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SYNCHROTRON RADIATION PRODUCTION AND TRAPPING OF HIGHLY CHARGED IONS*

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ABSTRACT

Wiggler-enhanced synchrotron radiation will soon be available at dedicated facilities such as the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory. Two recent proposals to study highly-charged ions produced by successive photoionization with broad-band synchrotron radiation are based on the design parameters of the NSLS x-ray ring. Previous calculations indicated that in a suitable Kingdon trap, concentrations of $5 \times 10^7 \text{ Ar}^{18+}$ ions per cm can be attained in a few seconds trapping time and that in a Penning trap $5 \times 10^3 \text{ Ar}^{17+}$ ions could be stored at near thermal energies (300°K) to study, for example, charge transfer collision processes for cold, highly-charged ions. Here the previous work is reviewed and the earlier calculations are extended. The addition of an axial magnetic field to a Kingdon trap is shown to improve expected PHOBIS performance.

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1. Introduction

The successive photoionization of trapped ions has been proposed recently [1,2] as a viable new method for producing, storing, and observing highly-charged ions. The basic idea of PHOBIS, the PHOton Beam Ion Source, is to confine ions in a potential well and produce large concentrations of highly-charged ions through multi-step photoionization by wiggler-enhanced synchrotron radiation. The ions can then be either extracted for external experiments or studied in situ. There is much interest in this concept, because versatile ion sources for the production and study of any desired element, charge state, and beam energy are needed to extend and improve basic atomic physics experiments and to meet the atomic data needs of high-temperature plasma research.

In general, high-charge-state ions can be produced in one of two ways: by acceleration to high ion energy with electron stripping by passage through foil or gas and by confinement at low energy with electron stripping by bombardment. The acceleration approach can provide high beam currents and high charge states at beam energies of tens to hundreds of MeV or, with the recently developed accel-decel method [3], at energies as low as a few MeV. Production at lower ion beam energies requires bombardment sources [4] such as the electron beam ion source (EBIS), the electron cyclotron resonance ion source (ECRIS), and the recoil ion source. For these sources, ion beam currents are generally lower than for beams from accelerators, especially for very high charge states. Furthermore, the presence of

extraneous charged particles complicates source design while precluding the ability to use spectroscopy of the trapped ions as a diagnostic tool. For bombardment by intense broad-band synchrotron radiation, however, the uncharged ionizing agent simplifies trapping considerations while affording the opportunity to study charge exchange and other ion-ion interactions in a clean environment at very low collision energies.

The basic PHOBIS concept is a logical, perhaps even obvious, extension of the principles of charged-particle bombardment sources. What is not obvious is the idea that successive photoionization of trapped ions will yield sufficient numbers of highly-charged ions to make a reasonable ion source. Nevertheless, the calculations indicated not only that such an approach is feasible with the very-high-flux white x-ray beams available from dedicated high-performance synchrotron storage rings, but also that very-highly ionized ions can be produced independent of a particular choice of trap, and moreover that the performance levels with a Kingdon trap [5,6] can be comparable to existing sources. In a subsequent paper [2] the calculations were extended to another application of the PHOBIS concept, the production and storage in a Penning trap [7] of multi-charged ions with mean energies near room temperature. In the present paper, the previous discussions [1,2] are reviewed, improvements in trap design are considered, and the initial experiments planned for the dedicated atomic physics beam line at the National Synchrotron Light Source (NSLS) are described.

2. PHOBIS, the PHOTon Beam Ion Source

Independent of a particular choice of trap, the PHOBIS ion source is shown schematically in fig. 1. To obtain quantitative estimates of PHOBIS performance, it is assumed [1] that a 10-mr sagittal portion of the photon beam is focussed by a mirror into a spot which is 0.2 cm high by 1.0 cm long or an area of 0.2 cm². The photon beam intensity and energy distribution are taken from the design parameters [8] for the NSLS x-ray ring operating at 2.5 GeV with 500-mA electron beam current and a 25-pole wiggler to increase flux and photon energy range. Initial estimates of ionization times were first obtained [1] using a simple independent-electron model (IEM). This model assumes successive single ionization to be the dominant ionization mechanism for the trapped ions and ignores roughly offsetting contributions from multiple ionization [9,10] and successively increasing binding energies.

