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Production of U^{92+} with an EBIT

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Abstract

A super electron beam ion trap has been used to produce bare U^{92+} ions at an electron beam energy of 198 keV. Evaporative cooling with light ions was used to trap a population of 5×10^4 highly charged uranium ions for many seconds and reduce their temperature to less than 2q eV, suggesting that a very low emittance source of these ions is possible. Roughly 10 U^{92+} and 500 U^{91+} ions were present in the Super EBIT as determined from x-ray emission spectra of the trapped ions.

I. INTRODUCTION

Fully stripped U^{92+} is the highest charge state of the heaviest naturally occurring element. As such, it can be called the ultimate ion. It is also the most challenging to produce because of the high (130 keV) ionization threshold of the uranium K-shell electrons and the small (~10^{-24} cm^2) cross section for removing them by electron impact. For these reasons, U^{92+} ions have previously been produced only as relativistic (~400 MeV/amu) accelerator beams stripped in foil targets [1].

A source of low velocity U^{92+} has been a goal of atomic physics research for many years. To this end, beams of accelerator produced U^{92+} ions stored in a ring have recently been decelerated by a factor of 10 in energy to 49 MeV/amu [2]. The first production of U^{92+} at rest was achieved in an electron beam ion trap (EBIT) at the Lawrence Livermore National Laboratory (LLNL) [3]. The technique for producing U^{92+} with an EBIT is described in what follows.

II. EBIT AND SUPER EBIT

The EBIT was developed for x-ray measurements of trapped highly charged ions [4,5]. In an EBIT, ions are trapped radially by the negative space charge potential of an electron beam. In this respect the EBIT is similar to the electron beam ion source (EBIS) developed earlier as a source of highly charged ion beams [6]. Axial confinement of the ions in an EBIT is achieved by bias voltages applied to three drift tubes (i.e., trap electrodes) in an arrangement resembling a Penning trap. Collisions with beam electrons strip the ions to high charge states.

Compression of the EBIT electron beam to the smallest possible size is extremely important because the ionization rate is proportional to the electron current density. In the LLNL EBITs this is accomplished with a 3-tesla magnetic field from a split pair of superconducting coils, and current densities up to 5000 A/cm^2 are obtained. The trap electrodes are located in the center of the magnet coils so that x rays from electron ion collisions can be observed in the midplane between the two coils as shown in Fig. 1.

One of the EBITs at LLNL is dubbed "Super" because of the high (up to 200 keV) electron beam energy available. The 200-keV energy is essential for the production of bare uranium ions. A higher value would be even better because the ionization cross section of hydrogenlike U^{91+} rises slowly from zero at its 130-keV threshold [7]. A layout of the LLNL Super EBIT is shown in Fig.2. A high voltage electron gun and collector are located at the bottom and top of the machine, respectively, and the ion trap is in the middle. A more detailed description of the LLNL Super EBIT can be found elsewhere [8]. Super EBIT operating parameters used for the production of U^{92+} are listed in Table I.

III. PRODUCTION AND TRAPPING OF HIGHLY CHARGED URANIUM

If electron impact ionization were the only process experienced by uranium ions trapped in a Super EBIT, all the uranium ions would become fully stripped in a time determined by the product of the electron current density and the ionization cross sections of the preceding ionization stages. Unfortunately, three other processes reduce the amount of U^{92+} and other high charge states that can be produced. These three processes are electron beam heating of the trapped ions, radiative recombination, and charge exchange recombination with neutral gas. Production of very-highly-charged uranium ions in a Super EBIT requires understanding and control of these processes.

A. Ion heating and cooling

Highly charged ions trapped in an electron beam are heated by small-angle Coulomb collisions with beam electrons. The (nonrelativistic) heating rate is given by

$$dE_i/dt = \pi \frac{j_e}{e} \frac{q_i^2 e^4}{E_e} \frac{2m_e}{M_i} \ln\Lambda \qquad (1)$$

where E_i, q_i, and M_i are the ion energy, charge, and mass, respectively. E_e and j_e are the electron beam energy and current density, and $\ln\Lambda$ is the Coulomb logarithm [9]. For uranium ions with $q_i \approx 90$ in a 200-keV, 200-mA Super EBIT beam, $dE_i/dt \approx 6$ keV sec^{-1} per ion. A comparison of rates shows that, in the absence of a cooling mechanism, ions will "evaporate" from the beam before reaching high charge states.

