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Summary

The current status of ion beam excitation and ionization by high energy electrons and photons is discussed. Recent advances in multiply-charged ion source development are mentioned, and plans for electron-ion and synchrotron-ion crossed beam experiments at Brookhaven National Laboratory are described.

Introduction

The characteristics and interactions of multiply-charged ions have in recent years been recognized as an important factor in understanding the behavior of laboratory and astrophysical plasmas.[1-5] Recent advances in electronics and ion source technology have greatly expanded the possibilities for experiments which involve multiply-charged ions.

Beam-beam experiments are the preferred technique for the study of many types of ion-electron or ion-photon interactions. This type of experiment has the capability of being absolute, separable, and allowing full diagnostics on all experimental parameters.[6] There have been several excellent reviews of the data available on electron impact excitation and ionization of ions.[7] Until very recently, however, there were no data available on multiply-charged ions. The most recent updates of these reviews show an increasing interest and expertise in beam-beam experiments with multiply-charged ions.[9] Intense, tunable light sources for ion-photon interaction studies are restricted to lasers or synchrotrons. Until recently, there were very few synchrotron beam lines available for the use of atomic physics experimentalists. With the completion of new synchrotrons at Wisconsin and Brookhaven,[9] however, a larger number of users will have intense, monochromatic VUV and x-ray photon sources available to them which will make feasible a new area of research in the interaction of ion-photon interactions.

In this paper, we first survey the status of experiments with electrons and photons interacting with ions. We then consider the new developments in ion sources which can be used for this work. Finally, we describe the programs at BNL which are intended to use the new technologies in ion sources and synchrotrons for crossed ion-electron and ion-photon experiments.

Survey of Ion-Electron Experiments

The three main types of inelastic ion-electron interaction are recombination, excitation, and ionization. Cross section measurements in all three categories have been severely handicapped by the limitations of ion sources, especially for multiply-charged ions. Progress continues, however, and the current status of these areas of research are summarized below.

For free atomic ions in a thin target (such as a fusion plasma), dielectronic recombination is the only significant recombination process.[10] Small cross sections and high backgrounds have so far precluded accurate beam-beam measurements,[11] although numerous groups throughout the world are hotly pursuing the first clean experiment. Some of these experiments are designed to deal with highly-stripped ions, while others emphasize singly-charged ions, so a number of accurate measurements from widely varying targets and charge states may be available in the next few years. Such key data are necessary to establish the accuracy of theories and of extrapolation techniques.

The only completed cross section measurements for electron-impact excitation of multiply-charged ions remain the resonance transition studies on Li-like C^{3+} and N^{+4}.[12] A measurement of the excitation cross section for Al^{2+}, currently under way at Oak Ridge National Laboratory,[13] will be the first extension of the critical Na-like isoelectronic sequence into the multiple-charge region. The extremely low photon detection solid angles in beam-beam excitation experiments leads to a low signal rate. Backgrounds are usually high due to the inevitable stray photons. These experiments also are usually troubled by marginal ion beam intensity, especially for multiply-charged ions. There are several serious limitations to our knowledge about electron impact excitation. Only one absolute measurement has been made involving a forbidden transition.[14] This indicates a rather large gap in our knowledge of excitation cross sections (most of the measurements to date involve resonance transitions). Next, the recent publication[15] of the excitation cross section for Be^+ has emphasized that theory and experiment often disagree for singly-charged ions with no satisfactory predictability to the disagreement. Finally, probably the highest-priority problem to be faced in excitation work is the extrapolation of cross sections along isoelectronic sequences with reasonable (10-15%) accuracy. This task is made more difficult by the absence of data except at one edge of the isoelectronic sequence. In theory, extrapolation should become more accurate with increasing charge, but effects which may be ignored at low z for low charge states may become quite important for high z or high charge ions along the same sequence. Accurate scaling laws are, in practice, the information needed most by atomic process modelers.

The key to increased accuracy in predicting excitation cross sections is a series of absolute measurements for several targets over a wide range of charge states. These are, however, very difficult experiments, and only a few key measurements can be expected. The most important needs at the moment are for data on Na-like multiply-charged ions or on any highly-charged heavy ion.