As shown in [1], convoluting the photon flux distribution with the energy dependent photoionization cross section yields the photoionization rate,

$$\tau_i^{-1} = \int_0^{\infty} N_x(E) \sigma(E) dE, \quad (1)$$

at energy E , and $\sigma(E)$ is the photoionization cross section per electron in shell i . After the onset of ionization, the number of electrons remaining in the shell i at time t is given by

$$N_e(t) / N_e(0) = e^{-t/\tau_i}, \quad (2)$$

and the average time for full ionization is given by

$$T_1 = \tau_1 \sum_{k=1}^{N_1} 1/k \quad (3)$$

where N_1 is the initial number of electrons in the shell.

Table 1 gives the total ionization times T_1 obtained for the argon M, L, and K shells from the uncorrected IEM calculation (A), for corrections to IEM for the effects of multiple ionization and the filling of inner-shell vacancies by outer electrons (B), and for full corrections including these effects plus the charge-state dependence of binding energies (C). Note in Table 1 that the B calculation gives shorter times for the M shell where multiple ionization effects are largest, and somewhat longer times for the L and K shells, whereas the C calculation gives somewhat longer ionization times than A for all shells. These calculations indicate that irradiation of a given volume of an unspecified trap for a few seconds will produce high charge states up to and including completely stripped Ar ions.

3. The Kingdon Trap

Fig. 2 shows a schematic representation of a Kingdon trap [5,6], which is considered [1] to be the best PHOBIS candidate for efficient ion extraction to produce an external beam. Basically, the trap is two concentric cylinders with inner and outer radii a and b ($a \ll b$) with a potential difference V between them and two end caps at the same electrostatic potential as b . The only trapping field is electrostatic and the trapping potential is logarithmic.

In CGS units the number of trapped ions per unit length λ which can be kept in the trap is given by

$$\lambda = V/2 \ln(b/a) / eq \quad (4)$$

where q is the charge state of the ion of interest.

Construction of such a trap is subject to several practical constraints. For example, the applied voltage is limited to the breakdown voltage V_c given by

$$V_c = \epsilon_c a \ln(b/a) \quad (5)$$

where ϵ_c of order 3×10^4 V/cm is the maximum local field before breakdown occurs. This and relation (4) seem to favor large values of a . However, as the ions are created with a very low kinetic energy, their orbits are highly eccentric with "periaxis" much smaller than "apoaxis". Assuming that the ions are created near the outer wall of the trap, with a random initial distribution of velocities, and that collisions with the central wire are to be avoided, a and b must fulfill the inequality

$$(b/a)^2 > 3Ve_q/K \quad (6)$$

where $K/3$ is the part of the average initial kinetic energy related to transverse motion. As K is usually not much larger than thermal energies, b/a should be large, on the order of $10^2 - 10^3$.

Table 2 gives the typical operating parameters for a reasonably sized PHOBIS trap. As indicated in Fig. 2, ions could be extracted either radially or axially. Assuming efficient ion extraction, external ion beams can be produced with intensities determined chiefly by the ability of the trap to confine large numbers of highly charged

ions, i.e. large λ . The maximal value of λ is determined by the breakdown voltage V_c as given in eqn. (5). If a way can be found to avoid collisions with a thicker central wire (larger a), V_c can be increased.

One approach developed here, to improve the performance of a Kingdon trap, is to apply an axial magnetic field. This B field will reduce the eccentricity of the orbits of the trapped ions and the inequality for a and b given in relation (6) becomes

$$(b/a)^2 > (3Ve_q/K) / (1+3b^2e^2q^2B^2/8KMc^2) \quad (7)$$

in CGS units, where M is the mass of the ion.

Table 3 gives optimum values of λ for fixed outer radius b as a function of applied axial magnetic field B . First relation (7) is treated as an equality, then V is set equal to V_c from equation (5). For a given B , this results in two equations, (4) and (7), in two unknowns, a and λ .