An evaporative ion-ion cooling technique employing a mixture of low-charge and high-charge ions can be used to balance electron beam heating in an EBIT [5,10]. In the LLNL Super EBIT, a collimated beam of neon atoms with a carefully controlled density crosses the electron beam at 90 degrees as shown in Fig. 1. Roughly 0.2% of the neon atoms that intercept the electron beam are ionized and captured. Direct electron beam heating of the low-charge neon ions is small. They are heated primarily by collisions with high-charge uranium ions before escaping axially (evaporating) from the trap with the removal of $q_{Ne}V_A \sim 300$ eV per neon ion for the operating conditions of Table I. (V_A is the axial trapping potential over which the ions escape.)

Evaporative cooling is extremely effective, producing a population of cool uranium ions that remains trapped for several minutes, or even hours under optimum conditions. Usually the EBIT trap is initially "over filled" by the injection of a large number of low-charge uranium ions from a metal-vapor vacuum-arc source [11]. The number of uranium ions retained in the EBIT electron beam is then determined by the evaporative cooling power (i.e., the neutral neon density) and not by the number of uranium ions injected initially. This has been verified by measuring the dependence of the uranium x-ray emission rate on the neutral neon density. The dependence is linear when only a small fraction of the electron space charge is neutralized.

B. Ionization balance

Once highly charged uranium ions are cooled and trapped in the Super EBIT electron beam, the removal of the last few tightly bound electrons can take place. The equilibrium ionization balance for trapped highly charged uranium ions is determined by the relative rates for the ionization and recombination processes that couple adjacent ionization stages. The abundance ratio for hydrogenlike and bare uranium at equilibrium is given by

$$N_H/N_{Bare} = \frac{\sigma^{RR}_{Bare\rightarrow H}}{\sigma^{ion}_{H\rightarrow Bare}} + \frac{(e/j_e)\, n_0 v\, \sigma^{CX}_{Bare\rightarrow H}}{\sigma^{ion}_{H\rightarrow Bare}} \qquad (2)$$

where the second term accounts for charge exchange recombination with neutral neon atoms. Here n_0 is the neutral gas density and v is the average ion-neutral collision velocity (approximately the ion thermal velocity). The cross sections for radiative recombination (RR), ionization, and charge exchange (CX) are written in obvious notation. The density of background gas is kept very low by operating the trap at a temperature of 4 K.

The highest charge states are obtained by keeping the ratio n_0 / j_e small. For the production of U^{92+}, n_0 was chosen so that the charge exchange term in Eq. (2) was about 10% as large as the radiative recombination term. However, since $\sigma^{RR}{}_{Bare \rightarrow H}$ / $\sigma^{ion}{}_{H \rightarrow Bare} \approx 40$ for uranium at 198 keV, it is always true that $N_{Bare} << N_H$ and $N_H << N_{He}$. The fractional abundance of U^{92+} could be increased by operating at a higher electron energy. Dielectronic recombination, a resonant process, does not contribute at 198 keV, and three-body recombination is negligible at EBIT electron energies and densities.

The charge-state distribution of the trapped uranium ions can be derived from x-ray emission spectra such as that shown in Fig. 3. Radiative recombination of the uranium ions with the (monoenergetic) beam electrons produces a series of lines whose energy is equal to the sum of the electron energy and the binding energy of the vacant orbital into which the electron is captured. Bare and hydrogenlike target ions produce resolved radiative recombination lines for K-shell capture. Radiative recombination of the other high charge states of uranium is incompletely resolved, but the ionization balance can be obtained by fitting the radiative recombination spectrum. The cross sections for radiative recombination are well known [12]. The observed uranium ionization balance for U^{92+}

production at 198 keV is given in Table II. Out of a total of 5×10^4 highly charged uranium ions, there were an average of 500 hydrogenlike and 10 bare uranium ions. For the relatively low neutral neon densities used here ($\sim 2 \times 10^5$ cm^{-3} averaged over the length of the trap), the total compensation of the electron beam space charge by neon and uranium charges is less than 10%.

