Chapter 19

Generation of Atomic Beam for Laser Isotope Separation

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19.1 Introduction

Presently, Isotopes are used in both nuclear and non-nuclear applications like medical and non-destructive testing. Isotopes of uranium and zirconium are used in nuclear reactors while isotopes of Lutetium (Lu), ytterbium (Yb), samarium (Sm) are used for diagnosis or treatment of cancer, arthritis, and bone metastases [213, 222, 223]. However, for its effective use, these isotopes need to be enriched to a certain extent by any of the isotope separation process such as electromagnetic method, centrifugal method, Diffusion process or Atomic Vapor Laser Isotope separation (LIS) technique. Among all these methods, LIS technique can achieve highest separation factor in a single stage, can handle higher density and can be used for any isotope irrespective of whether the isotope is in middle or end of the mass spectrum [212]. However, for an efficient LIS process, it is desirable to generate atomic beam of required density ($\sim 10^{12}/\text{cm}^3$) with narrow Doppler width at the Laser interaction zone. This chapter will discuss various techniques such as resistive heating, electron bombardment heating and electron beam heating that can be adopted for generation of such an atomic

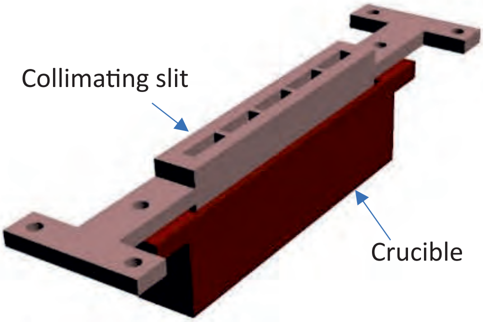

Figure 19.1: Design of crucible for linear vapor source.

beam. Due importance is also given to the important design considerations and the formulae to be used to estimate the process parameters.

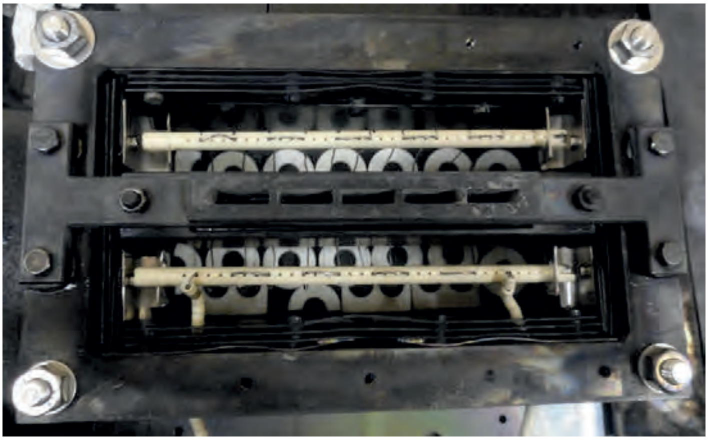

Figure 19.2: Photograph of a resistive heating furnace used for generation of Ytterbium (Yb) vapor.

19.2 Different Techniques for Vapor Generation

Generally, LIS process is carried out in vacuum with pressure of the order of $\sim 10^{-5}$ mbar. For generation of atomic vapor, the material (mostly metal) needs to be heated to high temperature so that the vapor pressure becomes more than the background pressure resulting in evaporation of metal. This vapor is than collimated by a slit, selectively ionized by the laser and finally collected by a product collector kept at negative voltage. The heating of the metal can be carried out by resistive heating, electron bombardment heating or electron beam heating. Generally, induction heating is not used as attaining very high temperature by this method is difficult and laser heating technique is not preferred because of low efficiency. Resistive heating is the simplest method although it can be used upto temperature of ~1500 ℃. The heating filament is generally made up of molybdenum, tantalum or tungsten depending upon the required temperature. The filament needs to me supported from an electrically insulating support. The vapor source is required to be surrounded by about 6 to 8 number of heat shields to minimize the heat loss from the crucible. To minimize the Doppler width of the atomic beam during interaction with laser (for better selectivity of isotope), the collimating slit of the vapor is partitioned along length as shown in Fig. 19.1. Photograph of a typical resistive heating furnace used for generation of Ytterbium (Yb) vapor is given in Fig. 19.2. When the required temperature of the vapor source is more than about 1500 ℃, it is generally preferable to use electron bombardment technique for heating the crucible. In this method, Filament temperature is raised to about ~2100 ℃ so that thermionic emission of electrons occurs and the crucible is held at ~2 kV so that electron are attracted towards it and bombard it at kinetic energy of 2 keV. Filament is generally made up of tantalum or tungsten. Primary part the power incident on the crucible, in this method, is due to bombardment of electrons and a smaller part is due to heat radiation coming from the filament. In this technique, the challenge is to keep the high temperature crucible electrically insulated so that it can hold 2 kV voltage and a good vacuum needs to be maintained all the time to avoid electrical discharges. Schematic diagram of an electron bombardment vapor source is given in Fig. 19.3 and photograph of a typical electron bombardment heating furnace used for generation of Lutetium (Lu) vapor is given in Fig. 19.4. The most complex type evaporation technique is the electron beam heating [224] which is used if the required temperature is more than 2500 °C. For evaporation of nuclear materials (uranium, zirconium etc) which have very low vapor pressure, temperatures ranging from 2700 °C to 3000 °C are required to be maintained. To achieve this, a concentrated beam of electrons is made to impinge upon the surface of target material where a localized high temperature is generated resulting in evaporation of materials. Crucible holding the target is water cooled. Advantage of this method is that since the heating is localized, outer skull of the target remains in solid state and so corrosion of the crucible by liquid metal is avoided. However, for better focusing of electron beam, energy of the electrons should be about 10 kV to 50 kV and hence high voltage discharge problems do occur in these systems. As about 40% incident electrons are backscattered, thermal design of the system should take care of it. In addition, due to electron beam hitting the surface from top, laser interaction zone needs to be kept at much higher height from the evaporating surface ultimately reducing the utilization efficiency of the atomic vapor. Scheme and photograph of a typical 270°, bent electron gun used for generation of uranium vapor are given in Fig. 19.5.

