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Experiments with Highly Ionized Low-Energy Tandem Accel-Decel Beams

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ABSTRACT

The present status of the production of low-energy highly ionized beams by the 4-stage tandem accel-decel method is surveyed, and their use in three atomic physics experiments is summarized. The experiments are: the measurement of the charge state dependence of K-x-ray production in S^{+9} -Ar collisions at 10 MeV, the impact-parameter dependence of quasimolecular x rays in S^{+15} -Ar collisions again at 10 MeV, and the determination of charge transfer cross sections in $S^{+9} + Ar, He$ collisions. The results of the three experiments give evidence that the 4-stage accel-decel ion production technique is extremely powerful and useful.

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1. Introduction

The production of low-velocity highly-ionized atoms is a basic technological problem in atomic physics. Recently developed methods such as the electron-beam, cyclotron resonance, laser-plasma, and ion-recoil sources, have greatly increased the availability of many ion species. These methods are often limited, however, to low intensities, low degrees of ionization, low upper limits of ion energy, or the production of many (not easily separable) charge states. The stripping of high-energy ion beams from Van de Graaff or other types of accelerators is currently the best method for producing fairly intense highly charged ion beams in well-known charge states.

Bayfield, et al.[1] demonstrated that two coupled tandem Van de Graaff accelerators could be operated in a 3-stage accel/decel mode to produce low-energy highly-stripped ion beams and pointed out that 4-stage operation would result in higher beam intensities and reduced low-energy limits. The unique 4-stage accel/decel operation of the Brookhaven Double MP Tandem Facility[2] and a survey of three experiments using S^{3-16+} beams at 6-30 MeV will be described here.

2. Tandem accel-decel production of low velocity multiply charged ions

The 4-stage tandem accel-decel method requires the use of two tandem Van de Graaff accelerators. There are thus only four laboratories in the world, at Brookhaven, the University of Oxford, the University of Pittsburgh, and the University of Washington, where this method could be used. And, at present, only Brookhaven is equipped for using its accelerators in this mode of operation. The Brookhaven machines are MP-type tandems which have been upgraded[3]

with substantial changes in insulating gas, accelerating tubes, charging systems and many other components over their lifetime. The two machines, designated MP6 and MP7, can now run with terminal voltages as high as +12 and -10 MV and as high as +16.5 and -11.8 MV, respectively.

The operation of the double tandem system is as follows. The first accelerator is used as a standard tandem to produce high-energy positive ions. The second tandem, running with a negative terminal potential, receives the ions produced by the first. These ions are thus further accelerated to the negative terminal where they are stripped of more electrons by passage through a foil or gas stripper. Since the highly-stripped positive ions must now return from negative high voltage to ground potential in the last half of the second tandem, a loss of energy occurs. By suitable adjustment of the two terminal potentials, it is possible to effectively use pairs of charge states which produce highly charged ions whose energy can be changed from nearly zero to the maximum energy limit of the tandems in continuously adjustable steps. With the maximum terminal voltages cited earlier, it is now possible to achieve fully stripped beams as heavy as Tl from about 0.1 to 8.0 MeV/amu with beam currents typically in the 10^9 particles/sec range. In the near future it is planned to add a supplemental electrostatic lens at the end of the last accelerating tube to improve the low-energy ion optics. The ion optics of the tube were recently improved by the addition of additional straight sections to reduce low-energy steering of the beam, and the vacuum was improved by installing internal ion pumps[4].

Future possible improvements include the planned use of a velocity selector and an additional stripper foil located between the two accelerators. The ion energies obtainable at the final stripper foil will be much higher and the range of ions which can be fully stripped will be extended. The ultimate maximum charge states that can be expected from the system are indicated in Fig. 1. Of course the actually obtainable ion beams will be strongly affected by the vacuum conditions in the accelerating tubes and beam transport system. However, even with conventional conditions (pressures in the range of 10^{-6} Torr) usable beams are delivered to the target chambers.

3. Experiments with accel-decel beams

The initial experimental program using the accel-decel beams reflects to a certain extent the previous interests and experimental work of the local atomic physics group. Thus, previous interest in the mechanisms involved in the production of inner-shell vacancies stimulated measurement of the charge-state dependence of K x-ray production in symmetric and asymmetric collision systems. The study of quasimolecular x rays has previously been hindered by collision broadening effects and the lack of complete control over the charge state and velocity of the incident ions. The flexibility of the accel-decel process opened new experimental possibilities in this area. Interest in charge transfer processes is naturally related to the inner-shell phenomena since processes in the outer electrons can ultimately lead to production of vacancies in deeper shells. In addition, since charge transfer processes are important for consideration of neutral beam heating of tokamak plasmas, it is

desirable to check theoretical formulations of scaling laws over as wide a range of projectile velocity and charge state as possible. The three experiments mentioned here are thus diverse and illustrative of the wide applicability of accel-decel beams in accelerator-based atomic physics research.