Fig. 3 shows the variation of V and λ versus B for the same geometry as Table 2 (dashed curves), and for a four times larger inner radius (solid curves). As before for given B relation (7) is taken as an equality. For fixed a and b , V is then given directly by equation (7), with the constraint that V cannot be greater than V_c . Substitution of V in equation (4) gives λ . Note that a thicker central wire results in degraded operation for $B=0$, but much improved performance at high B .

4. The Penning Ion Trap

A Penning trap is the best choice for the study of ion-ion interactions within a trap. The advantage here would be to eliminate both the energy increment added by the extraction process, and the problem of avoiding collisions with the central wire of a Kingdon trap. Ion-ion collision measurements could then be extended down to near-thermal energies. Although a Kingdon trap has been used for measurements such as electron capture of trapped Ne^{9+} ions at mean collision energies from 1.0-70.0 eV [10], it was shown [2] that a Penning trap [6] could provide the opportunity to study trapped Ar^{12+} ions at mean energies near 0.025 eV $\approx$ 300 K, that is at room temperature.

Fig. 5 shows a schematic representation of a Penning trap [7], which consists of a cylindrically symmetrical electrostatic quadrupole potential and a superimposed axial magnetic field. (Note the absence of a central wire.) The figure also shows the radio frequency excitation circuits for detection and charge-to-mass ratio selection of stored ions, based on cyclotron excitation.

A detailed discussion of the application of Penning traps will not be repeated here, but Table 4 gives typical operating parameters [2] for a suitable PHOBIS trap. For further information, the reader is referred to [2] and [6] and references therein.

5. Summary and Conclusions

A new ion source for the production and storage of highly-charged ions, PHOBIS — the Photon Beam Ion Source, has been reviewed and

previous calculations of expected performance have been extended. The design parameters for wiggler-enhanced synchrotron radiation from the NSLS x-ray ring were used to predict expected operating parameters of PHOBIS for Ar^{q+} with q as high as 18 (fully-stripped argon). After the general performance with an unspecified trap was considered, two particular ion traps were chosen to be best suited for the two alternative approaches to PHOBIS: extraction of ions to produce an external beam and observation of the interaction of ions within the trap.

An ion source is generally considered to be a device that produces a beam of ions. A Kingdon trap was chosen for this application of PHOBIS, because the design and construction are simple and either radial or axial ion extraction is expected to be efficient. Typical operating parameters for a conventional Kingdon trap were summarized, and then the addition of an axial magnetic field was shown to improve expected performance.

The alternative PHOBIS approach is to study atomic collisions within the ion trap. The idea here is to extend measurements to extremely low collision energies. Since any very low energy ion in a Kingdon trap will be lost by collision with the central wire, a Penning trap with no central wire was chosen for this approach to PHOBIS. A summary of calculated performance for typical operation indicated that Ar^{12+} ions could be trapped at room temperature, 300 K or 25 meV.

The conclusion is that PHOBIS, an ion source based on photoionization of trapped ions, is feasible, cheap, and simple to construct and operate. Design and construction of suitable traps is well underway and initial experiments are planned for early 1985.

The development of a Penning trap for PHOBIS is a joint project with Professors D.A. Church and I.A. Sellin. We are indebted to Dr. M.H. Prior for helpful discussions on the use of the Kingdon trap.

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Table 1

Average times in seconds for full ionization of each shell of Ar in a PHOBIS source from simple^{a)} (A), corrected^{b)} (B), and fully corrected^{c)} (C) calculations.

Calculation	T_M (s)	T_L (s)	T_K (s)
Aa)	0.09	0.53	2.7
Bb)	0.06	0.57	3.2
Cc)	0.13	1.9	6.9

- a) Independent electron model (IEM) assuming only successive single ionization.
- b) Corrections to IEM for effects of multiple ionization and filling of inner-shell vacancies.
- c) Corrections to IEM for effects of multiple ionization, filling of inner-shell vacancies, and the charge-state dependence of binding energies.

Table 2

Typical parameters for a Kingdon trap for PHOBIS. Performance characteristic for Ar^{18+} .

