

Supersonic sodium atomic beam hyperfine structure measurement orthogonally with dye laser R6G

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Abstract

Supersonic sodium atomic beam of limited broadening, of angular divergence of 5.15° was generated to investigate the hyperfine structure of sodium D_2 line. R6G dye laser was orthogonally with Na-atomic beam and recoding of fluorescence signal ($\lambda=5896\text{\AA}$) showed a hyperfine structure of Na- D_2 line of 1.03 GHz.

Keywords: Sodium atomic beam, supersonic, laser.

Introduction

Atomic and molecular beams have been studied since their ties for the generation of limited divergence atomic or molecular beam for gases or vapor (Smith, 1955; Ramsey, 1956; Shapiro, 1963; Valyi, 1977). The literature mostly includes the generation of an atomic beam from an oven by effusion from a slit to a less pressure boundary. The slit has to be of the order of the mean free path of the heated element as obtained from the P-T curve in the case of evaporation from solids or liquids. The beam is then generated according to Fig.1 where the divergence takes a shape of cosine distribution, the beam is collimated by further insertion of slits which would also limit the net flux of the beam due to the solid angle introduced (Valyi, 1977). The maximum beam flux from effusive sources, reaches of the order 10^{10} part/sec steradian which makes it a source of limited yield (Valyi, 1977).

The need to generate sources of high flux, minimum divergence and high speed throughputs has been felt. Nozzles have intense yield that vary between 10^{14} - 10^{16} part/sec steradian and with limited divergence of the atomic or molecular beam. The velocity distribution of beam reduces with super atomic or molecular beam from gases, but the literature is scarce on the generation of supersonic beam by evaporating metals (Werkstoffkunde, 1959).

This report present the endeavour to design a nozzle for the generation of supersonic atomic beam as obtained with sodium metal.

Theory and design

The basic concept of fluid dynamic (Ramsey,1956) and aerodynamics theory as explained by T.Von Karman (1954), contains the mean features for the explanation and formulation of fluid flow and nozzle design. The main requirements for the fulfillment of supersonic flow are as follows (Shapiro, 1963; Valyi, 1977):

Frictionless flow

The surface smoothness for the nozzle and temperature distribution where the skin friction of viscosity of the fluid and the rate of which the velocity increases above the surface.

Steady flow

No surface protrusions (sharp ends) that might cause disturbances which results in a shock wave formation (Valyi, 1977).

Continuum flow

To obtain a continuous stream of atoms or molecules through the nozzle, the throat diameter of the nozzle should be much larger than the mean free path of the particles (mfp) (Streeter, 1975; Zalick *et al.*, 1993).

$\phi \gg \text{mfp}$

$$\text{mfp} = \frac{1}{\sqrt{2n\pi\sigma^2}} \dots\dots\dots(1)$$

where

ϕ =nozzle throat diameter

n = density of particles

σ = molecular collision diameter

= 3.72×10^{-8} cm for sodium at room temperature (Valyi, 1977).

Adiabatic flow

Conditions are near to ideal case where no friction, heat or gain into the system. The equations of isentropic flow states (Werkstoffkunde, 1959):

$\gamma = 1.4$ diatomic molecules

$\gamma = 1.667$ monoatomic molecules

$$T / T_o = (P / P_o)^{\frac{\gamma-1}{\gamma}} \dots\dots\dots(2)$$

$$n / n_o = (P / P_o)^{\frac{1}{\gamma}} \dots\dots\dots(3)$$

$$v = \frac{1}{\left(1 + \frac{\gamma-1}{2} M^2\right)^{1/2}} (\gamma T_o R)^{1/2} \dots\dots\dots(4)$$

$$A_e / A_o = \frac{1}{M} \left[\left(\frac{2}{\gamma+1} \left(1 + \frac{\gamma-1}{2} M^2 \right) \right) \right]^{\frac{\gamma+1}{2(\gamma-1)}} \dots\dots\dots(5)$$

$J = nu$. Area of skimmer. Solid part/sec.

Where:

γ =ratio of specific heat

P =pressure outside nozzle

P_o =pressure inside nozzle container

T =temperature outside (downstream)

T_o =temperature inside nozzle container

n =density downstream

n_o =density inside nozzle container

M=mach no.
 A_e=area of exit
 A_o=throat area of nozzle
 R=universal gas constant

$$= \frac{8.314 \times 10^7}{\text{molecular weight}} \text{ erg/degree}$$

The main feature of the nozzle design is to start with the following (Werkstoffkunde, 1959; Shapiro, 1963):

1. Beside on the mass flow through the throat of the nozzle according to the pumps available that can handle this throughput.
 Gas density. Velocity. A throat = mass flow = constant.
2. Beside on a certain mach and work out the ratio of the following P/P_o, A/A_o and T/T_o.
 The final shape of the nozzle is obtained by trial and error due to the other unknown parameters, like friction between vapor and surface of nozzle. The final throat temperature should be higher than vapor temperature to avoid condensation or shock wave formation.
3. The divergence angle of the nozzle (exit) has to satisfy two main requirements.
 - a. Controlled slow expansion of the beam at the exit to avoid sudden expansion or shock wave formation (Streeter, 1975).
 - b. Jet boundary has to fulfill parallel flow (minimum divergence) where the pressure of the beam has to be equal to the pressure in the rest of the chamber.

