CONF-881154--6
BNL-42583

BNL--42583
DE89 010567

EXPERIMENTS WITH A SYNCHROTRON X-RAY SOURCE AND CONVENTIONAL, ECR, AND STORAGE-RING ION SOURCES

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Presented at

International Symposium on

Electron Beam Ion Sources and Their Applications

Broohaven National Laboratory, Upton, New York

November 14-18, 1988

EXPERIMENTS WITH A SYNCHROTRON X-RAY SOURCE AND CONVENTIONAL, ECR, AND STORAGE-RING ION SOURCES*

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ABSTRACT

The present intensities of photon beams produced by synchrotron-radiation x-ray sources and of ion beams from conventional ion sources, electron-cyclotron resonance ion sources (ECRIS), and cooled heavy-ion storage rings (CHISR) make possible investigations of photoionization and photoexcitation processes that have not previously been feasible. An evaluation of the signal and background rates for experiments that employ the different types of ion sources is given here.

INTRODUCTION

The performance of crossed- or merged-beam experiments in atomic physics is a difficult task in most cases. The ion densities that are produced are not high compared to the density of residual gas in the vacuum chamber and generally the signal of interest must be extracted from a sea of background events. The comparatively recent development of new types of ion sources now makes it possible to consider many new types of experiments. One of the most interesting areas is the study of the interaction of high-energy photon beams with ion beams.

Along with the new types of ion sources it is also necessary to have a suitable photon source. Lasers are appropriate for very low energies, but the regions of interest here are the hard x-ray energies. A brief calculation suffices to show that conventional x-ray sources can not produce sufficient flux to make the experiment feasible. It is necessary to use a synchrotron-radiation source (SRS). The purpose of the present discussion is to present estimates of signal and background rates for experiments that combine the use of the SRS with the three different types of ion sources: conventional sources of singly-charged ions, electron-cyclotron resonance ion source (ECRIS), and the cooled heavy-ion storage ring (CHISR).

SCIENTIFIC BACKGROUND

The reasons that measurements of photon-ion interactions are of interest to atomic physicists have been discussed by Manson[1] and by Jones et al.[2] Further discussions are given in a recent Brookhaven

*Work supported by the Fundamental Interactions Branch, Division of Chemical Sciences, Office of Basic Energy Sciences, US Department of Energy under Contract No. DE-AC02-76CH00016 and by the Brookhaven National Laboratory Exploratory Research Fund.

National Laboratory Conceptual Design Report for a National Atomic Physics Facility[3] and in the proceedings of a Workshop on Photon-Ion Interactions[4] held to study directions for ion physics experiments at the European Synchrotron Radiation Facility at Grenoble, France. The ideas that are listed can be grouped in three different categories: fundamental issues, poorly understood areas, and applications. The applications include the use of atomic physics in astronomy, plasmas, and Earth and planetary atmospheres.

One example of the type of experiment that might be done would be a measurement of the photoionization cross sections for a single element as a function of the ion charge state. This type of measurement has already been employed to study the importance of many-body correlations on atomic structure, but the scope was restricted because of the lack of a multi-purpose ion source.[5]

The conclusions drawn from this look at the scientific needs is that the ion source to be used in these experiments must be able to deliver beams of all elements for charge states that correspond to neutral to fully-stripped atoms. The needs for ion intensity for the performance of the experiments and associated questions of backgrounds will be considered below.

GENERAL CONSIDERATIONS

The usefulness of a particular type of ion source for a colliding- or merged-beam experiment is conveniently assessed in terms of the luminosity. The luminosity is defined as the number of interactions taking place per second per unit cross section. The luminosity can be evaluated for both the signal rate and for the background rate. Some, but not all, details of a particular experimental arrangement are contained within the luminosity value. For instance, the form factor that is used to define the overlap of the two beams is considered, but the detector efficiency and solid angle are not.

