Dielectronic Recombination for Br^{33+} Ions Channeled in an Au Crystal

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Dielectronic recombination for Br^{33+} has been measured for channeling along a ⟨110⟩ axis in Au. In contrast to the recent surprising observation by Belkacem *et al.*, both the resonance width and strength are in agreement with the predicted values for an electron gas with a density corresponding to the average electron density in ⟨110⟩ channels of Au.

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Dielectronic recombination (DR) for an ion in an electron gas comprises capture of an electron with simultaneous excitation of a bound electron, an inverse Auger process. For capture to the inner shells of highly charged ions this process can be studied by ion channeling, as first demonstrated by Datz *et al.* [1]. Channeling confines the trajectories of swift ions in a crystal to the open space between atomic rows, where they only interact with the outer delocalized electrons, and hence the ions penetrate a medium approximating an electron gas. The DR process in crystals is often denoted as resonance transfer and excitation (RTE), which is the technical term for recombination in the same way with an electron initially bound in a target atom.

The electron gas in crystal channels is an attractive target for the study of DR processes because of its high density. The resonance condition is that, in the rest frame of the moving ion, the energy of the electron to be captured matches that of a *KLL* Auger transition,

$$E_r = E_K - 2E_L = (-m_e\mathbf{v}+\mathbf{p})^2/2m_e = m_e v^2/2 + p^2/2m_e - \mathbf{p}\cdot\mathbf{v}, \quad (1)$$

where E_K and E_L are the K- and L-shell binding energies of the highly stripped ion, m_e is the electron mass, $\mathbf{v}$ is the ion velocity, and $\mathbf{p}$ is the electron momentum in the laboratory frame. We have in this equation ignored small corrections of the order of 1%, the most important being the shift in energy due to the polarization potential induced by the projectile charge. Usually the last term dominates the resonance width. Since the Fermi distribution of one component of the electron momentum is proportional to $(1-p^2/p_F^2)$, the resonance width will be given by $\Delta E_{\mathrm{FWHM}}/E_r = 2(2E_F/E_r)^{1/2}$, where p_F is the Fermi momentum and E_F is the Fermi energy. For a gas with density ρ, the Fermi energy (in Rydberg units) is given by $E_F = (3\pi^2\rho a_0^3)^{2/3}$, where a_0 is the Bohr radius. All measurements of resonance capture for ions channeled in Si crystals have found resonance widths of (10–15)%, consistent with the Fermi-gas estimate [1–3].

It was therefore surprising and of great interest when Belkacem *et al.* [4] recently reported a *KLL* resonance for electron capture by channeled Ti^{20+} ions in gold which was narrower by an order of magnitude than the width corresponding to the expected density of crystal electrons. The Ti ions were channeled along a ⟨110⟩ axis in an Au crystal, for which band-structure calculations predict an average electron density in the channels of about three electrons per Au atom, or 0.18 $Å^{-3}$ [5]. For a uniform gas of this density the Fermi energy is 12 eV and the resonance width should be about 17%, as compared to the reported width of only about 2%. Considering that the Fermi momentum, and hence the resonance width, scales with $\rho^{1/3}$ this is a dramatic difference. The narrowness cannot be explained by a very low density since the measured resonance strength in Ref. [4] in fact corresponds to a surprisingly high density.

A possible explanation for how the observed resonance width in Au [4] could be narrower than the limit set by the Fermi momentum of a uniform electron gas would be a strong anisotropy of the momentum distribution of the electrons seen by the channeled ions. Since the resonance broadening results from the momentum component parallel to the ion velocity, the width could be much reduced for fixed electron density if the momentum distribution were like a pancake with the thinnest dimension parallel to the ion velocity. This would appear to be excluded because of the cubic lattice symmetry, but the selection by channeling of spatial coordinates in the two dimensions perpendicular to the velocity breaks the symmetry, and in fact calculations have indicated the existence of a preference for momentum perpendicular to the axis for elec-

trons in the middle of ⟨110⟩ channels in Au [5]. However, the calculated asymmetry is far too small to account for the observed narrowing.

