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DIELECTRONIC RECOMBINATION MEASUREMENTS ON MULTICHARGED IONS

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Our efforts are directed principally at the measurement of dielectronic recombination in multiply charged ions. To do this, we chose a merged beam approach to take advantage of our ability to produce high charge state, MeV/amu ions and a high current, high energy (1-3 keV) electron beam. The merged beam apparatus (outlined in Fig. 1) is constructed such that in the interaction region the ion beam is coaxial with and embedded within the electron beam for a distance of 84 cm.

The ion beam from the ORNL EN-tandem accelerator enters the interaction region through an axial, 0.64 mm

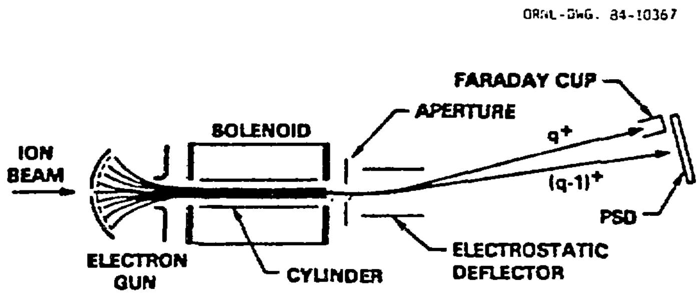

FIGURE 1. Schematic Diagram of Merged Beam Apparatus

diameter hole in the cathode of the electron gun. After exiting the interaction region, the ion beam is subjected to charge state analysis. In our earlier work, we used magnetic deflection; in our more recent efforts, we use electrostatic deflection. The initial charge state of the ion beam, q+ is deflected into a Faraday cup. The cup is connected to a current integrator and the output pulses are counted by a scaler. Ions that have picked up an electron (charge = (q-1)+) are deflected onto a solid state position sensitive detector (PSD). The ions having charge (q-1)+ arise from electron pickup of the q+ ions from the residual gas, slit edge scattering, and the sought after effect, DR.

The source of the electron beam is a double gridded Pierce-type high-intensity electron gun which is designed to produce a convergent, laminar electron beam. The gun is operated in the space charge limited mode where the space charge limited current, I_c, is given in terms of the cathode to anode voltage, V_c, by $I_c = PV_c^{3/2}$. The constant P (the "perveance") is determined by the electrode geometry and here equals 10^{-6}. The electron gun is magnetically shielded from the solenoidal field of the interaction region. The emerging electron beam comes to a focus ~ 7 mm from the anode where it has a diameter (containing 95% of the beam) of 3.15 mm. It enters a coaxial solenoidal magnetic field which is adjusted to establish Brillouin flow (e.g., ~ 0.18 T for 1 keV electrons) in which the beam radius stays constant and the beam rotates as a solid of revolution about its axis with the Larmor frequency, ω_L. Under Brillouin flow, the longitudinal velocity of an electron is independent of radius, the radial velocity is zero, and the azimuthal velocity is equal to ω_L times the radial position of a particular electron. Surrounding the electron beam is a coaxial cylinder 84 cm long having an inside diameter of 7.9 mm, which is normally electrically grounded. Following the interaction region, defined by the length of the coaxial cylinder and the solenoidal field, the electrons expand (due to space charge repulsion) and strike the chamber walls.

