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Atomic Physics with Relativistic Ion Beams, Using the Brookhaven 200 MeV Linac and 1.5 GeV Booster Synchrotron*

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A survey of atomic physics experiments with relativistic ion beams at the Brookhaven Neutral Beam Test Facility is presented and special techniques using 150 m flight paths and precision particle and laser beam optics are described.

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1. Basic Technique.

Intersecting laser and relativistic ion beams provide a technique for producing precisely controlled electronic excitations within the ions. The technique utilizes the relativistic Doppler shift to tune the photon frequency, as seen in the particle rest frame, through adjustment of the crossing angle between the beams. The frequency ν_{CM} in the ion center of mass is related to the laser frequency ν by

$$\nu_{CM} = \nu\{\gamma - (\gamma^2 - 1)^{1/2}\cos\phi\}$$

where γ is the ratio of the total particle energy to its rest mass and ϕ is the crossing angle. Good energy resolution is obtained when ϕ is well defined, requiring both laser and particle beams to exhibit low divergence. Typically, a fixed frequency laser system may be chosen to maximize the available intensity and optimize the laser beam quality, while commanding a continuously variable frequency range $\nu_{CM}(\text{maximum})/\nu_{CM}(\text{minimum}) = \{\gamma + (\gamma^2 - 1)^{1/2}\}/\{\gamma - (\gamma^2 - 1)^{1/2}\} \simeq 14$ for for 1.5 GeV/amu ions and crossing angles $\phi = 0$ to π.

When the highest possible energy resolution is required, it may be desirable to eliminate the effect of a spread in γ, due to any momentum dispersion the particle beam may have, by choosing a fixed crossing angle $\phi = \cos^{-1}(1 - 1/\gamma^2)^{1/2}$. At this angle $\nu_{CM} = \nu/\gamma$ exhibits a minimum sensitivity to small spreads in γ. In this case the correct frequency for a particular transition can be obtained through choosing the appropriate particle energy.

2. Techniques Developed at the Neutral Beam Test Facility (NBTF).

The NBTF complex has been operated for three years using 200 MeV H^- beams from the Brookhaven linac. Average currents of up to 30 mA over 500 μs long macropulses at a repetition frequency of 5 Hz are available. These macropulses have a 200 MHz microstructure of 1ns pulses. Special experimental equipment already in place at the NBTF includes the following:

(a) 160 m tunnel and 25m experimental hall with radiation-shielded clean room for laser

(b) high quality magnetic telescope supported by anti-vibration monuments for jitter-free microradian divergence particle beam formation

(c) 150m flight path in 30cm diameter beam tube with 10^{-7} torr vacuum; large vacuum vessels for experimental equipment

(d) vertical monument platforms for mounting critical in-vacuum components independently of the vacuum envelope

(e) microradian beam diagnostics

(f) high power, high resolution (3MHz), tunable dye laser system with associated microradian optics, interferometers, vacuum-ultra-violet (VUV) detectors.

It is planned to connect the Brookhaven Booster Synchrotron (expected commissioning 1991) to the NBTF line to extend the available range of ions from hydrogen to include species across the entire periodic table at energies up to 1.5 GeV/amu.

The long flight path in the NBTF tunnel provides the opportunity to measure small angle scattering from large impact-parameter collisions with unprecedented accuracy. For example, the angular distribution of hydrogen atoms due to transverse momenta, introduced in the stripping of an electron from 200 MeV H^- ions in the passage through a thin carbon foil, has been measured with sub-microradian accuracy [1,2]. In a subsequent laser resonance fluorescence (LRF) experiment, the 2S population induced in a neutral hydrogen beam (produced by foil-stripping of 200 MeV H^- ions) was pumped to the 3P levels, followed by observation of the VUV photons from the 3P-1S decay [3].

For the LRF experiment, precision beam optics and charge-change stripping ahead of the final dipole magnet pair, produced a parallel particle beam with an extremely sharp cross-section profile. Together with a beam dump, located 100m downstream from the laser interaction point, these precautions reduced the stray radiation background in the experimental hall to ambient (beam off) levels, allowing sensitive photon detectors to be employed within close proximity of the beam.