The only published attempt to reproduce the experimental result was unable to detect any resonance [6] for Ti ions channeled along the ⟨100⟩ axis of a thin Au crystal. However, in view of the remarks just presented concerning asymmetry, it is important to test the result by measurements for channeling along the ⟨110⟩ axis in Au. We report here the first such test, a measurement of *KLL* capture for Br^{33+} ions channeled along a ⟨110⟩ axis in Au. The resonance has been clearly observed and both the width and the strength agree with the estimate for a Fermi gas with a density corresponding to about three electrons per Au atom [5].

Our experiment was very similar in principle to the measurement by Belkacem *et al.* [4] but we used a magnetic spectrometer with much higher dispersion [$\sim$13 cm/%($\Delta p/p$)]. A beam of ^{79}Br ions with energy 17.9 MeV/u was provided by the TASCC Facility's Superconducting Cyclotron at Chalk River, Canada. The energy of the Br^{33+} beam on target was varied between 12.6 and 17.6 MeV/u by insertion of Al absorbers and selection of a narrow momentum bite with the beam-transport system; the beam direction was defined by two 0.5 mm collimators 1.6 m apart. The target was a {100} Au crystal, made by epitaxial growth on NaCl. The crystal was tilted by 45° to align the beam with a ⟨110⟩ axis, and the effective crystal thickness was then 0.9 μm, as measured by alpha-particle energy loss.

The charge states of Br ions exiting the crystal were separated by the high-resolution Q3D magnetic spectrometer and energy spectra were recorded by position sensitive gas counters placed in the focal plane. Electron capture by well-channeled ions could then be identified by selection of the lowest-energy-loss particles in the spectrum for 32^+ ions, as shown in Fig. 1, for incidence parallel to a ⟨110⟩ axis and to a {111} plane. A slight wrinkling of the gold crystal introduced a spread in beam direction relative to the axis of about $\pm 0.25°$ in a direction nearly parallel to a {111} plane, as determined from angular scans of the intensity of low-energy-loss ions. This angle is close to the critical angle for ⟨110⟩ channeling but since the angular spread is parallel to a {111} plane it does not add a random component to the beam. The particles that are poorly channeled relative to the ⟨110⟩ axis are still channeled with respect to the {111} plane, and, as seen in Fig. 1, the capture probability is the same for the best channeled particles along the {111} plane and along the ⟨110⟩ axis.

For well-channeled 33^+ ions the charge state is "frozen," as shown in Fig. 2, because capture and loss processes are strongly reduced, and the ratio $f(32^+)/[f(33^+)+0.5f(32^+)]$ should give the probability for capture; $f(N^+)$ is the number of N^+ ions and the denominator is the average number of 33^+ ions available