The experimental procedure consisted of optimizing the electron beam, at a particular V_c, and counting the $A^{(q-1)+}$ and A^{q+} beams while stepping through the relative energies of interest by changing the energy of the ion beam. This optimization was carried out by adjusting the orientation of the solenoid and the cylinder and making small adjustments to the solenoidal field such that the current to the cylinder was a minimum ($<0.01\ I_c$). It was then verified by observing the position spectrum while switching the electron beam on and off that the electrostatic field, due to the electron space charge, produced no steering of the ion beam. We believe that minimum ion beam steering indicates minimum misalignment between the ion and electron beams. The deviation of the ratio, R, of (q-1)+ ions to q+ ions from a monotonic trend with ion beam energy gives a measure of the DR cross section. In Fig. 2, we plot this ratio for two ion energy "sweeps" of a B^{2+} beam (14-18 MeV) merged with the electron beam. In the first sweep, V_c = 1022 V (solid squares); in the second sweep V_c = 1079 V (open circles). The lines through the data in Fig. 2 are to guide the eye. It can be seen that the DR signal shifts to higher ion energies as the electron energy is increased, i.e., the signal depends on the relative energy. To emphasize this point further, we plot this ratio, in Fig. 3, for the two B^{2+} sweeps versus the relative energy, E'_{rel} . In Fig. 4, this ratio is plotted for a C^{3+} beam (17.5 - 23 MeV) merged with an electron beam at V_C = 1079 V. The backbackground ratio, R_B, can be fitted by a monotonic trend

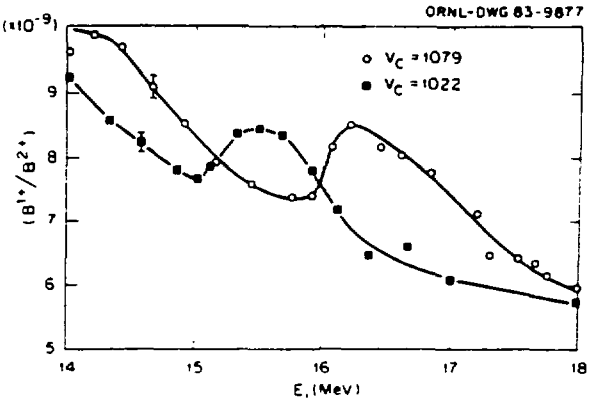

FIGURE 2. Ratio, B^{1+}/B^{2+}, as a function of B^{2+} ion energy for V_C = 1022 V (solid squares and V_C = 1079 V (open circles).

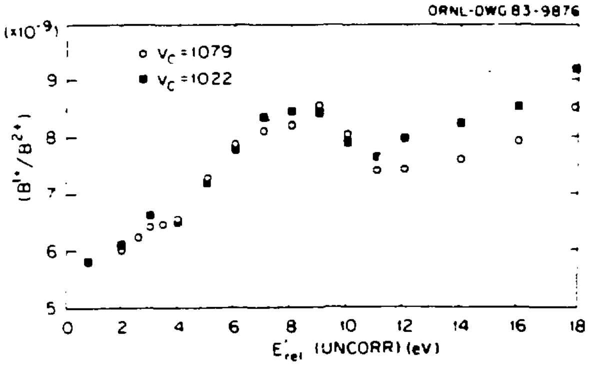

FIGURE 3. Ratio, B^{1+}/B^{2+}, vs. relative energy. For potential drop correction to the relative energy scale.

line as in Fig. 4. Subtracting R_B from R yields the signal ratio R_S. R_S is related to the DR cross section σ, by

$$R_S = \left(\iint v_r\sigma(v_r)\rho_e(v_r)\rho_i dv_r dV\right)/\int \rho_i v_i dA$$

where ρ_e is the electron density, ρ_i is the ion density, v_r is the relative velocity, v_i is the velocity of the ions, and V and A are the volume and cross sectional area of the interaction region, a cylinder whose radius is that of the ion beam r_i, and having the length of the electron beam, L. Since ρ_i and v_i are constant within V,

