A K-CELL injection system for SH-PermEBIT (Postprint)

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Abstract

In this paper, we report a newly developed Knudsen Cell injection system for SH-PermEBIT. This technique can overcome disadvantages of introducing organometallic gases and wired probes into EBIT and provide steady continuous injection. A specially designed vacuum line is used to ensure that the Knudsen Cell satisfies the vacuum level of SH-permEBIT. Using this system we successfully injected ytterbium into the SH-permEBIT and recorded a spectrum in the visible wavelength region.

Full Text

Preamble

A K-CELL Injection System for SH-PermEBIT

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We report the development of a novel Knudsen Cell injection system for the Shanghai permanent magnet Electron Beam Ion Trap (SH-PermEBIT). This technique overcomes the limitations associated with introducing organometallic gases and wire probes into EBIT systems while providing steady, continuous injection of metallic species. A specially designed vacuum line ensures that the

Knudsen Cell meets the vacuum requirements of SH-PermEBIT. Using this system, we successfully injected ytterbium into the trap and recorded its spectrum in the visible wavelength region.

Keywords: Knudsen Cell, EBIT, Metallic atom injection
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Introduction

Electron beam ion traps (EBITs) are devices designed for studying the spectra of highly charged ions and their interactions with electrons. Unlike traditional EBITs that occupy large areas due to requirements for high electron beam energy and cryogenic operation, the Shanghai permanent magnet EBIT (SH-PermEBIT) offers specific advantages: it can operate at relatively low electron beam energies (down to ~60 eV) and at room temperature. A major challenge for any EBIT is introducing the element of interest into the vacuum chamber for spectroscopic or electron collision studies.

For SH-PermEBIT, conventional injection methods used in traditional EBITs—such as metal-vapor vacuum arc and laser ion source—cannot be readily installed. While wire probes and organometallic gases have successfully introduced metal elements into EBITs, both approaches have significant drawbacks. Wire probes may distort the electron beam shape, and organometallic compounds can cause carbon and oxygen contamination in the trap. For SH-PermEBIT, condensation of organometallic compounds may even occur in the vacuum chamber when operating at room temperature, the same temperature as the injection system. Steady and continuous injection of pure elemental species is crucial for many experiments and for expanding the applications of SH-PermEBIT, which motivated the development of a dedicated Knudsen Cell (K-CELL) injection system.

Device Setup

A K-CELL is a high-temperature effusion cell that operates under high vacuum conditions and has been widely employed in molecular beam epitaxy experiments and electron cyclotron resonance ion sources. The Tokyo EBIT (a traditional EBIT) has previously used a K-CELL for metal vapor injection. However, traditional EBITs operate at liquid helium temperatures with ultra-high vacuum in their drift tube regions, whereas SH-PermEBIT operates at room temperature with a substantially different vacuum level in its drift tube region. Consequently, we modified the design to accommodate these specific operating conditions.

As shown in Fig. 1, the K-CELL is mounted via a four-way cross to the main body and central drift tube of the EBIT. A plate sloped at 45° containing a 1-mm aperture is installed at the center of the cross. The K-CELL injection system is isolated from the EBIT by a vacuum valve, and a short vacuum pipe leads into the EBIT, terminating at the central drift tube. Aperture 1 in the

45° plate confines the diffused metallic vapor effusing from the crucible. The vacuum between the two apertures is better than 10^{-6} Torr (1.3×10^{-4} Pa), and the mean free path of the gas exceeds 50 m—longer than the distance between the apertures. Therefore, after passing Aperture 1, the vacuum is sufficiently high for metal atoms to travel through the tube or strike the vacuum line walls without colliding with other atoms.

The valve maintains vacuum in the main chamber when the K-CELL crucible needs to be charged or changed, and prevents contamination from outgassing during initial heating. The straight pipe, connected to the EBIT via a flexible flange, contains a small aperture (Aperture 2) that opens into the main chamber near the center drift tube (DT2), allowing the atomic beam to enter the drift tube region and intersect with the electron beam. The drift tube features a 1 mm × 20 mm slit. Both Aperture 2 and the K-CELL crucible can be shifted by one or two millimeters by adjusting their support frames.