Adequate signal rates demand both high photon and high ion-beam intensities. The background rate is generally determined by interactions of the ion beam with residual gas molecules in the photon-ion interaction region. The signal-to-background ratio is then improved by increases in the photon flux or a reduction in the operating pressure. An increase in the ion current helps to improve the data acquisition rate, but will not improve the signal-to-background ratio.

For photoionization or excitation measurements of ion beams it is interesting to compare the values of ion densities produced by the various types of sources. This is done in Tables I-IV for the three types of ion sources that are under consideration here. For sake of comparison the density for a gas target is also included. It can be seen that the ion densities are always low compared to the gas target so that the crossed beam experiments are not easy to do.

The ion beams that are produced by the three sources are at radically different energies. The singly charged sources can be used at energies of a few keV. The ECRIS typically operates at a few tens of keV, while the operating energies of the heavy ion storage ring are in the 0.1-10 MeV/u region. The differences in velocities imply different ion densities for a given ion current. The effect is quite large as is evidenced by comparison of the currents produced by an ECRIS and a CHISR shown in Figure 1 with the ion densities given in Tables I-IV. Even though the CHISR produced currents many orders of magnitude larger in some cases, the ion density for the two types of sources are pushed towards equality by the great difference in the ion velocities.

Table I Beam Density from a Surface Ionization Ion Source[6]
(energy = 2 keV)

Element	Beam Diameter cm^2	Ion Density cm^{-3}
Ba^+	0.2 x 0.3	2.0×10^5

Table II Density of Gas in Conventional Target Operated at 10^{-6} T

Density = 3.5×10^{10} cm^{-3}

Low pressure operation required for investigations of multiple-ionization processes following photoionization.

Table III Beam Densities from an ECRIS
(energy = 15 keV)

Element	Beam Diameter cm^2	Ion Density
O^{6+}	0.5 x 0.5	2.4(7)
Ar^{8+}	0.5 x 0.5	2.3(7)
Ar^{16+}	0.5 x 0.5	1.8(3)
Xe^{14+}	0.5 x 0.5	5.4(6)
Xe^{22+}	0.5 x 0.5	4.3(5)

Table IV Beam Densities from CHISR

No Acceleration

Ion	One Stripping Target: a* (cm)	One Stripping Target: Ion Density (cm^{-3})	Two Stripping Targets: a* (cm)	Two Stripping Targets: Ion Density (cm^{-3})
C^{5+}	.76	2.60(6)	.87	1.80(6)
S^{9+}	1.15	1.34(6)	1.13	5.35(5)
Cu^{11+}	1.26	1.34(6)	1.25	2.97(5)
I^{13+}	1.36	8.85(5)	1.36	1.81(5)
Au^{13+}	1.48	9.04(5)	1.55	1.39(5)

Acceleration to 2.2 Tesla-meter

Ion	One Stripping Target: a* (cm)	One Stripping Target: Ion Density (cm^{-3})	Two Stripping Targets: a* (cm)	Two Stripping Targets: Ion Density (cm^{-3})
C^{6+}	.36	1.16(7)	.35	1.18(7)
S^{14+}	.64	4.34(6)	.40	4.27(6)
Cu^{21+}	.88	2.21(6)	.45	2.29(6)
I^{29+}	1.23	1.08(6)	.55	1.11(6)
Au^{33+}	1.67	7.10(5)	.69	7.03(5)

*a is the beam radius and is related to the width of the gaussian distribution of the beam density by $a = \sqrt{\sigma} \cdot \sigma$, where σ is the standard deviation.