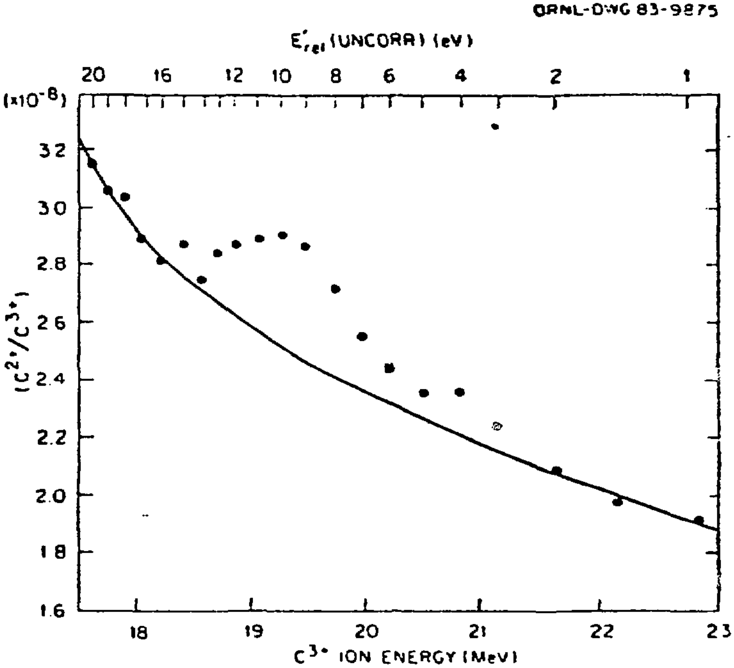

FIGURE 4. Ratio C^{2+}/C^{3+} as a function of C^{3+} ion energy for V_C = 1079 V. For potential drop correction to the relative energy scale, see Ref. 1.

the ion current $I_i = \int \rho_i v_i dA = \rho_i v_i A$. Approximating ρ_e by an average electron density $\bar{\rho}_e$, times a distribution in relative velocities $f(v_r)$, both being independent of position within V, we can write, $R_s = (\bar{\rho}_e L \langle v_r \sigma \rangle)/v_i$, where the triangular brackets denote the average over $f(v_r)$. Thus, from the measured quantities we can calculate $\langle v_r \sigma \rangle$ at every ion energy or relative energy, i.e., $\langle v_r \sigma \rangle = R_s v_i / \bar{\rho}_e L$.

The best possible resolution in relative energy for this cathode configuration would be $\gtrsim 2$ eV; about 0.5 eV arising from the non-zero radius of the ion beam in the space charge limited electron beam and ~2 eV from the cathode temperature (~ 1400°K) coupled with a compression factor of ~16.

In our first reported measurements,[1] we arrived at our signal level by simply subtracting a smooth extrapolated background drawn under the resonance region. This treatment indicated a resolution of ~3 eV, but subsequent improvements in measuring technique have shown this to be overly optimistic.

Our gun contains a gridded cathode; the initial idea was to modulate the electron beam to determine the background. This technique did not prove feasible because turning the electron beam on and off modulated the background gas density and gave rise to a large spurious signal even at energies where signals were not physically possible.

An alternative scheme has proved more successful. Here we modulate the voltage applied to the guide tube surrounding the merged beam region. For half the time the tube is grounded and for the other half the tube is raised in voltage such that the electron beam energy is shifted to be off resonance. The result of such an experiment is shown for S^{5+} in Fig. 5. Several jumps appear in the data which are much beyond the range of statistical error. These jumps probably occur because of slit edge scattering which may vary somewhat with ion beam steering at different energies. (Note that in our configuration the ion beam may be scattered at the narrow entrance aperture in the cathode.) These "jumps"