Electron-impact ionization has been studied more than excitation or recombination. There are a number of accurate, absolute beam-beam measurements on multiply-charged ions, with a least two research groups actively engaged in further work.[16] Several cross sections have been measured for doubly-charged ions by different groups,[17] and data extends as high in z and charge as Ar^{6+}.[18]

Ionization cross sections are easier to measure than excitation or recombination cross sections. Detection efficiencies may approach 1.0 since the signal is obtained by counting ions after charge state analysis (a relatively simple and low-loss process). Background is, again only relatively, a minor problem. The metastable content of the ion beam, however, must be measured and carefully considered in data analysis.[17] (This is of course also a problem in excitation and recombination measurements, but the researcher in these areas can simply choose not to use target species which may have metastable components. There are enough problems to be faced in those areas without metastable ions.)

There are sufficient ionization cross section data available to make some general comparisons with theory.[19] The He isoelectronic sequence shows good agreement between several theories and with experiment. Li isoelectronic sequence theories disagree over a wide energy range (threshold to at least 40 threshold units). In addition, experiment shows that inner-shell excitation followed by autoionization becomes a significant and even dominant process as one progresses along the Li isoelectronic sequence. This effect had not been included in calculations[20] (although it had previously been observed in two singly-charged ions[21]). The Li isoelectronic sequence was expected to be a difficult one for theory, and is proving to be an excellent test area. The Na isoelectronic sequence is expected, similarly, to be an extremely interesting series.

Measurements on Be and B isoelectronic sequences are plagued experimentally with a high metastable content in the ion beams from most ion sources. Those experiments performed to date[19] show the experimental cross sections to be consistently higher than the most complex theories. This result may indicate that some important processes are being ignored in the theories.

The remaining scattered measurements do not lend themselves to such generalizations along isoelectronic sequences. It is noteworthy that the two crossed-beam apparatuses that produced (so far) all of the absolute ionization data for ions over charge 2 are in good agreement on the one measurement where they overlap.[19,22]

Ion-Photon Interactions

Ion-photon interactions are generally difficult to study because of the low intensities of the available ion and photon beams. Some experiments have been done with lasers and beams of up to a few times ionized targets. However, the experiments have not been able to survey ion-photon interactions in any depth. The development of new ion and photon sources now makes possible the extension of the laser results into more general and higher energy studies.

The interesting and new possibilites for research were the subject of a Workshop on Atomic Physics at the NSLS held at Brookhaven September 15-17, 1980.[23] Many variations and extensions of existing atom-photon experiments were suggested by those attending, and several new types of experiment not previously possible were discussed. One of the main topics of the workshop was the physics of ions.

Figure 1 shows the intensity vs. energy curve for the UV, x-ray, and wiggler beam lines soon to be available at the National Synchrotron Light Source located at Brookhaven National Laboratory. The use of undulators will increase the fluxes shown by two to three orders of magnitude. It thus seems certain that many new experiments will be conceived as users become accustomed to the possibilities presented by the powerful new photon source at their disposal.

Multiply-Charged Ion Sources

The production of intense beams of multiply-charged heavy ions is a problem of long standing. The use of conventional ion sources such as the Colutron or PIG type source is warranted for the production of a few times ionized atoms. However, they are not capable of producing very highly charged ions such as Ne^{10+}. It is only within the past decade or so that substantial progress has been made in developing alternate sources.[24]

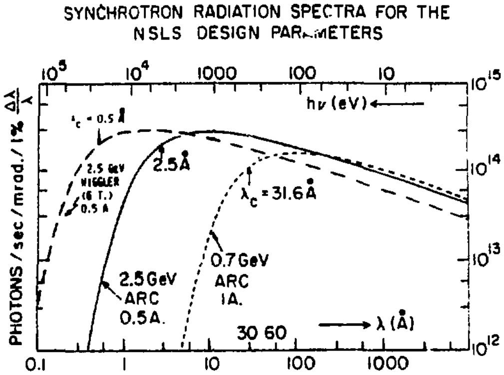

Figure 1. Predicted photon fluxes for the National Synchrotron Light Source: (left to right) Wiggler, X-ray, and VUV beam lines.

