Magnetic Field Enhancement of Dielectronic Recombination from a Continuum of Finite Bandwidth

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We have examined dielectronic recombination of Ba^+ and e^- from a continuum of finite bandwidth. Applying magnetic fields of up to 240 G perpendicular to small electric fields from 0.1 to 5 V/cm increases the recombination rate, while applying the magnetic field parallel to the electric field does not change the rate. The largest magnetic field enhancement observed was approximately 50%.

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Dielectronic recombination (DR), a form of radiative recombination, is the capture of an electron by an ion via an intermediate autoionizing state [1]. It is the most efficient recombination mechanism available to energetic electrons, and it is important in high temperature laboratory and astrophysical plasmas [1]. Since DR is, in essence, the inverse of photoionization, it is perhaps surprising that it is quite sensitive to very small external fields, but the origin of this sensitivity can be easily understood. The total, or energy integrated, DR rate is the sum of the DR rates through all the autoionizing states. If we use Ba as an example, the most important autoionizing states for DR are those converging to the $6p$ state of Ba^+. DR of a ground state Ba^+ $6s$ ion and an electron through one $6pn\ell$ state can be thought of as the two-step process

$$\mathrm{Ba}^+\ 6s + e^- \rightarrow \mathrm{Ba}\ 6pn\ell \rightarrow \mathrm{Ba}\ 6sn\ell + h\nu\,. \tag{1}$$

We follow the convention that n, ℓ, and m are the outer electron's principal, orbital angular momentum, and azimuthal angular momentum quantum numbers. In essence, the incoming electron excites the Ba^+ ion and is captured, forming the autoionizing Ba $6pn\ell$ Rydberg state. If this state decays radiatively to the bound $6sn\ell$ state, as opposed to autoionizing, DR has occurred.

The DR rate, $\Gamma_{n\ell}$, through one Ba $6pn\ell$ state, i.e., the rate for the process of Eq. (1), is the product of the electron capture rate into the $6pn\ell$ state and the branching ratio for radiative decay to the bound $6sn\ell$ state. Explicitly,

$$\Gamma_{n\ell} = \beta A_{n\ell}\frac{A_R}{A_{n\ell} + A_R} \approx \beta A_<\,. \tag{2}$$

Here $A_{n\ell}$ is the autoionization rate of the Ba $6pn\ell$ state, β is a constant, and by detailed balance $\beta A_{n\ell}$ is the capture rate into the Ba $6pn\ell$ state. A_R is the radiative decay rate of the process Ba $6pnd \rightarrow$ Ba $6sn\ell$, which is the Ba^+ $6p$ radiative decay rate and is independent of n and ℓ. $A_R/(A_{n\ell} + A_R)$ is the branching ratio for radiative decay. If we define $A_<$ as the lesser of A_R and $A_{n\ell}$, it is clear that to a good approximation $\Gamma_{n\ell} \approx \beta A_<$. Autoionization rates decrease as n^{-3} and even more rapidly with ℓ, and the bulk of the total DR rate comes from $6pn\ell$ states for which the autoionization rate exceeds the radiative decay rate, $A_{n\ell} > A_R$. We term these the contributing states. Setting $A_{n\ell} = A_R$ also gives an estimate for the highest value of n, n_u, which is important. Using the average rates of the $\ell \leq 4$ rates we estimate that $n_u = 280$. Irrespective of its autoionization rate, each of the contributing states makes the same contribution, $\Gamma_{n\ell} \approx \beta A_R$, to the total DR rate. A reasonable estimate of the total DR rate integrated over incident electron energy is obtained by simply counting the contributing states. Simply counting states ensures that the Rydberg states play a central role in DR.

Since Rydberg states are easily perturbed, it is not surprising that small external perturbations have significant effects on DR rates. Burgess and Summers [2] pointed out that in any but the most dilute plasmas electron collisions rapidly redistribute ℓ values, leading to an increased DR rate. Jacobs *et al.* [3] pointed out that the quasistatic electric microfields from the plasma ions would also raise the DR rate. To see why a small $\overline{E}$ field raises the DR rate we note that over most of the relevant energy range $A_{n\ell} \gg A_R$ for low ℓ states, while for high ℓ states the reverse is true. Consequently, in zero field low ℓ states contribute to DR, but high ℓ states do not.

