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STUDIES OF ION BEAM-PHOTON INTERACTIONS AT THE
NATIONAL SYNCHROTRON LIGHT SOURCE

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Summary

To date, synchrotron radiation has been used for atomic physics experiments with gas or vapor targets. Experiments with crossed or merged ion and photon beams are made possible by the advent of high-brightness synchrotrons such as the National Synchrotron Light Source. Some types of experimental programs which can now be pursued are considered. Design parameters for a proposed ion-photon beam apparatus are discussed.

Introduction

The field of accelerator-based atomic physics has developed rapidly during the last two decades. In large part, this resulted from the innovative application of new particle accelerators. Tandem Van de Graaff and linear accelerators were used to produce intense beams of multiply ionized heavy atoms which could be used for studies of atomic spectra, lifetimes, and vacancy production mechanisms among many experimental possibilities. Intense electron beams from synchrotrons were developed during this same time interval to serve as unique photon sources which had, as is well known, properties not duplicated by laboratory photon sources. Many innovative atomic physics experiments could be performed with these accelerators, but it was still not possible to consider the use of targets other than those that could be produced as gases or vapors.

At the present time, accelerators such as the National Synchrotron Light Source (NSLS) at Brookhaven are being brought into operation and, when the design parameters are reached, a major improvement in photon flux will be attained. It will then be possible to do experiments which study the excitation and ionization of neutral, negative-ion, and positive-ion beams of all elements in the Periodic Table. Furthermore, the recent development of electron beam ion sources (EBIS) and electron cyclotron resonance sources (ECR) for multiply charged ions indicate that in the near future it will be possible to make measurements as a function of ion charge for many elements.

In this survey of the experimental potentialities of the proposed ion-photon facility at the NSLS, a brief summary of several recent experiments is given and contrasted with the possibilities opened up by use of the NSLS with appropriate ion sources. The experimental apparatus required is then considered and interaction rates, background and other experimental problems discussed.

Present and Future Experiments

One of the most straightforward experiments that can now be performed is the measurement of the absorption as a function of photon energy. A recent example has been reported by Breinig, et al.¹ who measured the absorption edges of the Ar, K, Kr, Xe L_1 , L_2 , and L levels at the Stanford Positron-Electron Accelerator Ring (SPEAR). Their work depended essentially on the production of photons with a narrow bandwidth, less than 1 eV, and an energy which is also known to

better than 1 eV. Once the photon beam has been prepared, the actual experiment involves only the measurement of the absorption of the photon beam by a cell filled with the gas of interest. This measurement is readily done by measuring the photon flux change with ion chambers placed before and after the cell. From analysis of the absorption curves it is possible to obtain the binding energies for each shell for comparison with theory. When the comparison is made it is found that electron correlations must be included in the theoretical calculations in order to obtain agreement for the K-shell measurements. The discrepancy between theory and experiment was larger for the Xe 2s states and is attributed to the neglect of many-body effects. These theoretical many-body calculations are not yet available.

More complex experiments which study such things as the energy and angular distributions and polarizations of photoelectrons give a more sensitive test of the various channels which contribute to the absorption cross sections. In these experiments the available flux of photons becomes more important since it is necessary to measure the energy of the ejected photoelectrons, a measurement which entails the use of low pressure gas targets and electron spectrometers with small solid angles. As an example of this type of measurement, we cite the work of Krummacher, et al.² who studied correlation processes in atomic sodium by determining the photoelectron spectra at several photon energies with a 0.9% energy resolution cylindrical mirror analyzer. The resulting spectra could, for example, be used to find the $^3P/^1P$ branching ratio for comparison with Hartree-Fock calculations.

It is fairly clear that in the future experiments will be devised to take advantage of the higher photon energy and flux which is available at the NSLS and other new accelerators. Future experimental directions have been the subject of a recent review³ and a workshop.⁴ The conclusions of the workshop on the possible areas of interest for study at the NSLS are summarized in Table I. It can be seen that the high energy photons available from the NSLS are required for inner-shell spectroscopy measurements and for photoabsorption measurements on ions. Studies of open-shell atoms and of ions imply the use of low density targets and hence the need for very high fluxes.

