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APPLICATIONS OF DECELERATED IONS*

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Abstract

Many facilities whose sole purpose had been to accelerate ion beams are now becoming decelerators as well. The development and current status of accel-decel operations is reviewed here. Applications of decelerated ions in atomic physics experiments are discussed.

1. Introduction

Many studies of atomic collision phenomena benefit from the use of decelerated ions, that is highly-charged, low-velocity ion beams. Most accelerator operations groups seem to understand the constant pressure from experimenters to repeatedly upgrade their facilities to achieve ever higher energies and more reliable high-energy operation, but they may be puzzled by the recent requests from atomic physicists to develop deceleration capabilities. After a brief discussion of the development and current status of accel-decel technology, this paper will address the following questions: Why are decelerated ions useful; what are their applications; and why are so many accelerator facilities beginning to produce them?

2. Accel-Decel Facilities

Accelerator laboratories which already have or plan to implement decelerator operations are listed in Table I. This list is impressive, because the production of decelerated ions with electrostatic

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accelerators was first demonstrated just five years ago at Pittsburgh,[1] where two model EN tandems were coupled in a three-stage configuration. Shortly thereafter improved capabilities were developed at Brookhaven,[2] where two MP tandems were coupled in a four-stage mode. The primary advantage of the four-stage approach is that the last stripping takes place at much higher energies resulting in higher final charge states. Fig. 1 shows schematic representationsof one-, two-, three-, and four-stage operation of the BNL dual MP tandems, and indicates the current four-stage capabilities for S^{16+}. Fig. 2 shows the wide range of charge states and energies available. The versatility of the facility and the development of four-stage operation has been discussed at previous SNEAP meetings[3] and elsewhere.[2,4]

The production of decelerated ions is not limited to electrostatic accelerators. At Heidelberg beams from the MP tandem are slowed down using a portion of the linear accelerator which is normally used as a booster. At GSI most of the UNILAC cavities are used for acceleration, and then a few at the end are detuned to provide deceleration. At Argonne decelerated ions have just recently been produced and at KSU such capabilities are being incorporated into the design of the new facility. Details of the Argonne and KSU operations were discussed by other speakers at this meeting.[5,6]

3. Atomic Physics With Decelerated Ions

Accelerator-based atomic physics experiments are designed to study interacting atomic systems in much the same way that nuclear and elementary particle physics experiments study colliding nucleii. There are, however, important differences. For nuclear and elementary particle studies a certain minimum beam energy is required to produce interesting effects. For example, the Coulomb barrier must be overcome before nuclear excitation, fission, or fusion can occur. In addition small impact parameters are required, that is, the projectile and target nucleii must collide. In contrast, even at very low energies, when two atomic systems interact, a "near-miss" at large impact parameters can cause rearrangement of electron clouds and thereby produce interesting atomic perturbations. In fact low projectile velocities are often desireable, beacause they allow for longer interaction times and afford the opportunity to better study the dynamics of the atomic-collision process.

If low beam energy was our only requirement, conventional ion sources and small accelerators would suffice, but high charge states are also needed. Many atomic collision effects are negligibly small for neutral or low-charge-state projectiles, but are significant and measureably large for higher-charge states. For example, consider electron capture -- the process whereby a projectile ion captures one or more electrons from a target atom. If the beam ion is neutral ($q=0$) or is missing only one electron ($q=1+$), then electron loss is much more likely than electron capture. On the other hand, if the heavy-ion projectile is highly-charged, perhaps even fully stripped ($q= Z+$), then single and even multiple electron capture is highly probable.

Table II lists some recent accel-decel experiments. The scientists who have used decelerated ions at BNL are listed in Table III and brief descriptions of the experiments, including references to more detailed discussions, are given elsewhere.[7,8]

All of the studies indicated in Table II have benefitted from the use of decelerated ions, but the first on the list is by far the most important application. Atomic collisions often knock out inner-shell electrons. If these vacancies are filled by outer-shell electrons after the colliding partners separate, then the emitted x-rays are called "characteristic," but if the vacancies are filled during the time of the collision, then the emitted x-rays are called "quasimolecular." In the molecular orbital model, an ion-atom collision is viewed as the formation of a quasimolecule with electron binding energies changing from atomic values at large internuclear separation to united atom (Z_1+Z_2) vaules in the limit of zero separation. Many experimental approaches were tried to resolve stucture in quasimolecular x-ray spectra, but all of them failed until decelerated ions became available. After the first breakthrough experiment at BNL,[9] subsequent studies[10-12] led to the development of an entirely new field of research: quasimolecular x-ray spectroscopy.

4. Conclusions

Since low energy collisions can produce interesting atomic physics interactions, and highly-charged projectiles can enhance certain effects, decelerated ions are useful to extend the range of previous experimental studies. Furthermore, some experiments such as quasimolecular x-ray spectroscopy are possible only with the use of decelerated ions. The basic atomic physics interest coupled with the atomic data needs of astrophysical and laboratory plasma research account for the widespread development of decelerator capabilities.

Table I. Accel-Decel Facilities.

Pittsburgh (past)	Dual EN Tandem, 3-stage
BNL (Brookhaven)	Dual MP Tandem, 4-Stage
MPI (Heidelberg)	MP Tandem - Linac
GSI (Darmstadt)	Linac
ATLAS (Argonne)	FN Tandem - Linac
KSU (future)	EN Tandem - Linac

Table II. Accel-Decel Experiments.

Quasimolecular X-Ray Spectroscopy	Cl^{16+} + [illegible] S^{15+} + Ar Ge^{31+} + Kr	at BNL at MPI at GSI
Q Dependence of e^- Capture and K X-Ray Production	S^{q+} + He S^{q+} + Ar q=3-16	BNL, Weizmann, MPI, Frankfurt at BNL
K-shell to K-shell Electron Transfer	F^{q+} + Ne q=8,9	KSU, Frankfurt, MPI at BNL
Non-Resonant Electron Transfer and Excitation	S^{13+} + Ar	WMU, NUU, UNC, LBL, Wesleyan, BNL at BNL
e^- Impact Ioniz.	A^{q+} + e^-	BNL
Transfer Ioniz.	F^{q+} + He	MPI, BNL

Table III. Users of BNL Accel-Decel Beams.

B.M. Johnson, K.W. Jones, M. Meron	BNL
R. Schuch	Heidelberg
I. Tserruya	Weizmann
H. Schmidt-Böcking, S. Kelbch	Frankfurt
J. Barrette	BNL, Saclay
S. Hagmann, C.L. Cocke P. Richard, T.J. Gray	KSU
J.A. Tanis, E.M. Bernstein	WMU
W.G. Graham	NUU
M. Clark, S. Shafroth	UNC
R.H. McFarland	LBL
T.J. Morgan	Wesleyan

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