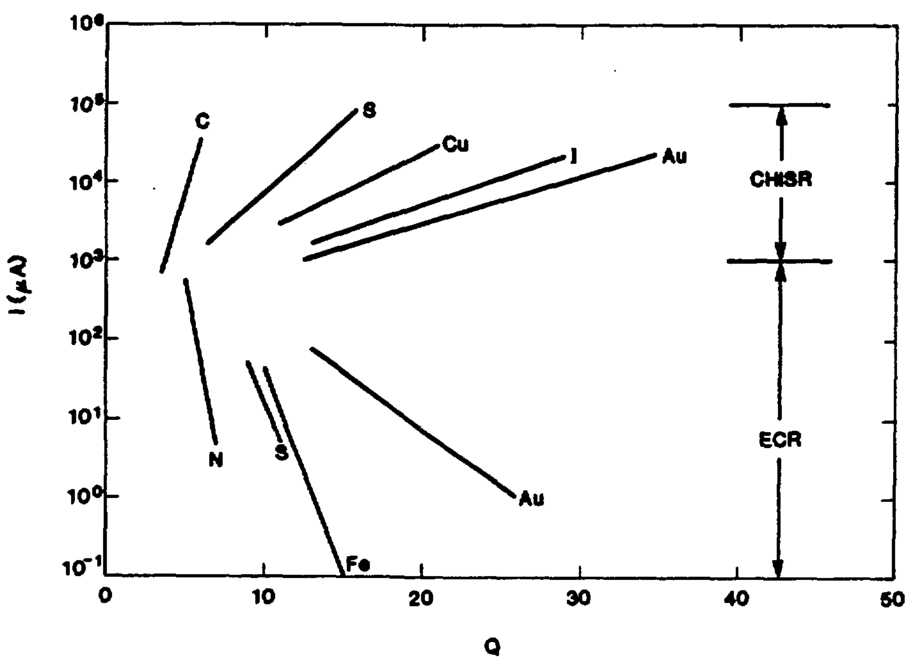

Fig. 1. Intensities of beams produced by ECRIS and CHISR.

Background effects that produce charge-changed ions are not the same for the three sources. At the low energies electron capture is the dominant process, while at the high energies of the CHISR the dominance of capture or loss mechanisms depends on the ion and the energy under consideration. An effect that is appreciable at the high energy end is direct Coulomb ionization of the inner-shells of the beam. In this case the center-of-mass energy for an ion-atom (e.g., hydrogen gas) encounter is of the order of several MeV and appreciable ionization results. In the case of the storage ring the capture and loss reactions also work to limit the lifetime of the stored ions in the ring.

THE PHOTON SOURCE

The photon source used for the only SR experiment to date, that by Lyon et al.,[6] was the ring located at Daresbury in England. The use of an ECRIS or CHISR has not yet been attempted at a SRS. For these cases, it has been assumed that the SRS is a superconducting wiggler device located at the National Synchrotron Light Source (NSLS) at Brookhaven. The use of a superconducting wiggler makes it feasible to consider ionization of K-shells of all elements. The spectrum produced by the wiggler is given in Figure 2 and typical photon beams that can be delivered to the location of the ion beam are given in Table V.