Table I. Areas in Atomic Physics for Study at NSLS **

I. Three-Body Continuum Problem

- A. Double Photodetachment and Photoionization
- B. Detachment (or Ionization with Simultaneous Excitation)
- C. Highly Excited Autoionizing States
- D. Threshold Auger ($e, 2e$) Experiments

II. Open-Shell Atoms

III. Photoionization of Heavy (High-Z) Atoms

END

IV. Inner-Shell Spectroscopy

V. Spectroscopy of Autoionizing States

VI. Ions

A. Photoabsorption Cross Sections

B. Discrete Oscillator Strengths

VII. Excited State Photoionization

VIII. Field Effects in Atomic Photoionization

** See pp. 191-193 of Reference 4.

NSLS Characteristics

The characteristics of the NSLS have been discussed in the literature⁵ and the current status has been described by W.C. Thomlinson.⁶ For our purposes it suffices to show in Fig. 1 the calculated⁷ brightness for photons from the 2.5 GeV x-ray ring. It can be seen that an arc source at the NSLS x-ray ring is one to two orders of magnitude brighter than at other storage rings such as SPEAR, SRS at Daresbury, and ADONE at Frascati. This advantage is most pronounced at the higher energies in the region from 10-20 keV. The predicted brightness for the proposed European Synchrotron Radiation Facility (ESRF) is also shown to give an idea of what might be expected in 5-10 years' time when the next generation of synchrotron light sources come into operation. It can be seen that a further improvement of 1-2 orders of magnitude in brightness can be anticipated. Of course, if it is possible to use wigglers or undulators, the brightness from NSLS will be around 10^{18} photons/s/0.1% bandwidth/ m^2/mm^2 and values around 10^{17} photons/s/0.1% bandwidth/ m^2/mm^2 will be obtained from other accelerators, SPEAR, SRS, ADONE, etc. The prospect of the very high photon flux to be available over a wider energy span is

immediately a very strong stimulus to see if it is possible to do crossed ion beam-photon beam experiments in an effort to explore some of the scientific problem areas listed in Table I.

Components of Crossed Beam Experiment

The various components of a proposed atomic physics beam line for crossed beam experiments at the NSLS are relatively simple. A schematic layout of two beam lines which would share a single front end on the x-ray ring of the NSLS is shown in Fig. 2. One line will be devoted to an x-ray microprobe which will be used mainly for trace element determinations at levels of 1 ppm by weight with spatial resolutions in the 1-20 μm range. As shown in Fig. 2, there will be essentially no interference with the atomic physics experimental hutch. Some of the justifications and details of this proposed facility are discussed by Sparks⁸ and by Howells and Hasings.⁹

For the atomic physics line it is intended to put together a reasonably comprehensive facility, but one which will not be too difficult to operate in the early stages of experimentation. Since the major design requirement is to maximize signal/background, the choice is made to maximize monochromator throughput for the initial experiments. This choice merely underlines the basic thought that there are not universal monochromators available. Since the crossed beam experiments will be difficult to align, there is strong reason to try to cover as wide a range of wavelengths as possible on this beam line. Conceivably, this might even include the use of the line into the VUV wavelength region is the proper monochromator and vacuum conditions could be provided. Ultimately, it will no doubt also be desirable to have monochromators with the ultimate in energy resolution for investigation of thresholds and resonances. However, we feel that for the first set of experiments it is crucial to emphasize obtaining maximum intensity at the higher energies available at the x-ray ring.

One possible approach to the choice of monochromator is to use a two crystal monochromator with the second crystal cylindrically bent as proposed by Sparks, et al.⁸ This arrangement will function over the energy range 5 to 40 keV. The cylindrical shape provides sagittal focusing and an acceptance of some 10 mrad of radiation while still giving image sizes on the order of a few square millimeters. This monochromator therefore can give good energy resolution and, in addition, provide some beam focusing. Since the Darwin width is not appreciably worsened by elastic bending distortions^{10,11} the energy resolution should be excellent, 3×10^{-4} . The drawback to this scheme is the difficulty of bending crystals to a different, but well-defined, radius at each energy. An interim solution bypassing the crystal bending problem is to use a 'channel cut' artificial multi-layer, giving a beam bandwidth of 2-3% but not focusing. The disadvantage is that the output moves with photon energy. If we refer to the curve shown in Fig. 1 and use a bandpass of 0.3% for the sagittal focusing device it appears that a flux of around 6×10^{13} photons/sec should be attainable in a spot size of about $1 \times 4 \text{ mm}^2$, i.e. about 1.5×10^{15} photons/sec/ cm^2 . If a bandpass of 2% is obtained with an acceptance angle of 1 mr, then it should be possible to obtain about 1.2×10^{15} photons/sec/ cm^2 . For rate calculations we will use the lower of the two values.

Several types of ion sources exist which will be suitable for crossed beam experiments. As an example, consider the Danfysik 910 source.¹² Positive ion beams of essentially all elements in the Periodic Table can

Fig. 1 Photon brightness obtained from: SRS at Daresbury, SPEAR at Stanford, ADONE at Frascati, NSLS at Brookhaven, and the proposed European Synchrotron Radiation Facility.