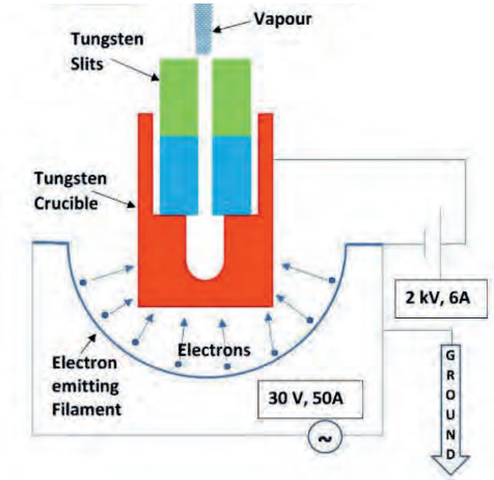

Figure 19.3: Schematic diagram of an electron bombardment vapor source.

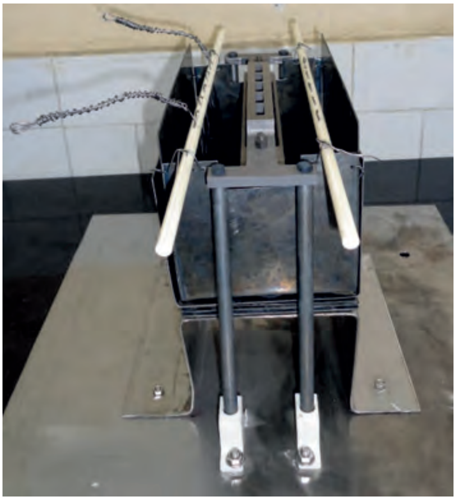

Figure 19.4: Photograph of a electron bombardment heating furnace used for generation of Lutetium (Lu) vapor.

19.3 Estimation of Atomic Beam Characteristics

During LIS process, the atom density at the laser interaction zone needs to be correctly estimated and Doppler width of vapor during interaction with laser should be ascertained to be less than a predefined value so that no undesired atoms are ionized during the process. Although the vapor source can be chosen to be either circularly symmetric or linear, linear vapor source is preferred in LIS process as this provides higher laser-vapor interaction volume leading to higher product quantity. This section will provide the generally used important mathematical formulae for calculations of atom density and Doppler width at the interaction zone. If ‘T’ is the temperature of the vapor source as measured by a thermocouple or a

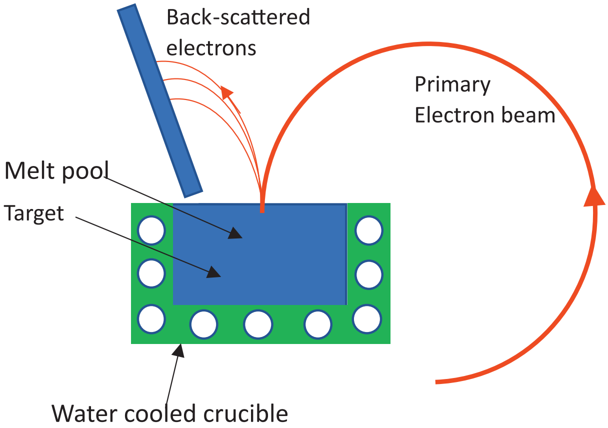

Figure 19.5: Basic scheme of 270° bent electron beam heating for generation of metal vapor.