The effect of a small $\overline{E}$ field is to convert the zero field $6pn\ell m$ states into $6pnkm$ Stark states with the same n and m. Each of the Stark states contains low ℓ character and, to a reasonable approximation, has the average autoionization rate of all ℓ states of the same n and m. This rate typically exceeds A_R, so the effect of the field is to convert the high ℓ states to Stark states which contribute to the DR rate. An electric field does not mix m states, so high m states still do not contribute to DR in an electric field. As pointed out by Robicheaux and Pindzola [4], a magnetic field perpendicular to the electric field creates states which are mixtures of m states, and by this mixing the high m states can be given high enough autoionization rates to contribute to DR. For fields low enough that diamagnetism can be neglected we would expect a magnetic fixed parallel to the electric field to have no effect. As shown by LaGattuta and Borca [5], DR in combined $\overline{E}$ and $\overline{B}$ fields is complex. They calculated DR rates for $Mg^+ + e^-$ and found a nontrivial dependence on the angle between $\overline{E}$ and $\overline{B}$ [5].

While the importance of DR is in plasmas, the most illuminating measurements of DR have come from beam

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experiments. In fact, these measurements have shown the importance of small external fields. Using crossed Mg^+ and e^- beams Belic *et al.* [6] observed a DR signal 5 times higher than expected from an earlier calculation [7]. The discrepancy largely disappeared when the motional electric field due to the magnetic field in the apparatus was taken into account [8]. Recently, using a storage ring Bartsch *et al.* [9] have shown that a magnetic field alters the DR rate. Specifically, they have shown that as the magnetic field is increased from 200 to 650 G, the DR rate for $Cl^{14+} + e^-$ decreases.

In all the beam experiments done to date there has been a magnetic field, making it difficult to isolate the effects due to fields. Here we report the enhancement of DR from a continuum of finite bandwidth [10] by a magnetic field $\overline{B}$ perpendicular to an electric field $\overline{E}$. With this approach we can have arbitrarily small $\overline{E}$ and $\overline{B}$ fields, and we have observed, for the first time, the predicted magnetic field enhancement of the DR rate. In the following sections we describe DR from a continuum of finite bandwidth and present and discuss our experimental results.

The essential notion of a continuum of finite bandwidth is most easily understood by considering our experiment. As shown in Fig. 1, the continuum of finite bandwidth is the broad autoionizing $6p_{3/2}11d$ state which straddles the Ba^+ $6p_{1/2}$ limit. We excite Ba atoms from the ground state to a well-defined energy in the continuum of finite bandwidth using three 5 ns dye laser pulses via the route $6s^2 \rightarrow 6s6p \rightarrow 6s11d \rightarrow 6p_{3/2}11d$, as shown in Fig. 1.

In a classical view of the $6p_{3/2}11d$ state the outer $11d$ electron makes roughly 20 orbits before it is inelastically scattered by the Ba^+ $6p_{3/2}$ core and autoionizes. If the electron induces the Ba^+ $6p_{3/2} \rightarrow 6s_{1/2}$ dipole transition autoionization occurs, while if it induces the Ba^+ $6p_{3/2} \rightarrow 6p_{1/2}$ quadrupole transition it is captured into the degenerate $6p_{1/2}nd(ns)$ state. Once in the $6p_{1/2}nd(ns)$ state the atom can either autoionize, directly or via the $6p_{3/2}11d$ state, or radiatively decay to the bound $6s_{1/2}nd(ns)$ state. The latter completes DR, and we detect by field ionization those atoms which have radiatively decayed to the bound $6s_{1/2}n\ell$ states.