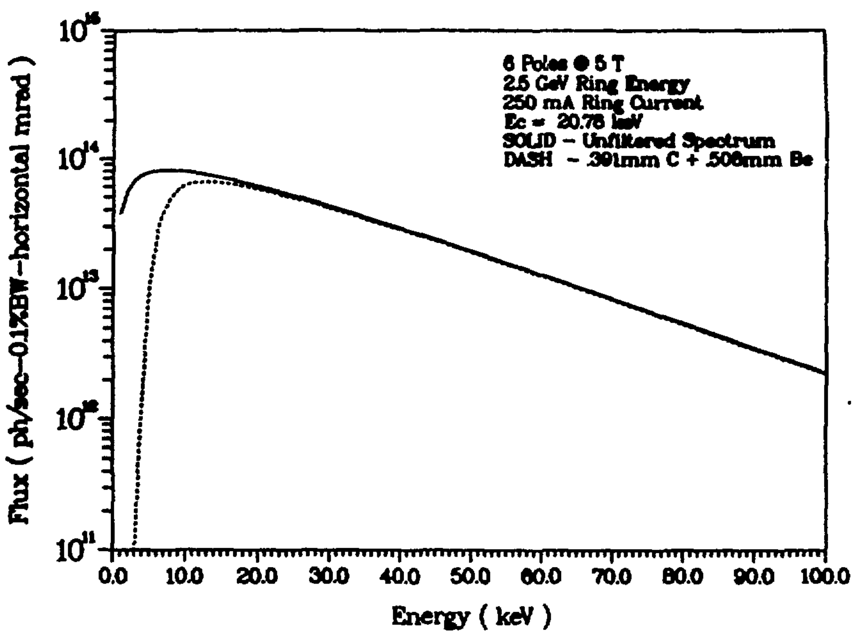

Fig. 2. Energy spectrum of photons produced by superconducting wiggler at the NSLS.

Table V Typical Photon Beams from the Superconducting Wiggler at the CHISR Ring

Beam Energy keV	ΔE and $\Delta E/E$	Horizontal Size (2σ) mm	Vertical Size (2σ) mm	Flux photons/(s-mr)
A. <u>Unfocussed White Beam</u>				
5		60	25	1×10^{17}
20		60	14	5×10^{16}
100		60	7	
B. <u>Focussed White Beam</u>				
5		10	25	1×10^{17}
20		10	14	
(High Energy Cut-Off at 20 keV.				
C. <u>Silicon Monochromator</u>				
5	1.0×10^{-3}			1.2×10^{13}
10	1.7×10^{-3}			1.1×10^{13}
20	2.7×10^{-3}			7.9×10^{12}
50	5.2×10^{-3}			2.2×10^{12}
100	9.0×10^{-3}			2.5×10^{11}

It must be remembered that the SRS is a pulsed machine. The NSLS produces bursts of photons with a width of 0.6-1. ns (4σ) that occur at intervals of 18.9 ns. The microstructure of the beam makes measurements of the background in the beam-beam experiments fairly easy.

PHOTOIONIZATION WITH A CONVENTIONAL ION SOURCE

The only experiments on the photoionization of an ion beam to date[6] used a surface ionization type source to produce beams such as Ba+ and K+. Currents of about 10 nA were obtained at an energy of 2 keV and a beam size of 2 mm x 3 mm. The photon fluxes incident on the ion beam varied from 10^9 to 6×10^{10} photons/s depending on the energy resolution of the monochromator employed. A merging length of 12.5 cm was used to achieve a signal rate of 100 events/s with the high resolution beam and a cross section of about 10^{-15} cm^2. By definition the luminosity is of the order of 10^{17} cm^{-2} s^{-1} for the long path length of 12.5 cm. This can be verified by direct calculation of the expected rate for the conditions mentioned above. The background rate was about 1/2 to 1/5 the signal at the point of highest cross section. The background luminosity is then around 2-5 x 10^{16} cm^{-2} s^{-1}. Extracting the signal from this background ultimately limits the size of cross section which can be investigated. Lyon et al.[6] cite a value of about 10^{20} cm^2 for that number.

EXPERIMENTS WITH AN ECRIS

The use of an ECRIS is a natural extension of the work done with the source of singly-charged ions. The variety of ion beams that can be produced are essential for systematic investigation of many problems in atomic physics. The luminosity of an experiment with an ECRIS and the NSLS can be easily calculated from the ion density and the assumption that the experiment is done with a photon beam of 10^{14} photons/s. If a 15-keV energy is assumed for a typical beam, such as Ar^{8+} confined to a region of about 5 mm x 5 mm in transverse dimension with a beam of 1.5×10^{14} particle/s, the luminosity is found to be 2.3×10^{21} $cm^{-2}s^{-1}$. The luminosity has increased by a factor of 2×10^{4} compared to the Daresbury experiment and the signal-to-background ratio has also been improved since the photon flux is increased by 4-5 orders of magnitude. That, is the signal will be approximately equal to the background (assuming that the background rates do not change appreciably from the barium case) at about 10^{-20} cm^{2}. Under these conditions it might sometimes be feasible to do experiments at the level of 1 b cross sections. It should be noted that with the crossed beam geometry it will be possible to use a much smaller interaction length and the background will be reduced by at least an order of magnitude.

