud out in both the r and z directions and there are ions lost to the electrodes.

The shift $\Delta U/2$ in the potential of the electrodes can be observed experimentally and from this value, Fisher obtained densities n of 2×10^6 cm⁻³ for Nitrogen



Figure III-9 Effect of the space charge in the trap on the Mathieu stability diagram, according to Fisher (Fi59). Note that this figure shows the Mathieu stability diagram for negative ions, it is inverted. (Reproduced from Da69)



Figure III-10 Schematic representation of the Dehmelt wells in r - and z-directions. (Reproduced from La70)

and $4 \times 10^6 \ cm^{-3}$ for Krypton.

The second model is due to Dehmelt (De67) and assumes that when $q_{r,z}$ are small, the ions can be visualized as undergoing simple harmonic motion in a threedimensional parabolic well. The depth of the pseudo-potentials Φ_{pseudo} in the r and z directions are

$$D_z = \frac{eV^2}{4mz_0^2\omega^2} \quad \text{and} \quad (III - 24)$$
$$D_r = \frac{eV^2}{4mr_0^2\omega^2}$$

and since $r_0^2 = 2z_0^2$,

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$$D_z = 2D_r. (III - 25)$$

Figure III-10 shows the Dehmelt wells schematically.

Since Φ_{pseudo} is due to the charges, Poisson's equation can be invoked

$$\nabla^2 \Phi_{pseudo} = 4\pi \rho_{max} \qquad (III - 26)$$

where ρ_{max} is the maximum charge density allowed by space charge. Using the pseudo-potential depths defined in (III-24)

$$\Phi_{pseudo} = \frac{D_r}{r_0^2} r^2 + \frac{D_z}{z_0^2} z^2 \qquad (III - 27)$$

and replacing $D_r = D_z/2$ and $r_0^2 = 2z_0^2$

$$\Phi_{pseudo} = \frac{D_z}{4z_0^2} (r^2 + z^2)$$
 (III - 28)

hence

$$\nabla^2 \Phi_{pseudo} = \frac{3D_z}{z_0^2}.$$
 (III-29)

Equating equations (III-26) and (III-29) gives

$$\rho_{max} = \frac{3D_z}{4\pi z_0^2}$$
 (III - 30)

or, dividing by e to get the ion density

$$n = \frac{3D_z}{4\pi e z_0^2} \tag{III-31}$$

Replacing D_z , using equation (III-24), and $V^2 = (m^2 z_0^4 \omega^4 / 4e^2) q_z^2$,

$$n = \frac{3}{64\pi} \frac{m\omega^2}{e^2} q_z^2$$
 (III - 32)

With singly-ionized Argon, $r_0 = 1.0 \ cm$, $\omega = 0.762 \ MHz$ and $q_z = 0.59$, Todd, Lawson and Bonner obtain a theoretical maximum density of $n = 3.5 \times 10^7 \ cm^{-3}$ from this model (Da76).

To actually detect the ions and measure experimentally the number N of ions in the trap, three techniques are available. The first two methods, one due to Fisher (Fi59a) and one to Rettinghaus (Re67), are mainly mass selective techniques. They measure the number of ions of a certain species by observing the absorption of energy in an auxiliary resonant circuit due to the movement of the ions in the trap. They are called mass selective because one can make use of the Mathieu stability diagram to bring into resonance only the particular species of ions to be observed. If more than one species of ions are present in the trap, they can be brought to resonance one by one, providing that it is possible to keep the non-resonant ions in stable orbits while making measurements on the resonant ones.

The third method is to pulse the ions out through a small hole in one of the end-cap electrode and detect the resulting current on a "channeltron" (Da69) or on an electron multiplier (Ha71). This third method is "destructive" in the sense that the ions are lost in the process. These experimental measurements of N agree with each other to give maximum densities of ions in the trap in the range 10^5 - 10^6 cm⁻³. In trapping experiments performed at the Foster Radiation Lab on Cs^+ ions with a trap similar to the one used by the author, S. Gulick, R.B. Moore and M.D.N. Lunney observed the number of ions extracted from the trap and detected by an electron multiplier through the third method (Mo88). They get a maximum number of 7.5×10^5 ions for a trapping volume of approximately 25 cm^3 . It is in agreement with the expected space charge limit of 10^6 for a trap of the geometry they used.