We assembled the K-CELL, four-way cross, valve, and straight pipe line, ensuring alignment of the crucible center and both apertures along the K-CELL axis. The entire injection system was then installed on the EBIT, with the flexible flange used to precisely align the K-CELL axis with the drift tube slit.

Compared to traditional designs (Fig. 2), our configuration halves the transport distance of effusing vapor from the crucible to Aperture 1, drastically reducing the loss of metallic atoms according to the transport-residual formula:

$$n_x = n_0 e^{-x/s}$$

where n_x is the number of residual atoms after transport length x, n_0 is the total number of atoms effusing from the crucible, and s is the mean free path of the vapor. Additionally, placing Aperture 2 near the slit of the center drift tube reduces divergence of the atomic beam and increases injection efficiency, as described by the injection rate formula:

$$J = P(2\pi mkT)^{-1/2} \cdot e^{-x/s} \pi^{-1} l^{-2} \cdot S$$

where J is the injection rate, P is pressure, m is atomic weight, k is the Boltzmann constant, T is temperature in Kelvin, l is the length from crucible to the DT2 slit, and S is the aperture area.

Temperature was controlled by a Eurotherm 2408 Temperature Controller with an accuracy of \$±2°C.TheK−CELL′suppertemperaturelimitis1400°Caccordingtothemanufacturer,andthe
3}\$ Torr (0.13 Pa). While it is often difficult and sometimes unnecessary to determine the exact injection rate for a given element—the absolute spectral intensity from EBITs depends on numerous factors including chamber vacuum and residual gases from previous experiments—the injection pressure is typically set when a good spectrum of the injected element is obtained.

Relative spectral intensities from an element injected by traditional versus improved K-CELL systems under identical operating conditions demonstrate our improvement. Magnesium injection efficiencies into SH-PermEBIT using both systems are shown in Fig. 3. With the crucible at 350 °C and 10^{-4} Torr (0.013 Pa), using 730 eV electron beams of about 8.0 mA and a trap depth of 50 eV, spectra were recorded for one hour with an Andor SR-303i spectrometer (30 μm slit, 1200 l/mm grating blazed at 300 nm). The traditional K-CELL yielded only a weak Mg I line (285.21 nm), whereas the improved design produced a much stronger Mg I line and clearly resolved two Mg II lines (279.55 nm, 280.27 nm).

Experimental

We conducted an experiment using the K-CELL injection system to observe the $2F_7/_2 \rightarrow 2F_5/_2$ M1 transition line in Ag-like Yb (Yb^{23+}). The temperature-vapor pressure relationship for ytterbium is listed in Table 1. In this experiment, the crucible was heated to 400 °C, producing a vapor pressure of approximately 10^{-4} Torr (0.013 Pa). Excited ions were produced and confined in the drift tube region, with some decaying via photon emission.

The emitted light was analyzed by an Andor Czerny-Turner spectrometer (SR-303i) covering 200–800 nm. To maximize the collection solid angle, we positioned a quartz lens (f = 185 mm) between the EBIT window and the spectrometer' s 30-μm entrance slit. Light from the drift tube center was dispersed by a 1200 l/mm grating blazed at 300 nm and detected by an Andor DU940P-BU2 charge-coupled device, with spectra recorded on the CCD-controlling computer. A typical spectrum is shown in Fig. 4. For the first time, we observed this M1 line; detailed analysis is underway for future publication.

Conclusion

The K-CELL injection system performs effectively with SH-PermEBIT and can be used to inject many metal or rare earth elements, eliminating the need for wire probes or organometallic gases. We anticipate numerous future experiments combining the EBIT and K-CELL capabilities.

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Note: Figure translations are in progress. See original paper for figures.