Another improvement in the ion currents may be effected by use of bunching as suggested by Andrä.[7] Klystron bunching could be used to bunch the beam by a factor of 20 or more and gain a further increment in current. This would correspond to producing ion bunches at the beam of 1 ns in length every 19 ns. Space charge will ultimately set a limit to the actual gains.

Luminosity values for the ECRIS are shown in Table VI for a number of different elements and charge states. The values in the table do not include the possible use of bunching. The values for the beam currents were taken from the data of Bourg et al.[8] Similar values are cited by Jones et al.[2]

EXPERIMENTS WITH CHISR

A new approach to the production of very high currents of heavy ions is the use of the cooled heavy ion storage ring. In this case, a beam of ions is produced by the stripping of high-energy beams produced by a conventional accelerator or by use of an ECRIS and subsequent acceleration to higher energies. The beam is then captured in a synchrotron storage ring where it can be recirculated for long periods of time. The synchrotron can be used to accelerate or decelerate the beam through a broad expanse of energies. Electron cooling can be used to produce beams of high quality, superior to the emittance of the conventional source. The average currents provided in the ring are generally far-superior to those that can be made with the ECRIS or electron-beam ion source (EBIS).

Table VI Luminosity Values for ECRIS and CHISR Calculated for 10^{14} photons/s Incident on the Ion Beam in Crossed-Beam Geometry. The energy of the ions from ECRIS is 15 keV/u in all cases.

Ion	Source	Luminosity $cm^{-2}\ s^{-1}$
C^{5+}	CHISR	1.3(21)
C^{6+}	CHISR	1.3(21)
O^{6+}	ECRIS	2.3(21)
S^{9+}	CHISR	8.8(20)
S^{14+}	CHISR	5.7(20)
Ar^{8+}	ECRIS	2.3(21)
Ar^{16+}	ECRIS	1.8(17)
Cu^{11+}	CHISR	6.1(20)
Cu^{21+}	CHISR	3.2(20)
I^{13+}	CHISR	4.3(20)
I^{29+}	CHISR	1.9(20)
Xe^{14+}	ECRIS	5.4(20)
Xe^{22+}	ECRIS	9.6(18)
Au^{13+}	CHISR	3.7(20)
Au^{33+}	CHISR	1.5(20)

A number of these rings are in the commissioning or construction stage at the present time. In all cases they are designed for possible experiments with auxiliary beams of electrons, ions, or laser photons. At Brookhaven a unique possibility exists for use of a storage ring in association with the photon beams produced at the National Synchrotron Light Source.[2,3,4,9] A summary of typical ion beams and beam densities in CHISR are shown in Table IV. The effective beam currents are very high because the revolution time of an ion in the ring is of the order of 500 ns. The effective beam current is then found by multiplying the number of stored ions by their revolution frequency. The beam currents are then of the order of mA. A comparison of the beam currents predicted for CHISR at BNL is made with the ECRIS currents obtained at Grenoble by Bourg et al.[8] in Figure 1. The current values for CHISR are very much higher. A comparison of the two sources is more complex and applicability of the two sources should consider the luminosities for signal and background.