Ion injection and extraction

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Until recently, the ions in RFQ traps were created inside the trap. One would fill the trap with a gas of atoms to be studied and ionize them by shooting electrons at them through a hole in one of the electrodes. Another method was to evaporate and ionize atoms from a substrate by laser heating. The main problem with having to create the ions from inside the device is that it considerably limits the use of the RFQ trap. One also has to deal with the added complications and the ionization technique could introduce impurities in the sample to be studied.

R.B. Moore et al. of McGill's Foster Radiation Laboratory found a way to trap ions coming from outside the RFQ trap (Mo88) and this method is also used in this project. Because the ions come from the outside of the trap through a small hole in one of the endcap electrode, they have enough energy to just go through and out again. Energy has to be taken away from the ions before they reach the opposite

endcap electrode. This is done by applying an alternating retardation voltage across the far endcap and by introducing a neutral inert buffer gas in the trap. By adjusting carefully the frequency and amplitude of the retardation voltage, and the phase of the RF voltage at which the ions are introduced, one extracts energy momentarily from the ions until the buffer gas cools them. If there isn't any cooling through the buffer gas, the energy extracted by the retardation voltage is eventually given back to the ions and they escape the trap. To keep the phase relationship between the RF drive voltage and the retardation voltage and maximize the amount of energy momentarily extracted, a submultiple of the drive frequency is used for the retardation. Ions are introduced in the trap in small pulses, once every retardation cycle. Computer simulations were conducted by Lunney on the acceptance of the trap as a function of the RF phase at which the ions are pulsed into the trap (Lu86). The phases with best trapping efficiency depend mostly on the initial energy of the ions for given RF frequency. Helium at pressures of $\approx 10^{-4}$ Torr serves as a buffer gas to provide the necessary damping. With this method, Moore et al. calculated a trapping efficiency of 50% (Mo88).

To extract pulses of ions from the trap, a high DC pulse on the far endcap electrodes is applied. This is the extraction method used also in this work. Details are given in the later sections.

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B. The RFQ trap set-up

The following is a description of the RFQ trap used in this work and, of the associated electronics. This section is divided in three major parts: (i) the trap and its set of electrodes, (ii) the electric and electronic devices required to control it and (ii) the multichannel plates used to detect the ion bunches.

(i) **RFQ** trap and electrodes

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Figure III-11 shows the configuration of electrodes of the RFQ trap used by the author. The trap itself consists of a ring electrode (on which the RF voltage is applied) and two endcap electrodes (R, NE and FE in figure II-9 and figure III-11). It is mounted on the ion gun flange so that the ion gun heat shield fit into the near endcap. The ions diffuse into the trap through the small hole (8 mm) in the endcap. The far endcap also has a small hole (8 mm) to allow the extraction of the ion bunch. The output bunch then goes through the extraction electrode and the acceleration electrode (EX and GR). All the above electrodes are made of aluminium. The electrodes being held generally at different voltages, they are isolated by ceramic spacers. Typically, the three trap electrodes are held at $5\,000\,V$, with an RF voltage of approximately $V = 175-375 V_{op}$ (Volts zero-to-peak) superimposed on the ring electrode. A negative voltage output pulse used to extract the bunches is applied on the far endcap. The extraction and acceleration electrodes are biased to maximize transmission of well formed bunches (typically 4980 V on extraction and 0 V on acceleration) using EG&G Ortec model 459 0-5000 V bias supplies.





Figure III-11 RFQ trap and electronics. Most of the electronics is in a Faraday cage at 5000 V. Command signal from the ion trap electronics at ground potential are communicated via fiber optics to the instruments in the cage. (G. NE, R, FE, EX and GR correspond to those in figure II-9)

(ii) Trap electronics

Figure III-11 also gives a schematic of the RFQ trap associated electronics. The radio-frequency generator (Clough-Brengle model 110A) is connected to the "trap box" at ground potential. The output signals from the trap box control the trapping of ions: from the RF generator's low voltage signal (1 V_{op} at 650 kHz), it generates

- 1) a switched RF signal (0 to 1 V_{op} at 650 kHz) for the ring electrode,
- 2) an extraction pulse (0 to $-12.5 V_{op}$, 2 to 10 μs width at 0.135 to 135 000 Hz) with a sinusoidal retardation voltage in-between extraction pulses (0 to 12.5 V at 130 kHz), and
- 3) a logical gun pulse $(-12 \ V \text{ and } +12 \ V, 0.9 \text{ to } 5.6 \ \mu s \text{ width at } 130 \ kHz)$ to operate the ion gun in pulse mode. The trap box also had a trigger output pulse $(2 \ V_{op}$ at the extraction frequency) for detection purposes.