3.1. Characteristic K-x-ray production

The charge state dependence of K x-ray production has been studied in several experiments. An increase in K-x-ray production as vacancies in the L-shell of the projectile were brought into a nearly-symmetric collision had been interpreted as evidence for the existence of a $2p\pi - 2p\sigma$ rotational coupling mechanism. In our previous experiment[5] it was shown that this was also found for very asymmetric collisions where rotational coupling cannot occur. As in the previous experiments, however, the collision velocity was too high to adequately test the validity of rotational coupling predictions. The use of accel-decel beams made it possible to do the experiment at dramatically lower energies where adiabatic collision conditions are more nearly fulfilled.

In the accel-decel experiment[6] 10-30 MeV S^{3-16+} beams were used with thin He and Ar gas jet targets. Electrostatic analysis prior to the collision chamber assured a pure charge state in the incident beam. The results are in agreement with the higher energy experiment. The dependence of x-ray production on charge state is similar for the two target gases, that is, for nearly symmetric and very asymmetric collisions. This confirms the earlier result and again shows that the charge state dependence, although consistent with rotational coupling,

is not in itself confirmation of the process. The differences in the magnitudes of the cross sections are not inconsistent with the differences expected from the Z^2 dependence for the ordinary Coulomb excitation process. The results cited here suggest, as had been previously proposed, that Coulomb excitation to bound states could be the dominant x-ray production mechanism. The importance of fresh theoretical efforts that will give a unified approach to both symmetric and asymmetric collisions is therefore underlined.

3.2. Molecular orbital K-x-ray production

The study of quasimolecular x rays is another way to gain insight into what happens in the collision process. Since these x rays are emitted during the collision rather than in a subsequent de-excitation, they potentially give very direct information on the important mechanisms which produce the x rays. In this experiment[7] a beam of 10 MeV Cl^{+16} ions was used to bombard, under single collision conditions, a differentially-pumped gas cell filled with argon. The x rays were detected in coincidence with ions scattered at laboratory angles from 0.8° to 7.0° . The results thus give the x-ray energy dependence of the x-ray production at a particular impact parameter as well as the impact parameter dependence of production at a given energy. The most immediately striking feature of the spectra is a shoulder and possible peak in the energy spectra obtained for a fixed impact parameter. This is interpreted as the first direct evidence for the oscillations predicted initially by Lichten[8] and considered recently by Anholt[9] which are produced by interference between incoming and outgoing waves in a one-step process producing

quasimolecular x rays. The energy spectrum of x rays produced at an impact parameter of 1200 fm are shown in Fig. 2.

3.3. Charge transfer

Finally, our charge transfer experiment[10] on the $S^{+q} - \text{Ar}$ and He systems is an extension of earlier work including the 3-stage accel-decel experiments[1]. The measurements were again made with a differentially pumped gas cell and electrostatic charge state analysis of the incident and final beams. The final charge state distributions were measured with a position sensitive solid state detector. Measurements were made for charge states from 10-16 and energies from 6-20 MeV. The single electron capture results have been expressed in terms of the universal scaling model developed by Knudsen, et al.[11] and are shown in Fig. 3. The magnitude of the $S^{+q}-\text{Ar}$ data and the trend of the $S^{+q}-\text{He}$ data are in reasonable agreement with the theoretically proposed cross sections. The main point to be stressed is that the use of accel-decel and higher energy beams will make possible in the future an extended probe over a wide range of q and E for a single collision system. Such sensitive searches for deviations from the present theory would stimulate further effort to include shell structure and other effects in the calculations.

4. Conclusions

This survey of experiments that have been done at Brookhaven with accel-decel beams has attempted to delineate the range of ions and energies that can be produced and to show the interesting physics that can be done with their use. It is anticipated that heavy use will be

made of this mode of tandem operation for atomic physics experiments in the future. The accel-decel technique is useful in providing beams of multiply-charged ions at low energies not easily obtained with other sources.

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Figure Captions

- Fig. 1. Maximum charge states as a function of atomic number, Z , for the four-stage accel-decel mode of operation. Curve a is for foil stripping in the high voltage terminals of both machines. Curve b corresponds to having an additional foil stripper between the accelerators. The dashed line indicates fully stripped ions.
- Fig. 2. Energy dependence of x rays produced at an impact parameter of 1200 fm in collisions of Cl^{+16} with Ar. The solid curve is the result of a normalized theoretical calculation by Anholt[7].
- Fig. 3. One electron capture cross sections plotted in the reduced form proposed by Knudsen, et al. [11]. The data are indicated as closed and open circles and the calculations as solid and dashed curves for $\text{S}^{+q}\text{-Ar}$ and $\text{S}^{+q}\text{-He}$, respectively.

Figure 1

Figure 2

Figure 3