Much progress has been made in the development of ion sources which trap ions and raise them to very high charge states by repeated collisions with electrons. Development of the electron beam ion source (EBIS or CRYEBIS) by Donets et al.[25] and Arianer et al. have been very successful in reaching high degrees of ionization, but with currents much too weak for crossed beams experiments. Salzborn and coworkers[22] have used the Giessen EBIS in a DC mode to obtain usable beams up to Ar^{6+}.

Phaneuf et al.[26] have extracted low velocity ions from a laser-induced plasma to measure charge-exchange cross sections. Cocke et al.,[27] using a design adapted from similar work at Aarhus, produce low velocity multiply-charged ions by impact ionization of a target gas by a "hammer" beam from a tandem accelerator. The Micromafios source at Grenoble[28] (a two-stage E.C.R. ion source) produces 30 μA beams up to Ar^{8+} and 200 nA of Kr^{15+}. This source was designed for ease of duplication and low construction and operating costs.

The only practical sources of usable beams of highly-stripped heavy ions are still the conventional accelerators (tandem Van de Graaff, Linac, or cyclotron). The actual beam currents range from nanoamps up depending on the element accelerated and the type of accelerator used. A new use of these machines which holds some hope of opening new areas of research is the accel-decel mode pioneered by Bayfield et al.[29] at Pittsburgh. The BNL Dual MP Tandem Van de Graaff Facility has recently been tested in a four-stage mode to produce 1 nanoamp of 8 MeV S^{16+}.[30]

In summary, new ion source development (or new understanding of old sources) has a strong effect on which ion beam experiments can be performed. It is perhaps more important to have lower charge-state sources which can be inexpensively duplicated than to have a "super-source" which is unique and expensive to operate. The future looks very bright for experiments involving multiply-charged because of the current interest in such experiments and the emphasis on improved ion sources which will make new experiments possible.

BNL Program for Ion-Electron and Ion-Photon Experiments

At Brookhaven we have undertaken a comprehensive program to develop experimental facilities for ion-electron and ion-photon experiments. The work will be based on the use of the Dual MP Tandem Facility as a versatile source of heavy ions and on the use of the National Synchrotron Light Source as a source of high intensity, variable energy photons. While in principle it would be attractive to do beam-beam experiments with the two machines, this is not actually feasible because of the physical separation of the accelerators and the magnitude of the beams available from each. Rather it is necessary to provide a separate source of ions for the photon-ion work and to use electrons for excitation of the beams from the tandem. A schematic of the Brookhaven ion-electron crossed beam apparatus is shown in Figure 2. It is a general-purpose ultra-high vaccum unit for use at the BNL Dual-MP Tandem Van de Graaff Accelerator Facility. This apparatus will allow the study of highly-stripped heavy ions at energies from 10 MeV to 250 MeV. A typical signal count rate for an electron impact ionization experiment, for instance, is about 1 count/second for a 1 ampere 15-keV electron beam crossed with 1 particle-nanoamp of Fe^{18+}. It is instructive to note that this relatively high energy electron beam is just sufficient to remove the outer remaining electron in O-like Fe.

The BNL crossed beams apparatus features an electrostatic charge purifier and separation drift chamber immediately before the ion beam enters the main interaction chamber. The purifier eliminates ions which have undergone charge-changing collisions in the tandem beam line before entering the ultra-high vacuum region. A similar set of charge analysis deflectors immediately following the main interaction chamber allows the position-sensitive detection of all ions, including those which gain or lose electrons in the interaction region. A high-power electron gun, mounted on top of the interaction chamber, is capable of producing a well-focused electron beam of up to 3 amperes at energies up to 20 keV. The main interaction chamber allows easy access for foils, gas jets or cells, or other scattering media. Electron or photon detectors can be mounted in the interaction chamber for electron impact excitation experiments.