While the trigger output pulse stays at ground potential for the oscilloscopes, the three other signals are passed through fiber optic links to instruments in a Faraday cage where they are kept at 5000 V above ground. In this cage are: (i) the heating power supplies for the ion gun filaments, (ii) the DC ion gun bias supply (that puts the ion gun at a slightly higher potential than the trap), (iii) the pulsed gun bias (an amplifier for the logical gun pulse described earlier (Gain of 10)), (iv) the RF amplifier which consists of a ENI model 325LA RF power amplifier and a tunable resonant LC circuit bringing the low voltage RF from the optic link up to 175 to 375 V_{op} for the ring electrode and (v) the extraction amplifier (Gain of 67) which amplifies the extraction pulse (0 to -84 V) and damping voltage signal (0 to 21 V_{op}). Figure III-12 shows schematically the amplified trap box signals along



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Figure III-12 Schematic drawing of the different electrodes forming the ion gun, the trap and the extraction system. The waveforms and biases applied on the electrodes are shown and further explained below.



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Figure III-13 Comparison of the extraction pulse signal before (a) and after amplification (b). The difference is due to passage through the fiber optics and subsequent amplification.

with the box' specifications while as an example, figure III-13 shows the real-life extraction pulse. The final pulse on the trap has a rise-time of 1.6 μs which is longer than one full RF cycle (1.54 μs). The damping voltage is used to help the buffer gas to cool the ions. Helium was chosen as the buffer gas to allow good momentum transfer from the Na^+ while minimizing dephasing of the motion with the RF field (B179). Furthermore, the use of a noble gas lowers the loss of the ions in the trap by charge exchange.

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(iii) Multichannel plates

To detect the ion bunches and measure their amplitude and width, a pair of chevron multichannel plates or MCP (Galileo Electro-optics model 6300) are used. Figure III-14 explains their working principle and shows how the pair is mounted. A multichannel plate is an array of close-packed glass tube whose insides are covered by a thin layer of semiconducting material. The tubes typically have a diameter of 12 μm and center-to-center spacing of 15 μm . When an ion hits a plate, it goes into one such tube and is called the primary radiation. The wall of the tube acts as a continuous electron multiplier and the primary radiation creates an avalanche of electrons that is detected as a current on a Faraday plate at the exit of the tube. Each plate has a thickness of 0.53 mm. A sufficiently high bras between the front and back of the plate (typically 1000 V) ensures a forward current (figure III-14). The gain of a plate at 1000 V is typically 10⁴ and by combining two MCP's in series one can theoretically obtain gains as high as 10^8 ; it is preferable when doing so to have the tubes of the different plates oriented at an angle (as shown on figure

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TYPICAL CROSS SECTION

a) Mounted multichannel plate pair



(MCP tube reproduced from Ku79)

Figure III-14

III-14) so as to reduce a possible "ion feedback" backward current arising from the ionization of trace background gas in the tubes by the flow of forward electrons (Ku79).

A EG&G Ortec model 9301 fast pre-amplifier is placed at the output of the MCP pair (figure III-24 gives examples of bunches as seen on the scope). Comparison of the "size" of the bunches on the scope to that of single ion signals detected at the same MCP bias allows to calculate the number of ions per bunch: the "size" of the bunches and the singles is defined as the product of the FWHM (in μs) and the height (in mV) on the scope, the units being $mV\mu s$. When singles are too small to be seen on the scope (because of low MCP bias chosen not to saturate the detector) extrapolated values from a "singles area versus MCP bias" graph are used (figure II-15).

Most of the measurements were carried out with the MCP in place of the Penning vacuum gauge G1 (see figure II-9). In that configuration, G1 is connected to the window W1 near the trap and gives a reading of the buffer gas pressure in the trap. The MCP is situated in G2's place when measurements on the bunches take place in the interaction region. The MCP is mounted on a sliding rod and can be moved up and down so as to be taken out of the ion beam's way when not needed. At its final position (where it is situated in figure II-9), the deflecting plates (VD) direct the bunches on the MCP.

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Graph of the size of the single-ion detection versus the bias voltage on the multichannel plates' assembly. In this and all the following graphs of single-ion and bunch size, the error bars are smaller than the symbols used in the graph.
C. Trap results and analysis

In order to use the trap for spectroscopy purposes, an optimization with respect to ion bunch intensity and width is necessary. From the bunch intensity, the feasibility of the spectroscopy experience is evaluated; from the width of the bunches, the gating time for the photomultiplier can be determined; from the first information on the energy spread of the bunches δE , the expected resolution of a spectroscopic measurement can be calculated using equation (II-10) for the Doppler broadening. This section is devoted to the systematic study of the operating conditions that influences the ion bunch intensity, width and energy spread.