The central features of the apparatus are shown in Fig. 2. An atomic beam of Ba effuses from a resistively heated source, is collimated, and passes down the axis of four brass rods. The 0.24 cm diameter rods are 1.00 cm apart vertically and horizontally. By applying voltages to the upper and lower pairs or to the left and right pairs we can produce horizontal or vertical $\overline{E}$ fields. The three laser beams are counterpropagating to the atomic beam along the axis of the four rods. We detect that DR has occurred by applying a vertical 100 V/cm field pulse 200 ns after the laser excitation and collecting only those electrons produced by field ionization. There are, of course, many more electrons due to autoionization, but they appear immediately after the laser pulse. The magnetic field coils of Fig. 2 have 54 turns, are 2.54 cm in radius, and are

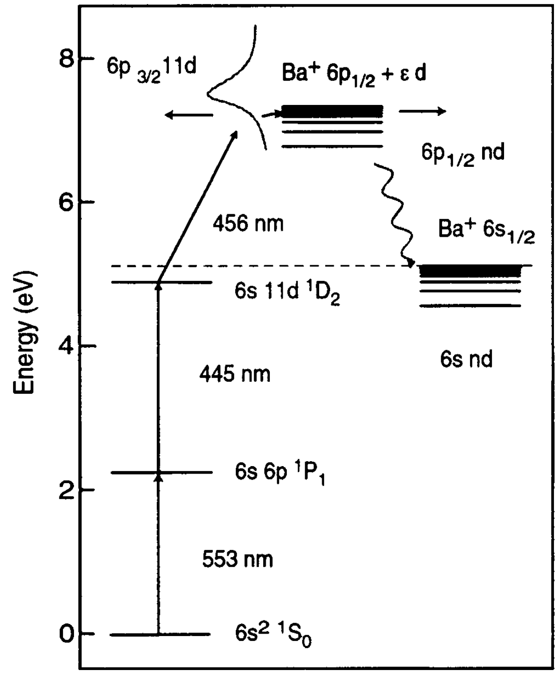

FIG. 1. Energy level diagram. Three dye lasers are used to drive the transitions from the Ba $6s^2$ ground state to the $6p_{3/2}11d$ state, the continuum of finite bandwidth. From the continuum of finite bandwidth the $11d$ electron can either autoionize into the true continuum or be captured into the degenerate $6p_{1/2}nd$ state, as shown by the horizontal arrows. If capture occurs, the $6p_{1/2}nd$ state can either autoionize, as shown by the horizontal arrows, or decay radiatively to the bound $6snd$ state. In the latter case dielectronic recombination has occurred, which we detect by field ionization of the bound $6snd$ Rydberg states.

2.54 cm apart. The $\overline{B}$ field is produced by discharging a 5 μF capacitor through the coils, producing a current pulse 100 μs long with a peak current of 14.7 A, leading to a peak magnetic field of 240 G, which we have calibrated using a gaussmeter. The laser is fired at the peak of the magnetic field pulse. The presence of a magnetic field increases, slightly, the detected electron signal. We have measured the increase by exciting and detecting bound $6snd$ Rydberg states with and without the $\overline{B}$ field. The

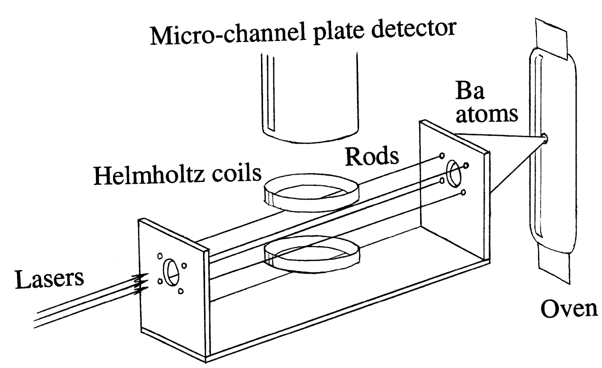

FIG. 2. Diagram of the interaction region of the apparatus.

increase of the detected signal can be described by the factor $\gamma = 1 - 2.5 \times 10^{-5}B + 4.5 \times 10^{-6}B^2$, where B is expressed in gauss.