Many of the backgrounds of importance for experiments in a ring depend on the lifetimes of the stored ions. The lifetimes can be estimated by using semi-empirical relationships for capture and loss cross sections.[10] While far from being perfect, these relationships are considered accurate to within a factor of two for capture and certainly to better than an order of magnitude for loss (with the possible exception of ions with only a K-shell electron left). In this context, our predictions for the lifetime of C are in agreement with recent measurements at the Heidelberg Test Storage Ring where a value of ~ 60 s was found for the lifetime of C^{+6} ions at an energy of 6.1 Mev/u and a pressure of 8×10^{-10} Torr.[11]

We emphasize that the superconducting wiggler used for the preliminary design of CHISR gives complete flexibility in doing photoionization of K-shells of all elements. This choice costs about a factor of 4 in flux when compared with predictions for a permanent magnet wiggler. This loss seems to be an acceptable price to pay to for the great versatility of the superconducting device.

An example of a photon-ion experiment is the measurement of photoionization cross sections. This is a very broad topic with many nuances. To show the practicality we consider a specific ion, Cu^{11+} and show that both K-shell and outer-shell photoionization measurements are feasible.

Figure 3 shows that the total photoionization cross section for Cu around the K-edge is 3×10^4 b/atom. The signal rate is found using the luminosity value of 4.3×10^{20} $cm^{-2} \cdot s^{-1}$ for Cu^{11+} cited in Table VI. The signal rate is then around 13 Hz using a photon energy resolution better than 8 eV and a photon flux of 10^{14} Hz (E/E = 0.1%). (Outer shell cross sections are much larger and the rates will be in excess of 100 Hz).

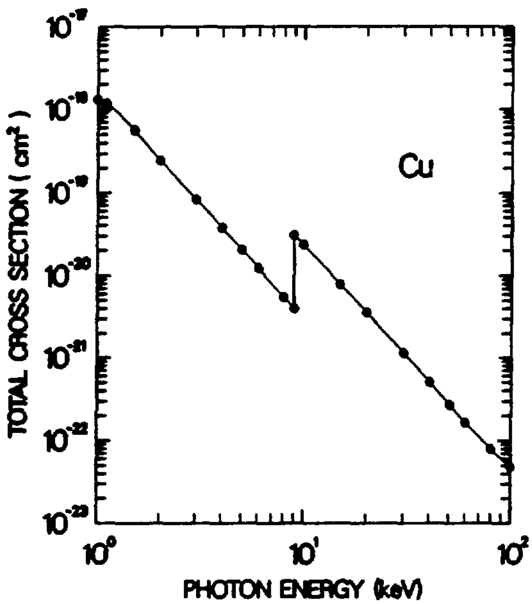

Fig. 3. Total cross section for the interaction of photons with copper as a function of energy.

The background rates can be easily calculated with the following approach. For the K-shell case, several electrons are removed in the photoionization process. Therefore, single charge-changing events are not a problem. The rate for direct Coulomb ionization of the K-shell can be found using a luminosity for interactions with the background gas in the experimental straight section of 2×10^{25} cm^2 s^{-1} and a K-shell vacancy production cross section of about 200 b for copper on hydrogen at about 2.9 MeV/u beam energy. The background rate is then found to be about 4000 Hz. This rate can be handled by conventional detectors with no difficulty.

The signal-to-background ratio is better than 13/4000 because advantage can be taken of the pulsed nature of synchrotron radiation by accepting events only when the photon beam is on. The correction for duty cycle improves the signal-to-background value. Normally, the NSLS operates with 25 x-ray bunches which have a width of 0.6-1.0 ns (4σ) and a revolution frequency of 567.7 ns. The duty factor is then 0.026 to 0.044 at the 4σ width. The duty factor is taken as about 0.03 for illustrative purposes. Therefore, we find: Signal/Background = 13/(4000 x .03) = .11.

Accurate measurements of the signal can be made in the course of a few minutes under these conditions. The uncertainty in the measurement, δ, is given by:

$$\delta^2 \approx \alpha \times b/(s^2 \times t_\delta)$$

where s is the signal counting rate, b the background counting rate, and α is the NSLS duty cycle, 0.03. Evaluation of this relationship for the calculated rates gives an uncertainty in the measurement of ± 10% for a measurement time of ~ 70 s and 5% for a measurement time of less than 5 min.