Trap operating parameters for $^{23}Na^+$

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The trap's physical operational parameters are: m the mass of the ions trapped, r_0 the inner radius of the ring electrode (with $\frac{z_0}{r_0} = \sqrt{2}$), U the DC voltage on the endcaps, V the zero-to-peak RF voltage on the ring electrode and ω the RF frequency (times 2π). m is 23 amu, r_0 is 20 mm and U is 0 V throughout the study (U is not to be confused with the 5000 V of acceleration voltage on the ions). That leaves to determine V and ω using the third equation (III-12) so as to get a q that will allow trapping (a is zero from the fact that U is zero). The Mathieu diagram (figure III-7), shows that for a = 0 trapping is achieved for $0.0 \le q \le 0.91$ but experiments showed that the usable region is limited to $0.4 \le q \le 0.91$ (Ma78). Table III-1 shows the region chosen: ω is fixed at $2\pi \times 650$ kHz and V is allowed to change and was chosen in this interval so as to optimize the signal (also in Table III-1 are the values of q and corresponding Dehmelt well depths). The fact that

f (kHz)	V (Vop)	q	Dz (eV)
65) 650 650 650 650 650 650 650	175 200 225 250 275 300 325 250	0.44 0.51 0.57 0.63 0.69 0.76 0.82 0.82	9.7 12.4 15.9 19.7 23.8 28.3 33.3 28.6
650 650	350	0.88	38.6 44.3

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Table III-1

Values of the RF voltage amplitude (Vop), Mathieu parameter q and Dehmelt well depth (Dz) for RF frequency 650 kHz.

ions are still being trapped at q = 0.94 — which lies outside of the stability region when a = 0 — can be mostly attributed to uncertainties in the calibration of the V measurements.

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Among the parameters varied to achieve better trapping, the ones this work concentrates on are (apart from the RF voltage V): (i) the extraction pulse voltage, width and phase, (ii) the extraction frequency, (iii) the He buffer gas pressure in the trap and (iv) the ion gun current. Efforts were made to use the retardation voltage and the gun pulse for phased injection as used by Moore et al, but no improvement of the overall trapping efficiency was observed in the author's experiments and thus the gun was used in DC mode, the RF field on the trap taking care of the injection window. As mentioned before, the number of ions per bunch extracted from the trap is determined by comparing their height and width on the scope to that of the singles. The bunches' width allows to estimate the energy spread in the bunches. In this study of the effect of the different parameters on the ion bunch size, the assumption is made that the parameters are decoupled from each other and that they can be varied independently. Unless otherwise specified, whenever a parameters is studied, all others are tuned so as to maximize the bunch size.

The procedure for trapping goes typically like follows: the ion gun is turned on, left to warm up gradually (30 min or so). Meanwhile, the trap box signals are checked for anomalies and the MCP bias is applied, along with the other relevant voltages (extraction electrode and flange biases). Approximately 2×10^{-4} Torr of He buffer gas is let in the trap region. A verification that the single pulses are visible on the scope completes the start-up procedures. Following trapping is relatively easy, one only need to adjust V (175-375 V_{op}) and the ion gun bias until the bunches are seen on the scope.

Extraction pulse

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Figure III-16 shows reproductions of four photographs of ion bunches as they are seen on the scope. These photographs were taken with the extraction pulse applied at different phase φ_{ep} of the RF cycle. φ_{ep} is defined so that $\varphi_{ep} = 0$ is the point of the RF cycle where the voltage crosses from negative to positive and refers to the start of the extraction pulse. Figure III-16 illustrates that some phases are better for extraction than others: when the extraction pulse is applied at $\varphi_{ep} = \pi$, a better signal results. The small secondary peak at the right of the main one is due to imperfect tuning of the RF amplitude V. This can be explained by viewing the trapped bunch as undergoing harmonic oscillation in a Dehmelt well at the frequency $\omega_0 = \frac{\beta \omega}{2} \approx 130 \ kHz$ (from equation III-20). If the well is "opened" by the extraction pulse when the bunch is going in the right direction (towards the far endcap), it comes out cleanly; if not, some ions — the ones with less energy going away from the far endcap — will get extracted in the first RF cycle while the others will get out on the second RF cycle, hence resulting in two peaks per extraction pulse. Figure III-17 shows a graph of the extracted bunch height as a function of the angle φ_{ep} sampled at 10 degrees intervals. These results of a marked dependance of the signal on the timing of the extraction pulse agree with those of Waldren and Todd (Wa79, Wa79a, To79, Wa79b) who have explained this phenomenon theoretically with the model of phase space ellipses.