C. Ionization cross sections

The ionization cross section of U^{91+} is the key to the production of U^{92+}. For several years, even the approximate size of this cross section was in doubt in view of an accelerator stripping measurement that obtained values 3 to 5 times larger than any theory [13]. This uncertainty was removed by the derivation of the U^{91+} ionization cross section from the equilibrium ionization balance in Super EBIT [3]. This was done using Eq. (2) and normalizing to the known radiative recombination cross section for U^{92+}. The result was 50% larger than theoretical calculations available at the time, but more recent calculations are in agreement with the Super EBIT result, as listed in Table III. The ionization cross section for U^{90+}, determined in a similar manner, is also listed in Table III.

IV. POSSIBILITIES FOR EXTRACTED ION BEAMS

Although the EBIT and Super EBIT were developed for x-ray measurements of highly charged trapped ions, the ions can also be extracted as they are from an EBIS. This is routinely done with the 30-keV EBIT at LLNL [14], but not yet with the Super EBIT. Two features make a Super EBIT attractive as an ion source. One is the remarkably high charge states produced and the other is the low emittance. A detailed computer model of the ion interactions in Super EBIT suggests that the uranium ion temperature for the conditions that produced U^{92+} is $\leq 2q$ eV [15]. Since this temperature is four times less than the space charge potential at the beam radius (neglecting the partial neutralization by positive charges), the radial extent of the uranium ions must be even less than the 35-μm electron beam radius. This small transverse phase space volume translates into a small emittance when the ions are extracted.

The time required to reach a high charge state is of minor importance for the operation of an EBIT as a trap, as long as it is small compared to the ion trapping time. However, the ion production time is very important for the operation of EBIT as an ion source. Traditionally, the production time τ_q to reach a charge state q has been estimated from the expression

$$\tau_q = \sum_{i=1}^{q} [(j_e/e)\,\sigma_i]^{-1} \qquad (3)$$

where j_e is the electron current density experienced by the ions and σ_i is the ionization cross section for the ith ionization stage. For U^{92+} production at 198 keV in the LLNL Super EBIT, this expression gives $\tau_{92} \approx 50$ sec. The actual U^{92+} production time is much shorter, about 4 sec, because of the fast radiative recombination rate of highly charged uranium ions. (The counter-intuitive fact that a high rate for destroying uranium U^{92+} speeds up the time constant for producing it can be verified by solving the differential equations for ionization and recombination.) The most abundant charge states (U^{88+} and U^{89+}) are produced even more quickly, so a yield of roughly 2×10^4 extracted ions per second can be expected for these charge states from the present LLNL Super EBIT.

V. CONCLUSIONS

The production of U^{92+} ions at rest in an EBIT has been demonstrated, and the processes that determine the total number of ions, charge-state distribution, ion temperature, and trapping time are now understood. In the future, the total yield of highly charged uranium ions could be increased with a more intense electron beam, and the fractional abundance of U^{92+} could be significantly increased with a higher-energy electron beam.

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Table I. Super EBIT parameters for the production of U^{92+}.

Beam energy	198 keV (~100 eV FWHM)
Beam current	200 mA
Current density	5000 A/cm^2 ($n_e \sim 10^{13}$ cm^{-3})
Number of high-Z ions	$\sim 5 \times 10^4$ ($n_i \sim 10^9$ cm^{-3})
Ion temperature	~ 2q eV
Radial trapping potential	~ 8 volts
Axial trapping potential	30 volts
Beam radius	35 µm
Ion confinement length	2 cm

Table II. The observed equilibrium ionization balance in the LLNL Super EBIT for uranium at 198-keV electron beam energy.

Ionization stage	Charge	Abundance (%)	Number of ions
Bare	92	0.02	10
H-like	91	1.0	500
He-like	90	17	8500
Li-like	89	34	17,000
Be-like	88	31	15,500
B-like	87	15	7500
C-like	86	3	1500
Total		100	5×10^4

Table III. Electron impact ionization cross sections for U^{90+} and U^{91+} at 198-keV electron energy in units of 10^{-24} cm^2 [3].