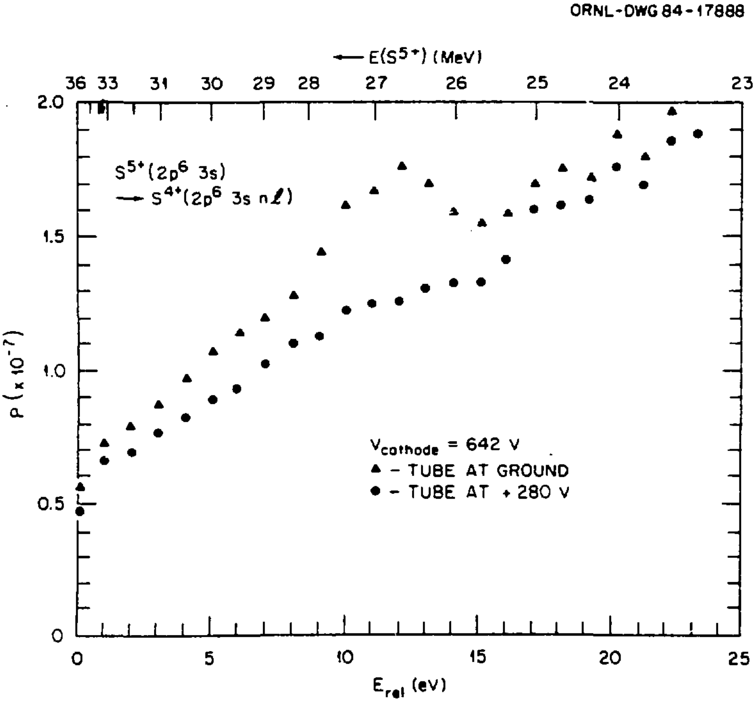

FIGURE 5. Ratio (S^{4+}/S^{5+}) as a function of S^{5+} ion energy (top) and relative energy (bottom) for a 617 eV merged electron and ion beam. The lower curve shows the effect of the offset in electron beam energy at the same ion energy.

disappear when we plot the difference signal as in Fig. 6. The effect of residual background modulation is seen in the non-zero level in the 16 to 24 eV region and may be subtracted to give the final signal values. The consistency of this method may be seen in Fig. 7 where we have plotted the rates ⟨vσ⟩ derived from such measurements for C^{3+} ions. The round points were determined with an electron beam moving slower than the ion beam (lab system), the square points from measurements where the electron beam was moving faster than the ion beam (lab system). Here, the observed peak is asymmetric with

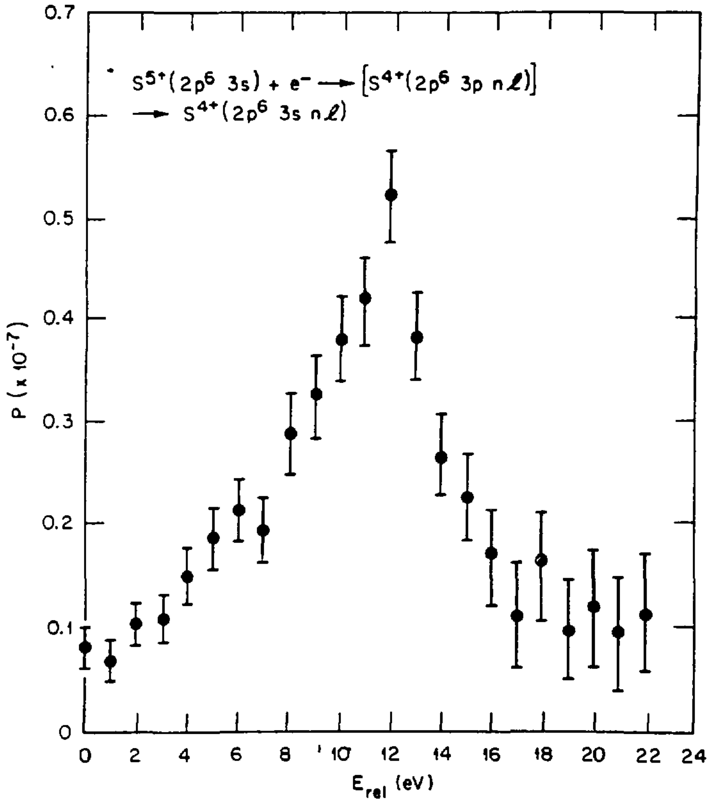

FIGURE 6. Difference signal of (S^{4+}/S^{5+}) ratio from Fig. 5.