Figure III-16

Extracted bunches (as seen on the oscilloscope) at different extraction phase along with the definition of the extraction phase on the RF cycle. The curves a)-d) are reproduced from photos taken with a polaroid camera. $_{68}$





Extracted bunch height versus the extraction phase, taken at each 10 degrees of the RF cycle.

Figure III-18a is a graph of the bunch size as a function of the extraction pulse amplitude (V_{ep}) . The three curves each refer to a different peak observed on the scope. Figure III-18b shows what is seen on the scope for different V_{ep} : with a high V_{ep} , only one well-formed bunch comes out per extraction pulse. As V_{ep} is lowered another smaller bunch appears as the first one diminishes in size Because of the finite rise-time of the extraction pulse (figure III-13), the ions in the trap don't all get out in the first RF cycle and some are left for the second time around. As V_{ep} is decreased further, a third peak appears and the first one disappears because the extraction pulse is not big enough in the first RF cycle. The second and third peak both grow, and then vanish as V_{ep} decreases still further. Figure III-18 illustrates that it is possible to get the ion bunches out of the trap more efficiently with a higher extraction pulse voltage, because, although a leveling off of the bunch size is seen for 68 $V < V_{ep} < 82 V$, there is further increase as V_{ep} goes up to 84 V. The fact that no saturation behaviour was observed agrees with similar results obtained by Waldren and Todd (Wa79b) where they also see a plateau in this extraction pulse amplitude region and then a steady increase in the bunch size up to $V_{ep} = 100 V$.

Furthermore it can be seen from figure III-18 that there is a minimum threshold voltage required to extract ions. The third bunch in figure III-18 vanishes at $V_{ep} \approx$ 47 V. This result agrees with those of Mather and Todd (Ma79) who observed an extraction threshold and showed that it is a function of the RF voltage amplitude V applied on the ring. This effect is due to the fact that the Dehmelt well depth is a function of V. When collecting the particular set of data used to graph figure III-18, V was 375 V_{op} , which corresponds to a Dehmelt well depth of $D_z = 44 \ eV$



Extraction pulse amplitude (V)



Figure III-18 a) Graph of the bunch size versus extraction pulse amplitude.

b) explains the occurrence of the 3 curves: as the extraction pulse amplitude is lowered, 2 and even 3 bunches are extracted per extraction pulse.

(see Table III-1). Thus the extraction pulse height is very close to the Dehmelt well depth for threshold extraction. This is expected from the fact that ions in favorable position for extraction only need having the well depth drop to zero to escape.

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Mather and Todd also showed that, theoretically, to extract all the ions in the trap on the first RF cycle, $V_{ep} = 4D_z$ (Ma79). Figure III-19 illustrates their reasoning: curve 1 exhibit a residual well when an extraction pulse of amplitude $V_{ep} = D_z$ is applied to the far endcap while curve 2 shows no well left at all when $V_{ep} = 4D_z$. With curve 2, even the ions with position and velocity least favorable to extraction (x in figure III-19) are extracted. From a well depth of 44 eV calculated above, one needs $V_{ep} = 176 V$ to extract all the ions on the first RF cycle while only S4 $V \approx 2D_z$ was available. This might explain why after the leveling off in figure III-18, there still is an increase in bunch size as V_{ep} increases. A better risetime from the extraction pulse amplifier is needed. This would not only take full advantage of the V_{ep} available in the first RF cycle but also ensure better phase resolution for tuning φ_{ep} . Time and technical restrictions, connected to post-fiberoptic amplification of the extraction pulse, are responsible for the absence of better rise-time in the electronics used in this work.

With V_{ep} at maximum, varying the extraction pulse width (W_{ep}) had hardly no effect until W_{ep} was small enough to impede on the first RF cycle extracted bunch. Just before the bunch size decrease as a consequence of a too narrow extraction pulse, a sharp increase of approximatively 10% in the bunch height was observed at $W_{ep} = 4 \ \mu s$. This is similar to results obtained by Waldren and Todd (Wa79) which also show such an increase in the bunch height, for $W_{ep} = 1 \ \mu s$ in their case





Effect of the extraction pulse on the height of the Dehmelt well depth. An extraction pulse amplitude of 4Dz permits the extraction of all the ions present in the trap. X represent an ion in the least favorable condition for extraction.