In Fig. 3 we show DR signals recorded by scanning the frequency of the third laser of Fig. 1 with $E = 0.5$ V/cm and $B = 240$ G with $\overline{B} \parallel \overline{E}$ and $\overline{B} \perp \overline{E}$. The energy scale is relative to the Ba^+ $6p_{1/2}$ limit. Not shown are the data for $B = 0$, which are identical to the $\overline{B} \parallel \overline{E}$ data when corrected by γ. When $\overline{B} \parallel \overline{E}$ adding the $\overline{B}$ field does nothing, as expected, since adding the $\overline{B}$ field does not change the symmetry and mix m states. It is quite apparent in Fig. 3 that there is a clear difference between $\overline{B} \perp \overline{E}$ and $\overline{B} \parallel \overline{E}$ and that $\overline{B} \perp \overline{E}$ produces an obvious enhancement of the DR rate.

If we integrate the signal $S(\overline{B}, \overline{E}, W)$ for a given $\overline{B}$ and $\overline{E}$, such as those of Fig. 3, over binding energy W we can define a magnetic field enhancement factor

$$R(\overline{B}, \overline{E}) = \frac{\int S(\overline{B}, \overline{E}, W)\, dW}{\int S(0, \overline{E}, W)\, dW}. \tag{3}$$

By repeating the scans leading to Fig. 3 for different combinations of $\overline{B}$ and $\overline{E}$ fields we can determine the $\overline{E}$ and $\overline{B}$ dependence of $R(\overline{B}, \overline{E})$, and in Fig. 4 we show plots of $R(\overline{B} \parallel \overline{E})$ and $R(\overline{B} \perp \overline{E})$ as a function of B for $E = 0.5$ and 2.0 V/cm. $E = 0.5$ V/cm is chosen because the DR rate in an $\overline{E}$ field alone attains its maximum at this value [11,12].

In Fig. 4 we can see explicitly that there is no enhancement with $\overline{B} \parallel \overline{E}$ and a clear enhancement with $\overline{B} \perp \overline{E}$. The lines in Fig. 4 are fits of the data to third order polynomials in B. With $E = 0.5$ V/cm the fit enhancement factor reaches a maximum of 1.51(2) at 190 G. In contrast, at $E = 2$ V/cm the maximum enhancement factor is only 1.38(2), and it does not occur until 205 G. The stated uncertainties are statistical. We estimate the systematic uncertainties to be comparable.

As shown by Fig. 4, adding the perpendicular magnetic field enhances the DR rate, by roughly a factor of 1.5, as calculated by Robicheaux and Pindzola [4]. Also in agreement with the calculations, and equally important, the enhancement factor reaches a maximum, the location of which depends on $\overline{E}$, and declines as $\overline{B}$ is further increased. While it is not immediately apparent that the maximum B field enhancement factor should be 1.5, it is clear that there