Ion	Super EBIT	Bevalac [a]	Rel. DW [b] Theory
$U^{90+}(1s^2)$	2.82 ± 0.35	9.7	2.94
$U^{91+}(1s)$	1.55 ± 0.27	3.4	1.40

[a] Values from Ref. [13] multiplied by 0.88 for adjustment to the Super EBIT electron energy. Uncertainties are a factor of 2.

[b] Relativistic distorted wave theory with Breit interaction. Ref. [7]

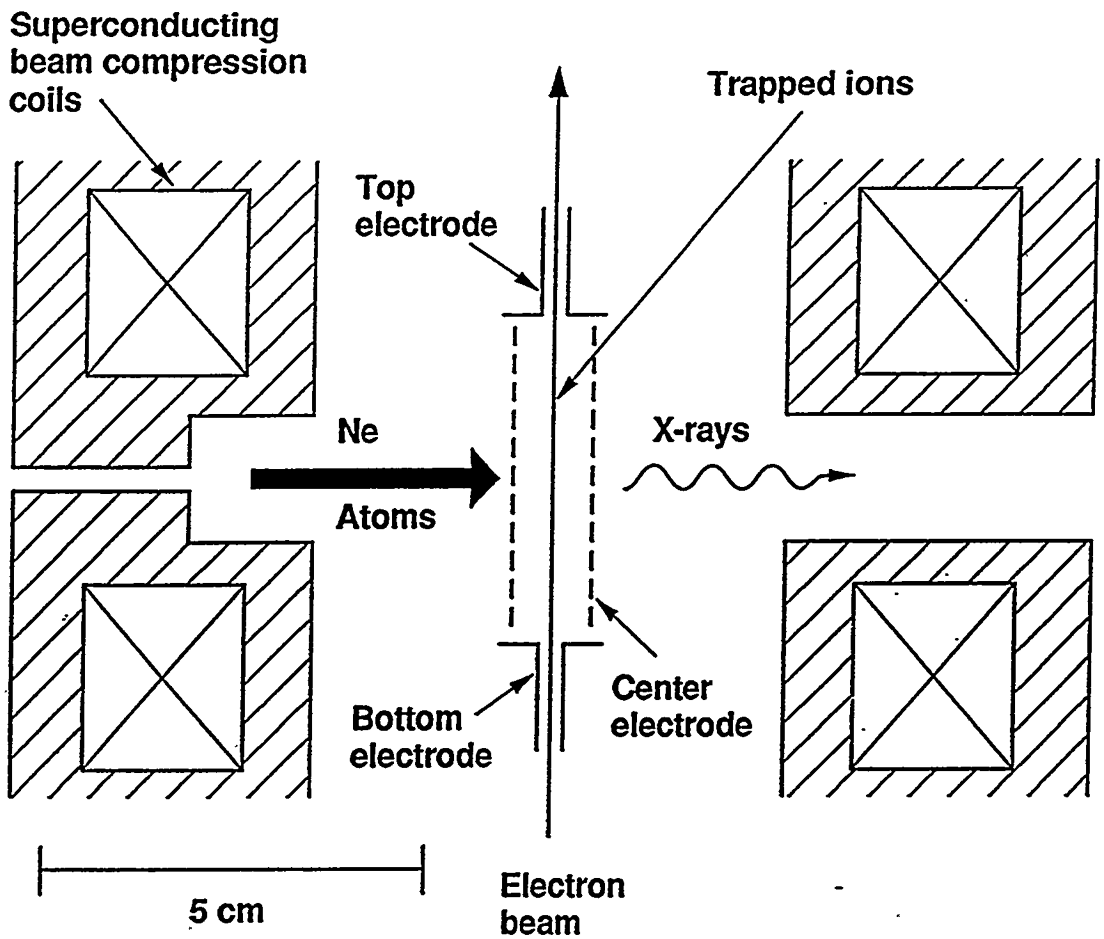

Fig. 1. Trap configuration. The cylindrical center electrode is slotted to facilitate x-ray emission and neon cooling gas injection.