(Reproduced from Ma79)

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(the difference can be explained by their using ions of a different mass and, mostly, an extraction pulse with far sharper rise-time).

Extraction frequency, buffer gas pressure and input ion current

In this section the effects of the buffer gas pressure and the extraction frequency on the bunch size are studied in details. The extraction frequency f_e was scanned at constant buffer gas pressure P_{bg} . This was done for a large domain of extraction frequencies (1.35 $Hz \leq f_e \leq 1.35 \ kHz$) and pressures (5 × 10⁻⁵ Torr $\leq P_{bg} \leq$ 3×10^{-4} Torr). The effect of a change in the ion input current was surveyed qualitatively. The ion input current was not a precisely controlled quantity and so the parameter that will differentiate between different ion input current will be the heating current delivered to the ion gun, in amperes.

Figure III-20 shows the bunch size as a function of the extraction frequency f_e for four different buffer gas pressures P_{bg} . The first feature one notices are the plateaux of constant bunch size for low f_e . This implies the t the trap reaches a secular equilibrium for the available ion input current before the extraction pulse is applied. At low f_e for high P_{bg} , smaller bunches are detected. This is to be expected as a higher buffer gas pressure creates a higher number of dephasing collisions, driving more ions out of the trap. As f_e increases, the plateaux end and the bunch size starts to decrease exponentially. The plateaux that end at higher f_e are the high P_{bg} ones. Again this is expected as a higher buffer gas pressure faster cooling and hence shorter filling times. The curves cross and at higher extraction frequencies the larger bunches are now the ones formed using a higher P_{bg} . In this



Graph of the bunch size versus the extraction frequency (fe) at different buffer gas pressure (P).

region, these results agree with those of Blatt, Schmeling and Werth (B179) which show an increase in bunch size with buffer gas pressure. This work's results at lower extraction frequencies illustrates that the Blatt, Schmeling and Werth results are f_e -dependent and, in the case in figure III-20, no longer apply for $f_e < 100 \text{ Hz}$

To get more quantitative information on the different processes involved in trapping and cooling of the ions in the trap, *bunch size* is graphed as a function of the extraction period T_e (figure III-21). To explain the time behaviour we consider the following simple model. The trap is filled at a constant rate and losses arise during storing due to collisions, unstable orbits, etc... "Mean lives" can be ascribed to the bunch forming and bunch loss processes. Let

$$N_1$$
 = total number of ions getting in the trap
 N_2 = total number of ions trapped, extracted and detected
then region I in the graph in figure III-21 we have

filling + loss
$$\Rightarrow dN_2 = \lambda_1 N_1 dt - \lambda_2 N_2 dt$$
 (III - 34)

with

$$\lambda_1 = (\text{mean fill time})^{-1},$$

 $\lambda_2 = (\text{mean loss time})^{-1}$ and $(III - 35)$

 $\lambda_1 N_1 = R =$ effective ion current going in the trap.

So replacing the third equation (III-35) into (III-34)

$$dN_2 = Rdt - \lambda_2 N_2 dt. \qquad (III - 36)$$



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Graph of the bunch size versus the extraction period (Te=1/fe) at different buffer gas pressure (P) (using the same data as in figure III-20).

Not all the ions that enter the trap get trapped. The input current is $\approx 10^{10} \ ions/s$, as measured on the electrodes of the trap when it was not trapping, which is at least a factor 10^5 larger than is detected at output of the trap. It can be said then that the mean fill time is very much longer than the mean loss time and that $\lambda_1 \ll \lambda_2$. The solved equation for $N_2(t)$, which is a measure of our bunch size as a function of the extraction period (T_e) , is (Re72)

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$$N_2(t) \approx \frac{R}{\lambda_2} (1 - e^{-\lambda_2 t}). \qquad (III - 37)$$

This equation has only one parameter to fit, λ_2 , because one can get $\frac{R}{\lambda_2}$ from region II in graph III-21. Region II corresponds to the condition $t \to \infty$ where $\lambda_1 N_1 = \lambda_2 N_2$ so

$$N_2(t \to \infty) = \frac{R}{\lambda_2} \tag{III-38}$$

and since $N_2(t \to \infty)$ is read on the graph, the final answer is

$$N_2(t) = N_2(t \to \infty)(1 - e^{-\lambda_2 t}).$$
 (III - 39)

Figure III-22 shows the theoretical fits of λ_2 for the data in figure III-21. The "mean loss time" $\tau_2 = \lambda_2^{-1}$ and the effective ion current $R = \lambda_2 N_2(t \to \infty) = \lambda_1 N_1$ are derived from the fit. Table III-2 gives the values of R, λ_2 , τ_2 and the half-life of the bunch inside the trap $\tau_{\frac{1}{2}} = \tau_2 \ln 2$, which is in the order of 10 ms. As expected, the bunch half-life goes down with increasing buffer gas pressure as the enhanced number of collisions takes effect. The agreement between the theoretical fit and the data breaks down at lower extraction periods, these values correspond to higher extraction frequencies. As the extraction frequency increases, the trapping period



Figure III-22 Fits of equation (III-39) on the data in figure III-21.