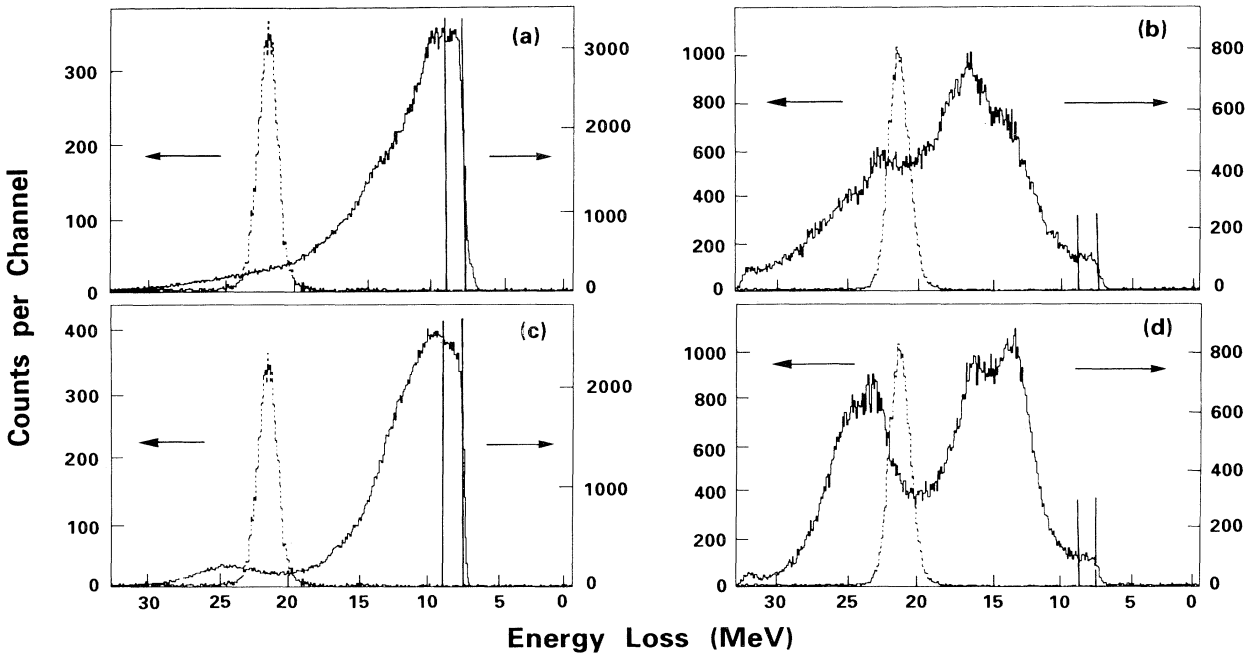

FIG. 1. Energy-loss spectra for 15.3 MeV/u Br ions after transmission through the Au crystal: (a) random (dashed) and ⟨110⟩ (solid lines) for exiting 33^+ ions, (b) as in (a) but for exiting 32^+ ions, (c) random and {111} for exiting 33^+ ions, and (d) as in (c) but for exiting 32^+ ions. The FWHM of the beam was 0.3 MeV. The energy-loss intervals used to derive the capture probabilities in Fig. 3 are indicated by vertical lines. Spectra for the two charge states were recorded simultaneously.

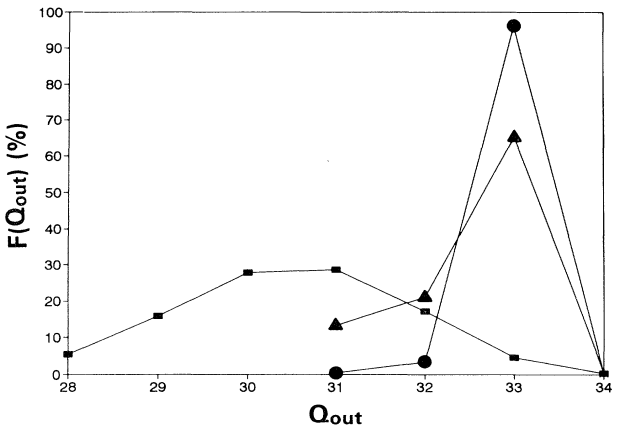

FIG. 2. Charge-state distributions for 13.45 MeV/u Br^{33+} ions after transmission through the Au crystal in random (■) and ⟨110⟩ (● and ▲) directions. For channeled ions both the total intensity (▲) and that within the energy interval indicated in Fig. 1 (●) are shown.

for capture. With the random-energy-loss peak and the beam energy as reference points, corresponding energy windows were selected in the spectra for well-channeled ions, taking into account the small difference in energy loss for exiting 33^+ and 32^+ ions, which on the average is 3%. The energy dependence of the capture probability for these well-channeled ions is shown in Fig. 3(a). In the region around the predicted resonance energy of 15.6 MeV/u there is a clear indication of a contribution from *KLL* dielectronic recombination. In Fig. 3(c) this contribution has been extracted by subtraction of a background proportional to E^{-n}, as in the analysis of the corresponding observation [3] for Br in Si⟨110⟩, shown in Figs. 3(b) and 3(d). The results of the two measurements are remarkably similar, as might have been expected since the electron densities seen by channeled ions are predicted [5] to be not very different for the two crystals. The FWHM of the observed resonance is about 10% and the area corresponds to a density of about three electrons per atom, if a total cross section of 5.6×10^5 eVb is assumed for DR