The lack of available beam lines and the low expected signal rates have combined to prevent any attempts at ion-synchrotron experiments until recently. A Windowless Gas Phase Beam Line is planned for the VUV ring at the NSLS, and a Research Team has been formed to design an x-ray beam line for atomic physics experiments. One type of experiment that we plan to pursue is the study of the properties of energy levels in elements which are of crucial interest for tokamak construction, such as C, O, Ti, Fe, and Ni. It will be possible in most cases for the first time, to obtain data on the excitation probabilities for these ions to be used in calculating energy losses from tokamak plasmas. Measurements of lifetimes of metastable states in these ions, which are of great interest in astrophysics as well as tokamak diagnostics, will be made possible and convenient for the first time. A particularly attractive thought is to use a storage ring or ion trap at the NSLS for long term (> 1 ns) storage of excited ions so that the decay of metastable states can be determined. It is our belief that research in these and other areas will provide a substantial foundation for an extensive program in atomic physics at the NSLS.

The unique combination of facilities available at Brookhaven gives us an unparalleled opportunity to study atomic interactions involving ions, electrons, and photons. We conclude that atomic physics involving multiply-charged ions is a bright and interesting field for future research because of the recent advances in sources of ions and photons.

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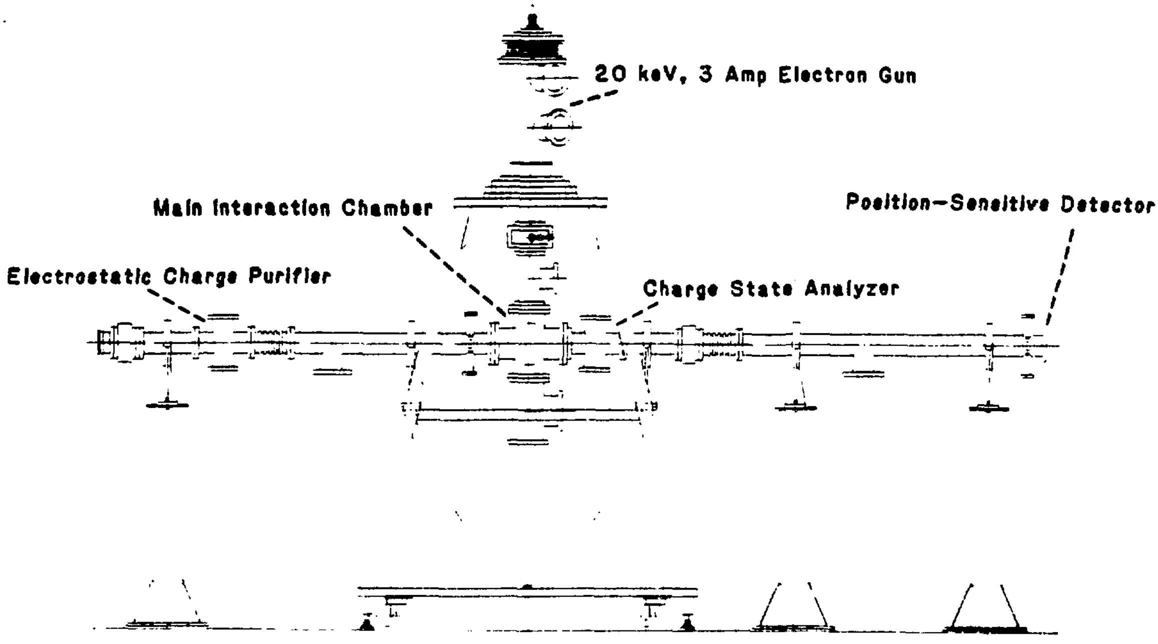

Figure 2. Brookhaven National Laboratory ion-electron crossed beams apparatus

NSLS. The working group summary report by S. T. Manson of Georgia State University was especially useful. We have had several quite informative conversations on the subject of dielectronic recombination with J. B. A. Mitchell of the University of Western Ontario. Figure 1 is used with the permission and cooperation of the National Synchrotron Light Source. This work was supported in part by the Division of Basic Energy Sciences, U. S. Department of Energy, under Contract No. DE-AC02-76CH00016.

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