P (Tor	rr)	R (ions/s)	Lambda2 (Hz)	Tau2 (ms)	Tau1/2 (ms)
0.85 ×10^{	-4}	1.64 x10 ⁵	C7.18	10 29	14 85
1.0 ×10^{	-4}	1.97 x10 ⁵	104.32	9 59	13 84
2.0 ×10^{	-4}	2.62 x10 ⁵	191.30	5.23	7.55
3.0 ×10^{	-4}	4 26 x10 ⁵	269 67	3.71	5.35

Table III-2

Values of the parameters derived from the fits of equation (III-39) to the data in figure III-21. The first column lists the buffer gas pressure while the second, third, fourth and fifth columns list the corresponding effective ion current (R), the reciprocal of the mean loss time (Lambda2= λ_z , the variable that was fitted), the mean loss time (Tau2= τ_z) and the bunch half-life in the trap (Tau1/2= τ_{y_z}).

decreases and the bunch size becomes set by the trapping time more than by the loss mechanisms in the trap. It is noticeable that R, which was defined as the effective ion current going into the trap, grows with P_{bg} which exemplify that it is easier to trap with high buffer gas pressure although the bunches might be smaller. R has values of about 10⁵ ions/s. From the input ion current of 10¹⁰ ions/s quoted earlier for DC ion injection, a trapping efficiency of $\approx 10^{-5}$ is evaluated, which agrees with the values of Gulick (Gu86) obtained with a similar set-up.

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A change in the ion current I_i , through an increase in the gun heating current, brings about higher and wider bunches as well as an extension of the plateau in figure III-20 into the high f_e region (figure III-23). This is to be expected as the increase in the number of ions coming in the trap increases the probability of ions being trapped at any time. The technical limitations of the ion source did not allow to increase the ion input current indefinitely. Hence no saturation, due to space charge of the trap, was observed at the lowest f_e 's.



Figure III-23 Graph of the bunch size as a function of the extraction frequency at different gun heating current.

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Energy spread in the bunch

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The energy spread of the bunches and the resolution of the technique can be estimated as follows. By measuring the change in FWHM in μs of the bunches on the scope at two different positions (at G1 and G2 in figure II-9), the energy spread δE can be evaluated. Figure III-24 shows reproductions of photographs of two of those bunches. Figure III-24a was taken at G1 and III-24b at G2, two positio is separated by d = 1.08 m. From the acceleration voltage (U = 4500 V), the average velocity of the bunches is

$$\overline{v} = \sqrt{\frac{2eU}{m}} = 193\,624\,m/s \qquad (III - 40)$$

and the average transit time is

$$\bar{t} = \frac{d}{\bar{v}} = 5.5578 \ \mu s.$$
 (III - 41)

The time spread δt of $\pm 25 \ ns$ between the two bunches translates into a velocity spread of

$$\frac{d}{\bar{t} + \delta t} = 192761 \ m/s < v < 194496 \ m/s = \frac{d}{\bar{t} - \delta t}$$
(III - 42)

and, through $E = \frac{1}{2}mv^2$, to a total energy spread of 80 eV. Making use of equation II-10 for the Doppler broadening, this energy spread of 80 eV transforms into a linewidth of 2.9 GHz. This value is larger than the separation between the two hyperfine groups observed in chapter II.

This result derived from the change in width of the bunch from the energy spread must be used cautiously as the acquisition of the data involves serious uncertainties. Due to the fact that only one set of multichannel plates was available





Comparison of the width and height of two bunches. a) was measured with MCP at G1 (see figure II-9) and b) was measured at G2. The 50% decrease in height from a) to b) is attributed to the bunch transport through the line; the 100% increase in width is due to the initial energy spread. (Reproduced from photographs on scope)

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Figure III-25

Graph showing the physical width of the bunches from data taken with MCP at G1 (see figure II-9).

for these measurements, the system had to be turned off, the vacuum broken and the system turned on again when vacuum was re-established in the apparatus, in order to move the MCP from one measurement position to the other. Although care was taken to operate the gun and trap under the same condition for both measurements, there remains some doubt on the reproducibility of the ion gun current and, as mentioned earlier, a change in the ion input current does change the width of the bunches and could account for some of the difference in the two measurements. Thus this measurement represents an upper limit for the energy spread.