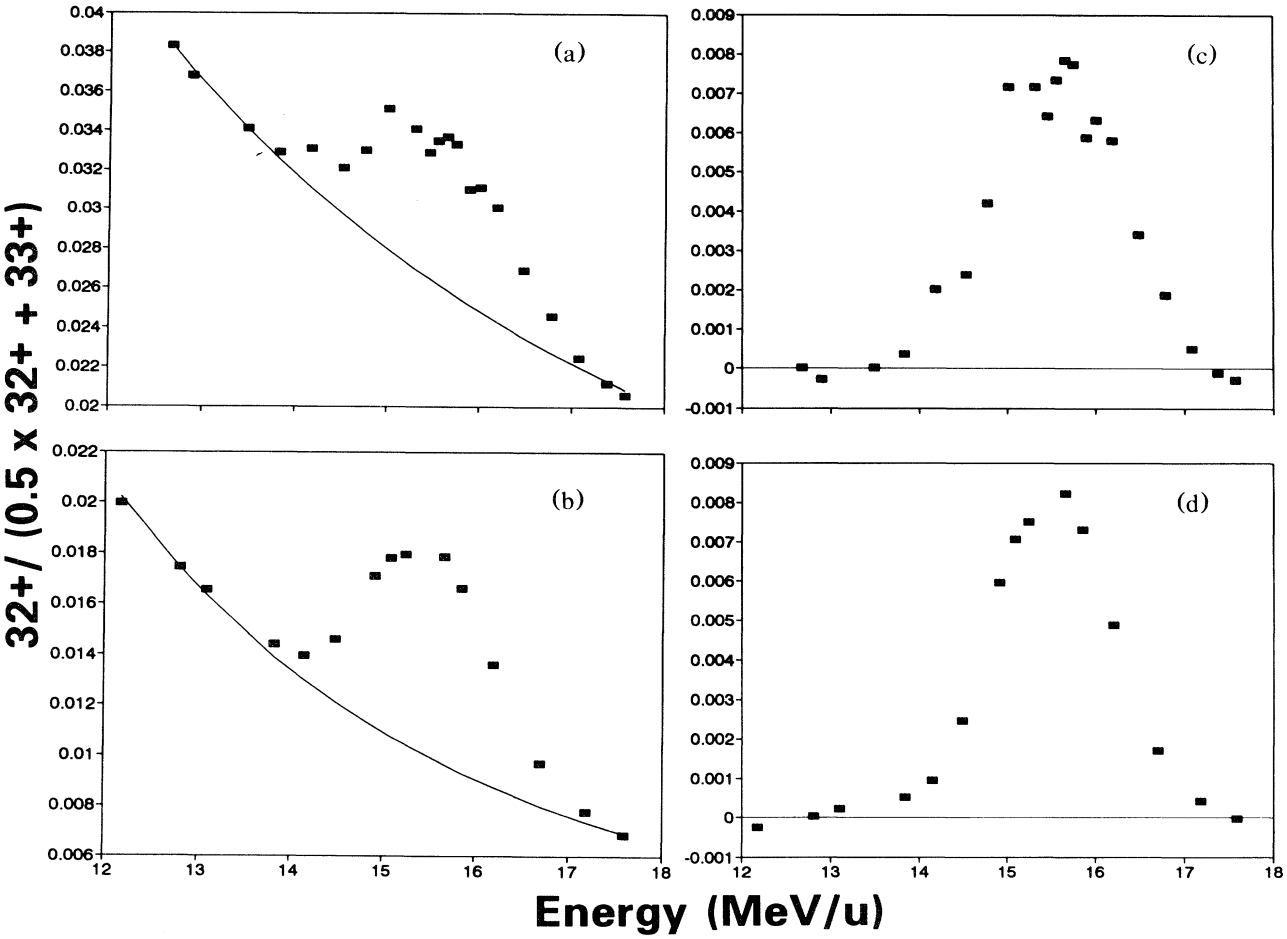

FIG. 3. Energy dependence of the electron-capture probability for Br^{33+} ions transmitted through a (a) 0.9 μm Au crystal and (b) a 1.0 μm Si crystal. The solid lines are fits to the background (not DR) by a power law E^{-n}. The contributions from dielectronic recombination obtained by subtraction of the background are shown in (c) and (d). The Si data are from Ref. [4].

capture to the L shell [7]. These values are consistent with the limit set by the Fermi-gas relation between density and momentum spread.

In conclusion, we have observed the DR resonance in electron capture for Br ions channeled along a ⟨110⟩ direction in Au and shown that both the width and the strength of the resonance are consistent with theoretical predictions for a uniform and isotropic electron gas with a density equal to the average electron density in a Au⟨110⟩ channel. This strongly suggests that the recently reported anomalous results for the DR resonance in electron capture by Ti ions were incorrect [4]. The main improvement in the present experiment results from the high resolution of the Q3D spectrometer and the focal-plane detectors, allowing a precise selection of corresponding energy-loss intervals for different charge states.

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