Parameter	Symbol	Typical value
Inner radius	a	0.01 cm
Outer radius	b	4 cm
Operating pressure	P	1×10^{-8} Torr
Applied voltage	V	300 V
Trapped ions (Ar^{18+})	N_T	1×10^7 ions/cm

Table 3

Optimum values of λ in a modified Kingdon trap for PHOBIS, with fixed outer radius b as a function of applied axial magnetic field B . Calculations are for Ar^{18+} ions according to relations (4), (5) and (7) assuming an outer radius b of 4.0 cm, a breakdown field ϵ_c of 3×10^4 V/cm, and an initial ion energy K of 0.1 eV.

B (gauss)	a (cm)	V (volts)	λ (ion/cm)
0	5.30×10^{-3}	1.05×10^3	3.07×10^7
10	9.75×10^{-3}	1.76×10^3	5.64×10^7
20	1.51×10^{-2}	2.53×10^3	8.76×10^7
30	2.00×10^{-2}	3.18×10^3	1.16×10^8
40	2.45×10^{-2}	3.74×10^3	1.41×10^8
50	2.86×10^{-2}	4.24×10^3	1.66×10^8
60	3.26×10^{-2}	4.70×10^3	1.88×10^8
70	3.64×10^{-2}	5.13×10^3	2.10×10^8
80	4.00×10^{-2}	5.53×10^3	2.31×10^8
90	4.35×10^{-2}	5.90×10^3	2.52×10^8
100	4.70×10^{-2}	6.26×10^3	2.72×10^8

Table 4

Typical parameters [2] for a Penning trap for PHOBIS.

Parameter	Symbol	Typical value
Trap height	$2z_0$	3 cm
Trap radius	$r = \sqrt{2} z_0$	2.12 cm
Quadrupole potential	V_0	4 V
Operating pressure	P	5×10^{-10} Torr
Potential well depth	$D = V_0/2$	2 V
Radial electric field	$E_r = Dr/z_0^2$	1.9 V
Total charge ^{a)}	q	12 e
Maximum confining energy ^{a)}	qD	24 eV
Axial frequency ^{a)}	ν_z	1.1×10^5 Hz
Cyclotron angular frequency ^{a)}	ν_c	2.3×10^5 Hz
Magnetron drift frequency	ν_-	2865 Hz
Mean cyclotron radius ^{a)}	r_c	.01 cm
Magnetic field	B	0.05 T
Mean trapped ion energy ^{a)}	$E_{\perp}$	25 meV = 300 K

a) Performance characteristics for Ar^{12+} .

FIGURE CAPTIONS

- Fig. 1. Conceptual design of PHOBIS apparatus. Many possible types of traps and experimental geometries can be envisaged for different experiments. Two possibilities are indicated: the extraction of ions from the trap and the study of radiation from interactions within the trap.
- Fig. 2. Schematic representation of a Kingdon trap for PHOBIS. A logarithmic trapping potential is produced by a voltage V between the central wire or inner cylinder A (radius a) and the outer cylinder B (radius b). Suitable openings in the endcaps allow synchrotron radiation (photons) to pass through the trap. Ions could be extracted either radially or axially. See Table 2 and text for geometrical and operating parameters.
- Fig. 3. Plots of voltage (a) and trapped charge per unit length (b) for a modified Kingdon trap as a function of applied magnetic field for two fixed geometries: $a = .01$ cm, $b = 4$ cm (dashed curves) and $a = .03$ cm, $b = 4$ cm (solid curves).
- Fig. 4. Schematic representation of a Penning trap for PHOBIS. The cross-sectional view (upper) shows the introduction of synchrotron radiation (photons) into the trap, which is axially symmetric about the vector indicating the direction of the magnetic field, B . The representation of trap-ring electrodes (lower) indicates the slots for introduction of synchrotron radiation and the radio frequency excitation circuits for detection and charge-to-mass ratio of stored ions.

PHOBIS: PHOton Beam Ion Source

figure 1

KINGDON ION TRAP

figure 3

PENNING ION TRAP

Trap ring electrodes

figure 4