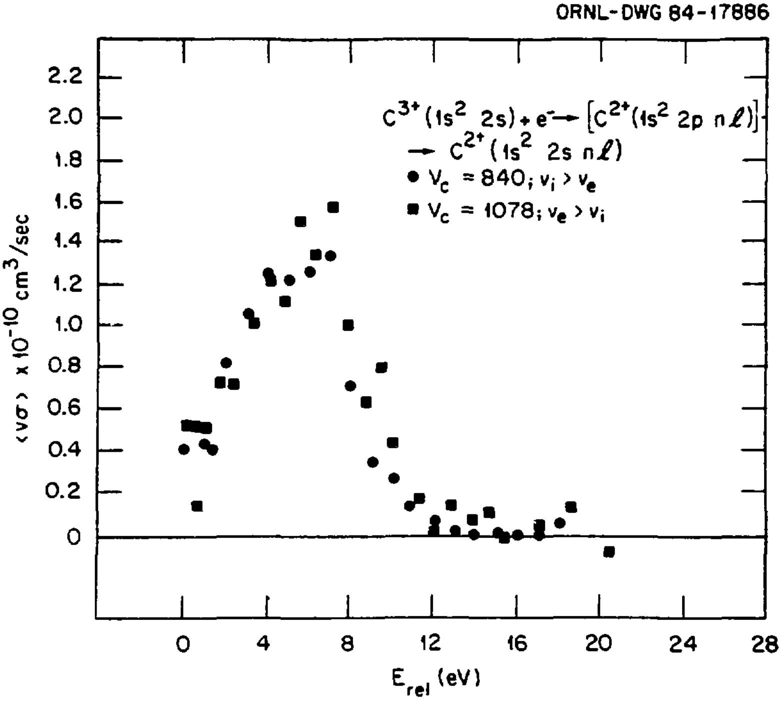

FIGURE 7. Measured rates ($\langle v\sigma \rangle$) for C^{3+} DR as a function of relative energy for: ■ ion velocity greater than electron velocity, and ● ion velocity lower than electron velocity.

a full width of ~6 eV (+2, -4). For C^{3+}, we expect a very sharp peak (almost a δ function on our scale) at 7 eV.[2] The observed spread around 7 eV is due to electron beam energy resolution. Using a two-parameter fit, one describing the longitudinal and the second the transverse distribution, we find we are able to fit the rates. The same two parameters fit for all the ions used (C^{3+}, O^{5+}, P^{4+}, S^{5+}, and Cl^{6+}) thus giving us some confidence that we have now characterized our electron beam.

The theoretically predicted probability of recombination observed in these experiments depends on the electric fields present in two regions: first, the electron-ion interaction region and second, the charge analysis region.

The electric fields in the charge analysis region can Stark strip Rydberg states formed in the electron-ion interaction. The maximum n state that can survive these fields is given by

$$n_{max} \approx (6.31 \times 10^8\ q^3/E)^{1/4}$$

where q is the core charge and E is the field in volts per cm. In our first experiments[1] we used a magnetic field of 0.1 T to separate the charge states of ions moving at ~2 MeV/u. This corresponds to a field of ~40 kV/cm so that for C^{3+} the highest surviving state is $n_{max} = 26$. Our more recent experiments use electrostatic deflection fields of ~4 kV/cm corresponding to $n_{max} = 44$ and indeed we observe a factor of 1.8 increase in C^{2+} signal at the peak under these conditions.

Less well understood is the effect of small fields in the interaction region which mix ℓ states for a given n and increase the DR cross section. This effect is extensively discussed in the paper by Griffin, Pindzola, and Bottcher,[3] contained in these proceedings. They calculate the increase in the effective DR cross section which would be obtained with complete Stark mixing of states. In our work we find that, for the Na-like ions P^{4+}, S^{5+}, and Cl^{6+}, the measured rates are intermediate between the no mixing and total mixing predictions while for the Li-like C^{3+} and O^{5+} complete mixing seems a better fit. Exact calculations for specific field conditions remain to be done.

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