It is expected that the unique facilities available at the NBTF will provide opportunities to expand the atomic physics program to cover a wide range of new experiments that could not be contemplated elsewhere. In particular it will be possible to address experiments that cannot be done at heavy-ion storage rings, either because of the geometric constraints imposed by limited access to beams circulating in storage rings or because high precision is required.

3. Experiments that could be done at the Neutral Beam Test Facility.

As an immediate follow-up experiment to the LRF work already completed at the NBTF, a high resolution (3MHz) 2S-3P excitation in hydrogen could be achieved, using the tunable ring dye laser. Such high resolution would provide a unique opportunity to perform an atomic physics analogue of time-resolved Mössbauer spectroscopy [4]. Of particular interest would be measurements on free atoms, in contrast to Mössbauer spectroscopy in which solid state effects of the lattice necessarily play a complicating role. The simultaneous measurements of the excitation energy and the decay time via the relativistic decay length, allows the determination of possible non-linear terms in the uncertainty relations.

Turning from this specific example to more general classes of experiments that could be performed when ions from the Booster Synchrotron become available, it is of interest to note the scope of basic laser excitation techniques as illustrated in the following example. Consider the excitation of the 2S-3P transition of hydrogen-like ions which emerge from a stripper with 2S excitation. Using a F_2(157nm) laser, excitations with single and multiple photons require:

H up to Be:	1 photon
Be up to C:	2 photons
F:	5 photons
Cu:	50 photons

Detailed experiments utilizing the continuous angle tuning can be performed via higher multiplicity multi-photon excitation and ionization, using lower frequency lasers offering the highest attainable intensity. A whole range of experiments in this category would be of great interest in constructing a data- base for unravelling the complex phenomena encountered in high temperature plasmas.

Other possible investigations could be the study of excitations during femtosecond transit times as relativistic ions pass through a tightly focussed laser beam. Photoabsorption over a few optical cycles can be observed in this way. Very large atomic level splitting can be examined through magnetically induced electric fields. The electric field E_{CM} in the particle rest frame, for a static magnetic field B, is given by:

$$E_{CM} = cB(\gamma^2 - 1)^{1/2}.$$

For ions of energy 1GeV/amu passing through a field of 18T this implies $E_{CM} = 10^{10}$ V/m. It should be noted that such experiments are not practical at ion storage rings.

Collective effects associated with atomic electron correlations can be examined via one photon – many electron excitations. A completely new technique, extending this concept to collective excitation of all electrons within an atom by identical amounts, is offered by neutron induced X-ray emission measurements [5]. Neutron scattering on the nucleus of a free atom leads to momentum transfer to the nucleus in a time of order 10^{-23} to 10^{-22}s.

The electrons are not affected by the passage of the neutron through the atom (except for perturbations of order of hyperfine splittings) and remain within orbital shells which are at rest. Only when the recoil motion of the nucleus has had time to generate a non-central atomic Coulomb field, do the electrons respond. It is evident that the excitation enery E^* of the atom is given by:

$$E^* = E_R Zm/M$$

where E_R is the recoil energy imparted to the nuclear mass M and Zm is the total mass of the electrons. At recoil energies of 10–15 MeV for medium mass atoms, the nucleus has a high probability of staying intact, while the equal division of excitation energy among all the electrons prevents immediate ionization. Subsequent intra-atomic relaxation processes can of course lead to multiple auto-ionization. Of greater interest might be the observation of collective deexcitation via photons in the X-ray energy region. A simple and elegant experimental configuration would make use of the linear relation between E^* and E_R by stopping the recoil atom in a particle detector with good energy resolution. X-ray detection from collective deexcitation can take place during the atoms flight from the target to the detector. Neither the neutron energy nor the scattering angle need be known since atomic excitation is determined by E_R. However, it is essential to have a windowless gas target since free atoms are required so that ionization collisions do not destroy the collectively excited atom. The NBTF is equipped with a differentially pumped gas jet target and neutron beams of small cross section can be tailored by installation of suitable shielding. Neutron production via the p,n reaction has been routinely available in the facility.

4. Summary and Conclusions.

Experiments on small angle scattering and laser resonance fluorescence with 200 MeV hydrogen beams at the NBTF have substantially advanced the state of the art in these fields. Unique techniques already developed at the facility, together with the wide range of relativistic ion beams that will become available from the Brookhaven Booster Synchrotron, offer the opportunity to extend the frontiers of atomic physics.

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