Now, look at the outer shell case. The signal rate is found as before, but now using a cross section of 1.2 Mb. The rate calculated using the above luminosity is 516 Hz.

The background in the one-electron loss detector is simply calculated. The electron loss lifetime[3] is 5000 s at a beam energy of 2.9 MeV/u and about 14,100 s at a beam energy of 7.1 MeV/u. The rate in the corresponding detector is then about around 5.5×10^5 Hz. This is still a rate which can be handled with a conventional detector. Or, the problem can be alleviated by running at reduced ion currents or using an aperture to reduce the fraction of beam accepted, etc.

Signal-to-background is then: Signal/Background = 516/(5.5×10^5 x .03) = .031 at the low beam energy and: Signal/Background = 516/(2.0×10^5 x .03) = .086 at the high beam energy.

The values are similar to the K-shell case calculated above and thus accurate measurements are also feasible within a matter of minutes. Using the formula cited above, we find that the time needed for a measurement with an uncertainty of 5% is 24 s at a beam energy of 2.9 MeV/u. Even if the ion beam current is reduced by an order of magnitude, to limit the count rate, the measurement time will still be below 5 min.

The above discussion shows that photoionization experiments in CHISR will be generally feasible without great experimental refinements. The photoionization experiments can be made more sophisticated by adding a detector at the target region to measure the photons/electrons emitted by the ionized atom. This additional specification makes it possible to measure the events following the ionization in much more detail and at the same time to considerably reduce background events due to much shorter interaction lengths. Detectors with large solid angles can be used so that the coincidence efficiency is very high. The luminosity can also be increased by using a broad-band of the synchrotron radiation spectrum. Improvements of up to 100-1000 could then be attained in the value of luminosity and signal-to-background ratio.

CONCLUSIONS

We have highlighted some aspects of photoionization or photoexcitation studies using three different types of ion sources. Conventional sources that produce beams of a few times ionized atoms were represented by a surface ionization source that was employed for the first such experiments. The extension of the first work to more highly ionized atoms using ECRIS and CHISR type devices was considered in terms of the signals and backgrounds involved. In a short discussion it is not possible to go into all the complexities of these experiments. Nevertheless, a good idea of the regions of applicability of each class source emerges from the data presented.

The conventional sources that can produce well-focussed beams from gaseous or solid materials are certainly best for cases of singly, and perhaps a few-times, ionized beams. The gains obtained by using the ECRIS are minimal. CHISR is not really at all suited to this work because the high-magnetic rigidity of the low-charge state ions makes it difficult or impossible to store them in the ring and because of short storage lifetimes at the low energies needed in the ring.

For light elements and ionization stages of heavier elements which are not too high the ECRIS is the simplest and most effective approach. The luminosities are comparable or better than those predicted for the CHISR approach. The beam quality in CHISR and other features associated with the higher energies could be helpful, but these points were not considered in this discussion. It can be seen, however, that the signal rate for Ar 14+ for the ECRIS beam is much less than for the beams produced by CHISR.

CHISR appears to be clearly superior for studies of beams of the highest charge states for elements from about sulfur through the rest of the periodic table. This assumes that there is a suitable source to produce the ions for injection of the ring. CHISR is also competitive in luminosity values with the ECRIS source for the lower charge states of the light elements and for many of the heavy elements. Again, it should be stated that the CHISR performance for lightly ionized atoms will be limited by magnetic rigidity and lifetime problems encountered in its operation.

It appears that the construction of a facility at a synchrotron light source that combines the features of these complementary devices would result in a superbly versatile and unique approach to the study of the interactions of the ion beams with photons from the synchrotron light source and also with beams of other ions or with beams of electrons. The extraordinary variety of fundamental experiments that could be done with the equipment would make it an extremely important tool for fundamental and applied atomic physics research.

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