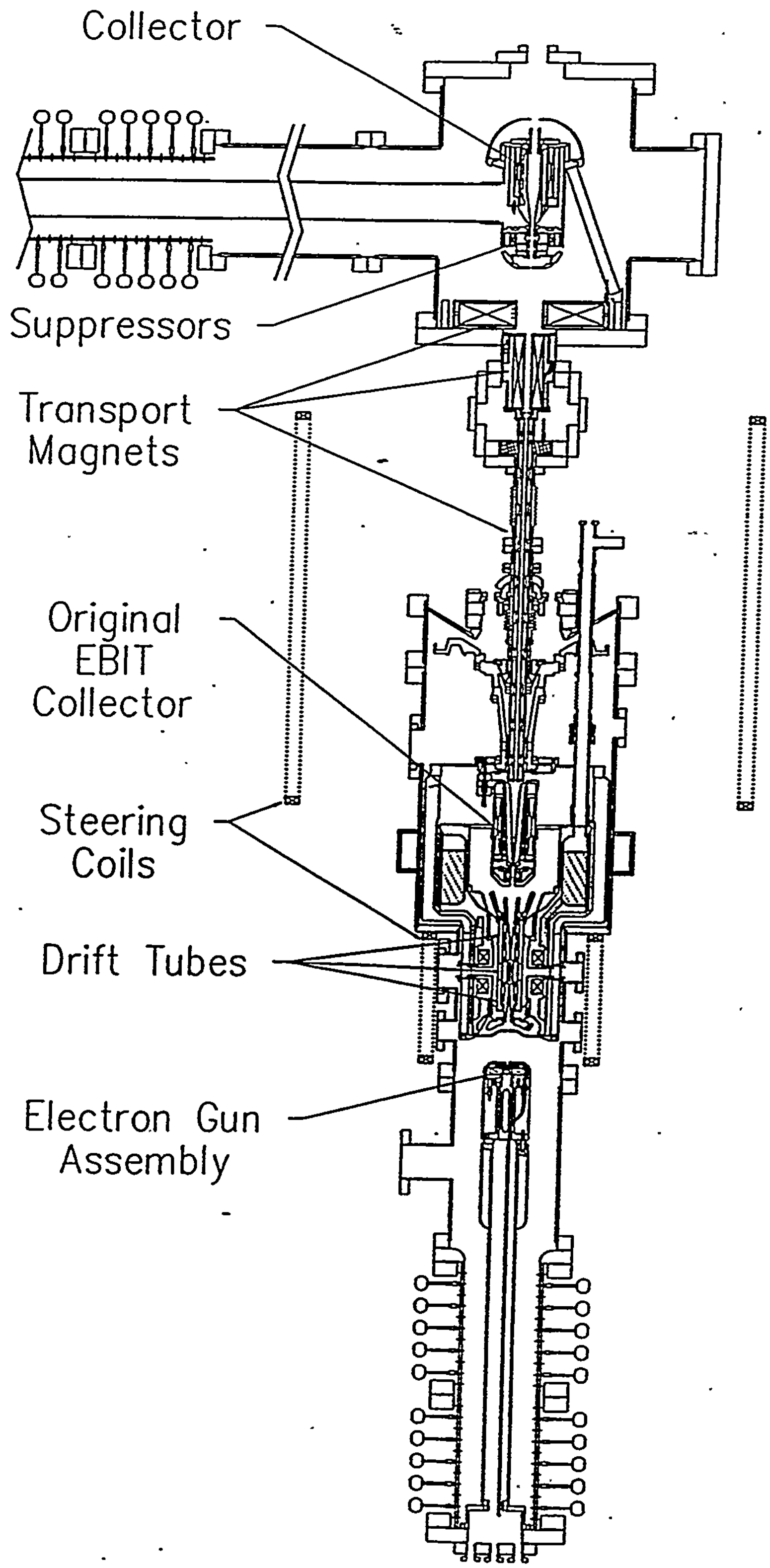

Fig. 2. Scale drawing of the Super EBIT device at LLNL. The electron gun and collector both float at a high negative potential (up to -165 kV). The electron beam passes through a drift tube structure where the ion trap is located and an additional +35 kV of bias can be applied.