Fig. 2 Schematic layout showing arrangement of beam lines for atomic physics experiments and for ultrasensitive trace element determinations with spatial resolutions on the order of 10-30 μm . The two lines share a common front end assembly for coupling to the NSLS x-ray ring, but are operated completely independently.

be obtained from this source with currents that depend on the element in question. Performance levels cited by the manufacturer are maximum currents of $500 M^{-1/2} \mu\text{A}$ where M is the ion mass in Atomic mass units. Other types of sources that produce similar currents are also available and could be used to optimize performance for a particular element. For design purposes the assumption is made that it will be possible to produce singly charged ion beams of a magnitude of $10 \mu\text{A}$ with a 2 mm diameter at the image point of the photon spectrometer. It should be noted that the NSLS x-ray ring will produce photon pulses ~ 2 ns long every 18.9 ns. It will thus be possible to increase the effective ion beam current by a maximum factor of 10 by bunching the ion beam with klystron bunching into similar bursts. Effective beam currents in the range from 50-100 μA should thus be obtainable at energies from 10-50 keV. Higher energies are favored since space charge problems are minimized, but this reduces the ion beam density, and ultimately, the photon-ion interaction rate.

After the feasibility of this type of experiment is demonstrated with standard type ion sources it will be an obvious next step to consider the use of multiply charged ions. One of us (V.O.K.) is now fabricating an electron beam ion source of comparatively modest size and cost.¹⁴ This source should produce fully stripped C, N, and O ions when operational. Beam currents of around 6×10^9 particles/sec, coupled with a storage device of some type to compensate for the poor duty cycle of the source, would be adequate for experiments with high brightness photon sources. Such an experimental facility would make possible a whole new realm of atomic physics experiments.

Interaction Rates for Crossed Beam Experiments

The interaction rates for a crossed beam experiment can now be estimated from the parameters for photon and ion beams that have been discussed. Both

Kruse¹⁵ and Kostroun¹⁶ have estimated the rates for these types of experiments. The rates for a merged beam geometry would be higher, of course, but use of an extended source is undesirable since the observation of photons or electrons emitted in the interaction is much more difficult. The ion velocities are very low so that simple classical mechanics can be used to calculate the ion density:

$$n_{\text{ion}} = \frac{1.43 \times 10^5 i}{qA} \sqrt{\frac{M}{E}}$$

where i is the ion current in μA , q is the degree of ionization, A is the cross-sectional area of the beam in cm^2 , as before, M is the ion mass in atomic mass units, and E the energy in keV. An areal ion density of $1.6 \times 10^7 \text{ cm}^{-2}$ is found for a 10 keV, $10 \mu\text{A}$ mass 50 singly charged beam with area $2 \times 2 \text{ mm}^2$. For a 4 mm^2 beam intersection area the number of incident photons, N_{γ} , is 4.8×10^{13} photons/sec for the multilayer monochromator. The interaction rate for an assumed cross section of 10^4 b , typical of K-vacancy production for medium weight elements, is then found to be 7.68 s^{-1} . This value is high enough to demonstrate that it should be possible to use high resolution spectrometers to examine the decay products from the ion-photon interaction although the rates would be low and necessitate lengthy data accumulation periods.

In addition to requiring an adequate interaction rate, it is also necessary to have an adequate signal-to-background ratio, S/B . The background in this type of experiment should arise mainly from collisions of the ion beam with the residual gas in the interaction chamber and, hence, $S/B \propto N_{\gamma}/N_G$ where N_G is the areal density of the residual gas. Therefore, it can be seen that use of the highest possible brightness photon beam is essential to give good interaction rates and the best possible S/B ratio. If a value of 10^{-9} Torr is assumed for the residual gas pressure, the actual back-

ground rates can be calculated. However, the cross sections for production of inner shell vacancies are not so well known for ion-atom collisions at these low energies. Cross sections for K-vacancy production in O-Fe or Ar-Fe collisions at 10 keV are negligible compared to the photon absorption cross sections. However, cross sections for electron capture are much larger, in the range of 10^{-16} cm². S/B values for measurements of the effects of inner-shell ionization should be much greater than one. The background for outer shell studies will be much higher and the experimental problems much more difficult, but even then should not be impossible to overcome.

Conclusions

The list of atomic physics experiments that are possible if a crossed ion-photon beam experiment can be implemented is striking and shows that a considerable effort to set up such an experiment is well justified. Our estimates of the interaction and background ratio that can be achieved with an arc source at the NSLS show that such experiments should be entirely feasible. As a result, we have concluded that the implementation of such an experimental facility is well worthwhile and should be attempted. At the present time we are starting by borrowing ion sources, beam line hardware, and vacuum equipment from other nuclear and atomic physics experiments at Brookhaven with the aim of producing the needed ion beams and interaction chamber in the near future. Proposals for funds for putting together the beam line, which was schematically indicated in Fig. 1, have also been made. It is our hope that all the elements required for the start of the experimental program will be achieved in the next one to two years. The present authors have organized a participating research team (PRT) in order to make sure that these proposed extensive experimental facilities will be generally available to the atomic physics community. We welcome further participants in the PRT as well as suggestions for development of the experimental equipment.

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