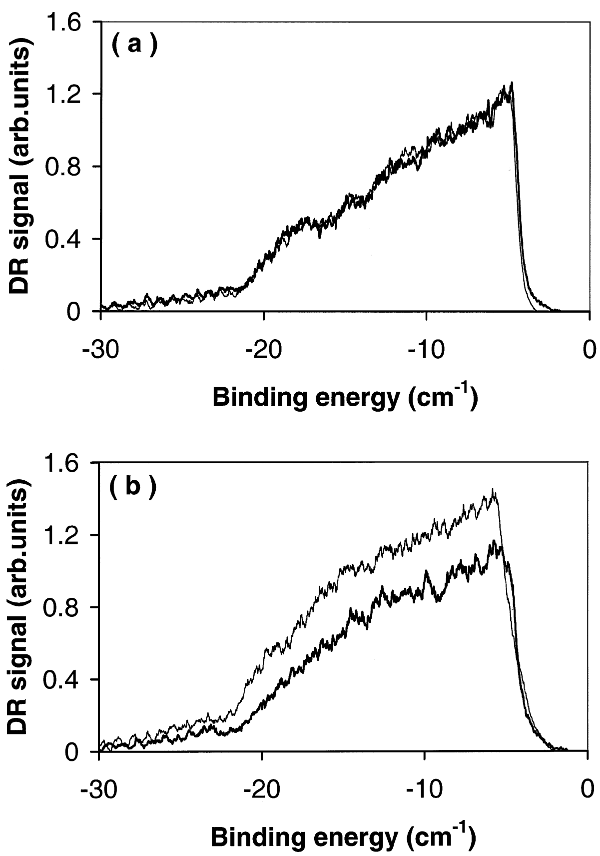

FIG. 3. Dielectronic recombination signals obtained by scanning the frequency of the third laser of Fig. 1, driving the $6s11d \rightarrow 6p_{3/2}11d$ transition. In all cases $E = 0.5$ V/cm (a) parallel fields, $\overline{B} \parallel \overline{E}$, with $B = 0$ (bold line) and $B = 240$ G (light line); (b) perpendicular fields, $\overline{B} \perp \overline{E}$, with $B = 0$ (bold line) and $B = 240$ G (light line). The enhancement for $\overline{B} \perp \overline{E}$ is evident as is the lack of enhancement for $\overline{B} \parallel \overline{E}$.

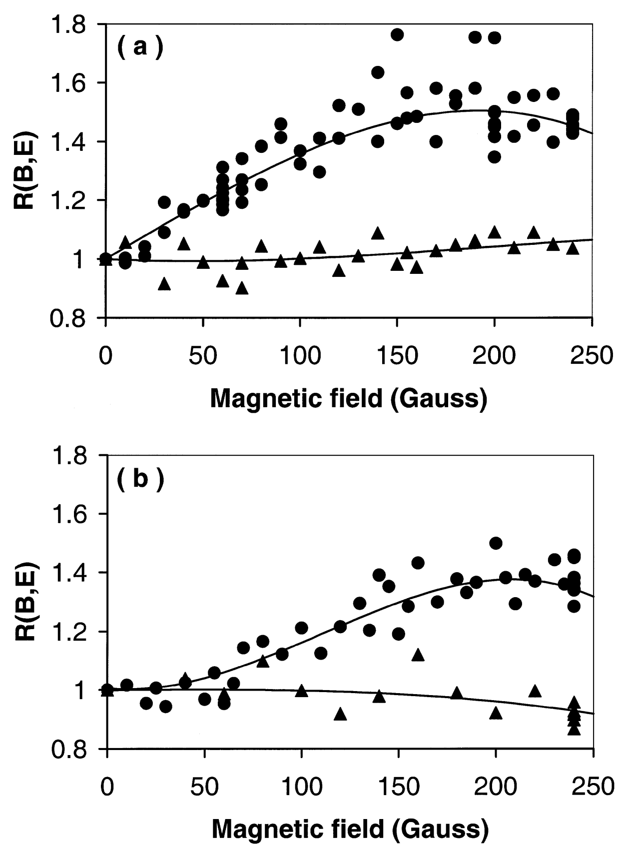

FIG. 4. Magnetic field enhancement factor $R(\overline{B}, \overline{E})$, the ratio of the energy integrated dielectronic recombination rate with and without the B field [see Eq. (3)] vs B. (a) $E = 0.5$ V/cm; (b) $E = 2.0$ V/cm. In both (a) and (b) $\overline{B} \parallel \overline{E}$ (▲) and $\overline{B} \perp \overline{E}$ (●). As shown, the maximum enhancement is 50% for $\overline{B} \perp \overline{E}$ while there is no enhancement for $\overline{B} \parallel \overline{E}$. The lines are fits of the data to third order polynomials.

must be a maximum. When the magnetic field interaction $\mu_B B$, where μ_B is the Bohr magneton, becomes larger than the electric field interaction the ℓ mixing is suppressed, and no enhancement of the DR rate occurs. Presumably, it is for this reason that Bartsch *et al.* [9] observed only a decrease in the DR rate as the magnetic field was increased from 200 to 650 G. For a large enough $\overline{B}$ field we would expect the DR rate in an $\overline{E}$ field to be reduced to approximately the $E = 0$ rate.

In conclusion, we have observed experimentally the predicted magnetic field enhancement of DR for $\overline{B} \perp \overline{E}$.

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