Figure III-25 shows the transverse width of the bunches, as measured by lowering the MCP in the path of the beam. Its FWHM is approximately 1 cm, which agrees with the width of the continuous beam used in chapter II for spectroscopic measurements.

Maximum output from the trap

* *

To summarize this the study of the different parameters affecting the performance of the trap, a list of the "best condition" parameter values so far is:

RF amplitude $V = 325 V_{op}$

Extraction phase angle $\varphi_{ep} = \pi$

Extraction pulse amplitude $V_{ep} = > 84 V$

Extraction pulse width $W_{ep} = 4 \ \mu s$ (III - 43)

Buffer gas pressure $P_{bg} = 2 \times 10^{-4}$ Torr

Ion input current $I_i = \text{gun heating current} > 1.2 A$

Extraction frequency $f_e = 150 Hz$

When looking to maximize the number of ions per bunch, typical maximum values of 1×10^5 ions/bunch at $f_e = 13.5$ Hz are achieved at the working limits of the ion gun. When maximizing the output current from the trap, 5×10^4 ions/bunch at extraction frequency $f_e = 50$ Hz is typical. These numbers, coupled with an ion input current of 10^{10} ions/s, give trapping efficiencies of $\approx 10^{-4}$, which is slightly better than those obtained with the earlier theoretical derivation from the λ_2 fit.

If spectroscopy was to be performed at an ion current of 10^{10} ions/s, the sensitivity limit of 4.5×10^{-7} counts/ion derived in chapter II would indicate a signal of 4.5×10^3 counts/s which, coupled to a background of 1.6×10^4 counts/s, yields a S/B of 0.28. At the same ion current of 10^{10} ions/s, bunches of 5×10^4 ions at a frequency of 50 Hz are obtained from the trap for a total current of 2.5×10^6 ions/s. By using a gate length of 200 ns on the photomultiplier (corresponding to the

full width of the larger bunches), a signal of 1.125 counts/s and a background of 0.16 counts/s combine to give S/B = 7.3. This is an improvement by a factor of 26 in the signal-to-background ratio. This shows that even with the presently poor injection efficiency, there is much to gain in sensitivity by using bunched beams from RFQ traps for laser spectroscopy studies on low abundance beams.

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CHAPTER IV — CONCLUSION

Fast beam collinear laser spectroscopy measurements on Sodium were carried out in order to determine the sensitivity limit of the apparatus built in the course of this work. The sensitivity limit of 4.5×10^{-7} counts/ion was obtained.

The systematic study of some of the parameters affecting the RFQ trap output current — mostly the extraction pulse, the buffer gas pressure and the extraction frequency — has helped assess the feasibility of fast-beam collinear laser spectroscopy on bunched atomic beam. The present trap output current $(2.5 \times 10^6 \text{ ions/s}$ given as bunches of $5 \times 10^4 \text{ ions}$ at 50 Hz) suffices to prove the technique a viable answer to low currents in exotic nuclei ISOL beams. A decrease in the signal-to-background ratio of approximately 26 is expected, and —me fine-tuning in the trapping stage will further increase S/B.

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D. Lunney is now attempting to achieve fast-beam collinear laser spectroscopy on bunched atomic Sodium beams. Once this is achieved, the apparatus could be used to study the energy spread of the trap's output bunches. Should the spread prove to be too large to be of any use in gathering new spectroscopic data, measures will be taken to reduce it. Work by R.B. Moore (Mo89) shows that although a bunch extracted from the RFQ trap conserve its overall volume in phase space, it has a distorted phase space in energy-time. Moore suggests a correcting beam transport system that restores the original low energy spread of the ion bunch. Such a correcting transport system might have to be built and installed at the output of the trap if resolution comparable to continuous beam spectroscopy is to be attained.

Future work should include on-line spectroscopy runs using the trap as a

buncher. Work is already being done by Moore and Rouleau on ISOLDE-II at CERN to trap the 60 kV mass-separated beams available there. Once they have perfected the technique of efficient in-flight trapping, it should be relatively easy to implement on-line fast beam laser spectroscopy on bunched atomic beams.

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