two-color pyrometer, the vapor pressure of metal at the source is given by,

$$\ln P_{atm} = -\frac{A}{T} + B \tag{19.1}$$

For uranium, A = 63563 and B = 15 at temperatures ~2500 K to 3000 K (as per ref [225]) Atom density and average velocity of atoms at the vapor source are given by,

$$n_s = \frac{P}{kT} \tag{19.2}$$

$$v_s = \sqrt{\frac{8}{\pi}\frac{kT}{m}} \tag{19.3}$$

Knudsen number is,

$$k_n = \frac{1}{\sqrt{2}\pi n_s d^2 w}$$

d = van der Wall's diameter of atom and w = width of vapor source. For a circular source of radius 'r_0', atom density at a height of 'h' is approximately given by,

$$n = n_s\left(\frac{r_0^2}{h^2}\right) \tag{19.4}$$

However, for a linear vapor source, variation of atom density with distance from the source can be calculated by using the empirical relations reported by Rosenguard's [226] Monte-Carlo simulation of atomic vapor emerging from a rectangular source. According to it, atom density 'n' and average velocity 'v' of the atoms at the height of 'h' above a rectangular source are given by,

$$n = C\,\frac{n_s w}{L}\left[\left(1 + \frac{L^2}{h^2}\right)^{\gamma} - 1\right] \tag{19.5}$$

$$v = v_s\left[1.4 - \frac{0.38}{1 + 0.126/k_n} - \frac{0.0625L}{h}\right] \tag{19.6}$$

where w = Width of vapor source; L= Length of vapor source; and C is a constant given by,

$$C = 0.12 + \frac{0.039}{1 + 0.25/k_n} \tag{19.7}$$

$$\gamma = 0.5 + 0.295\left(1 - \frac{0.039}{1 + 0.13/k_n}\right)\left(\frac{h}{L} - 0.3\right) \tag{19.8}$$

Atomic flux 'φ' at the height of 'h' is given by product of atom density 'n' and average velocity 'v' of the atoms given by Eqs. (19.5) and (19.6), i.e.

$$\varphi = nv = n_s v_s C\,\frac{w}{L}\left[\left(1 + \frac{L^2}{h^2}\right)^{\gamma} - 1\right]\left[1.4 - \frac{0.38}{1 + 0.126/k_n} - \frac{0.0625L}{h}\right] \tag{19.9}$$

Atomic flux φ at the laser interaction zone can be directly measured by a quartz crystal thickness monitor. If rate of increase of thickness of coating on the sensor is 'S' (Å/sec), atomic weight of metal is m, density is ρ, atomic flux is given by,

$$\varphi = \frac{\rho S}{m} \tag{19.10}$$

By dividing flux by velocity, one can get the atom density n at the interaction zone. Of course, if higher accuracy of result is desired, it is essential to consider the value of velocity to be higher than the average velocity as given in [227]. Doppler width of the atomic vapor is important from the point of view of the selective photo-ionization of the atoms by the laser. In general Doppler width (FWHM) of the vapor just at the point of evaporation is given by [228],

$$\Delta\nu_s = 7.16 \times 10^{-17}\nu_0\sqrt{\frac{T}{m}} \tag{19.11}$$

However, because of collimation by slits [228], Doppler width is reduced by the multiplying factor $\sin\phi$, where $\phi = \tan^{-1}(a/b)$ ('a' and 'b' are the half of slit length and slit height from the vapor source respectively). So, Doppler width at the laser interaction zone is given by,

$$\Delta\nu_a = [Sin\phi]\,7.16 \times 10^{-17}\nu_0\sqrt{\frac{T}{m}} \tag{19.12}$$

One very effective way to reduce the Doppler width is to place few metal plates in close separation along length of the slit which reduces the divergence half-angle ϕ. By using such a Doppler reducer, it was possible to reduce the Doppler width of Yb atomic from ~450 MHz to ~240 MHz.

19.4 Conclusion

Generation of atomic beam with desired parameters is an important aspect for successful Atomic Vapor Laser Isotope Separation. Depending upon the required temperature of the vapor source, one may adopt any of the heating techniques such as resistive heating (for low temperatures), electron bombardment (medium temperature) or electron beam heating (for high temperatures). This concept is further explained through the schematic and design considerations of each of the techniques with their advantages and disadvantages. Finally, in this discussion, many key formulae are presented that are used to estimate the atom density and Doppler width of the atomic beam at the laser interaction zone. Most importantly, a physical technique to bring down the Doppler width to acceptable level has been demonstrated.