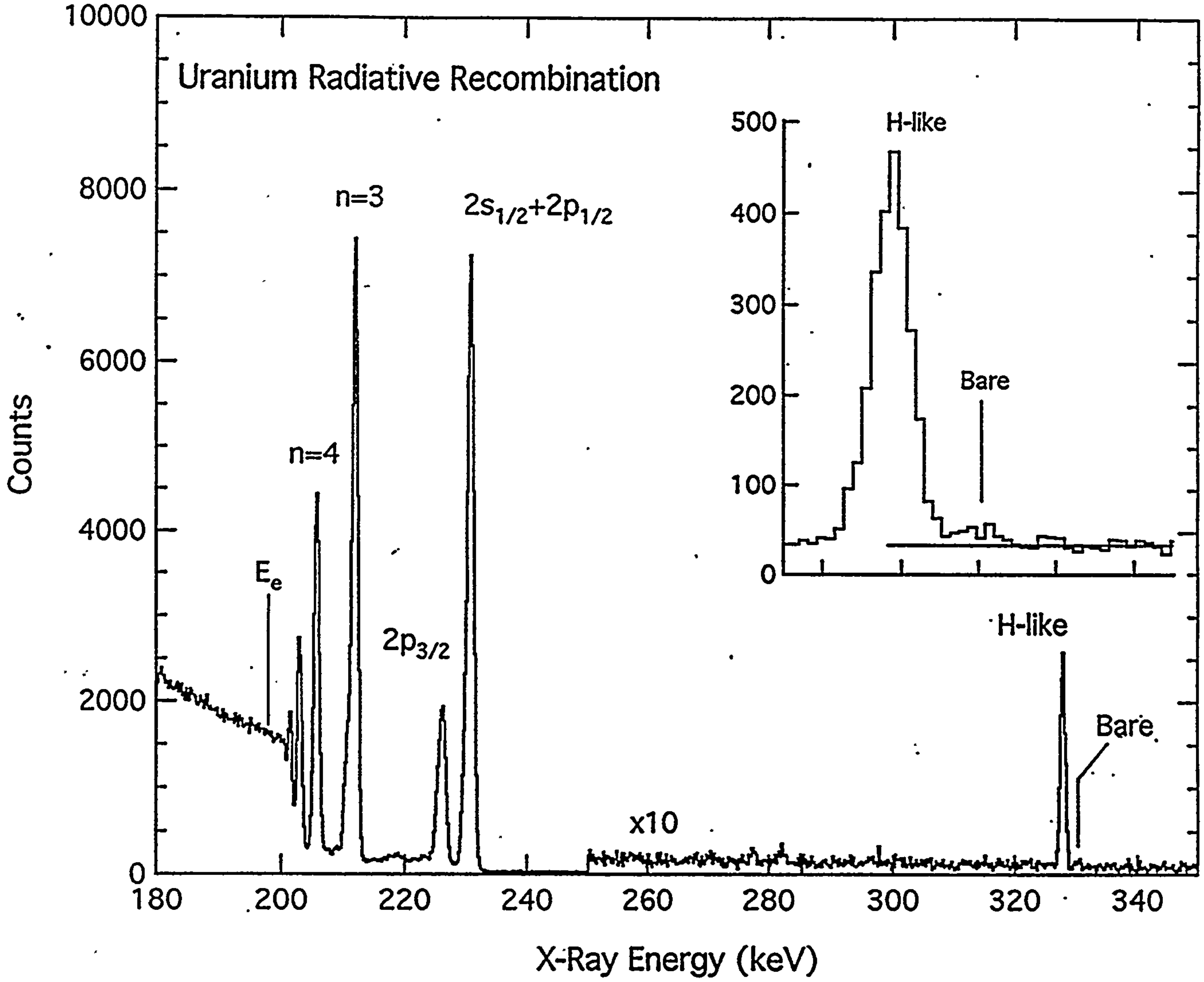

Fig. 3. Radiative recombination spectrum of uranium ions at 198-keV electron energy observed in a 40-cm^3 germanium detector. The inset shows the K-shell radiative recombination feature from a similar 90-cm^3 detector; the solid horizontal line is the average background level above the peaks.