P_{jet}=P_{chamber}

If otherwise

P_j>P_c beam is over-expanded

P_j< P_c beam is under-expanded

and in both cases the beam does not take parallel flow

$$dP = 0 = \frac{\partial P}{\partial A} + \frac{\partial P}{\partial \theta} d\theta \dots \dots \dots (6)$$

dP=Pressure change along jet boundary

$$\frac{\partial P}{\partial A} dM + \frac{\partial P}{\partial \theta} d\theta = 0 \dots \dots \dots (7)$$

change in area dA result in a change in mach dM for isentropic flow:

$$\theta = \left(\frac{\gamma - 1}{\gamma + 1} \right)^{1/2} \tan^{-1} \left(\frac{\gamma - 1}{\gamma + 1} \beta \right)^{1/2} - \tan^{-1} \beta - \left[\left(\frac{\gamma + 1}{\gamma - 1} \right)^{1/2} \tan^{-1} \left(\frac{\gamma - 1}{\gamma + 1} \right)^{1/2} \beta \tan^{-1} \beta \right] \dots \dots (8)$$

where

$$\beta = \sqrt{M^2 - 1}$$

θ= maximum nozzle divergence for parallel beam trajectory

4. Skimmer: For further confinement of beam geometry, skimmer is placed to certain position and shape to account for the following:
 - a. Internal angle of the skimmer is important to absorb the out flowing molecules to avoid shock wave formation and back scattering of molecules of the

skimmer is such to reflect sideways the molecules of the tail of the incoming beam, where they would be pumped out without affecting the main stream.

- b. The distance between the nozzle and skimmer (I_s), occurs around the first mach disk of the out flowing beam to prevent shock wave and with maximum throughput (Streeter, 1975)

$$\frac{r(M.D)}{\phi} = 0.67(P_o / P)^{1/2} \dots \dots \dots (9)$$

I_s< r(M.D)

M.D.: Mach disk

P_o: Pressure inside nozzle container

P: Pressure in chamber

I_s: Position between nozzle and skimmer

The above empirical equation (9) resembles the minimum distance of occurrence of mach disc.

Experiment

The throat of the nozzle was first 2mm diameter which was then reduced to 1mm diameter, different operating conditions were performed i.e. operation at different temperatures, hot gas injection was also tried while heating the sodium in the nozzle.

The results was not satisfactory, it should have a broad distribution of beam velocity but narrow geometry, this because the nitrogen hot acts as a carrier to the sodium atoms with no preferential in atomic out flowing velocities.

The test points were to photograph the fluorescence of the beam due to laser atomic beam interaction as shown in Fig.1 Schlieren shadow graph technique was also tried for further indication of the beam profile.

Various nozzles were tried with divergence of 8°, 30°, 40° and 60° of which the best nozzle was chosen according to minimum divergence of beam.

The length of the diverging part of the nozzle was not critical. The designed divergence length was 3mm and 5mm but in both cases showed to affect on the out flowing beam.

The main set up includes the differential pumping system as shown in Fig.2 which shows the designed heater of kanthal obtained as measured by Pt/13 Rh thermocouple placed at the throat of the nozzle more

details of the nozzle as shown in Fig.3 .

The water cooled jacket around the nozzle, adsorbs the plume effect of the beam that usual occur at the nozzle and cause further scattering of the beam.

The laser part includes 171-19 type spectra physics argon ion laser pumping ring dye laser type 380D spectra physics with stabilized single frequency output CW dye laser.

The laser with mode separation of 200MHz is tuned with piezo etalen free spectra range (FSR) 75 GHz, fine etalon FSR-900 GHz, and piezo mount M₂ mirror as shown in Fig.4.

Fig. 1. a. Shape of beam effusive, b. Supersonic nozzle beam, c. Photograph of laser with atomic beam fluorescence interaction

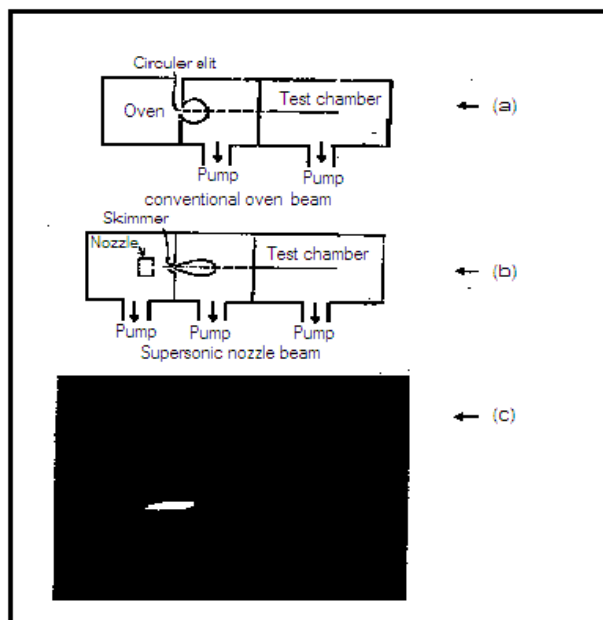


Fig. 2. Schematic diagram showing atomic beam interacting with dye laser

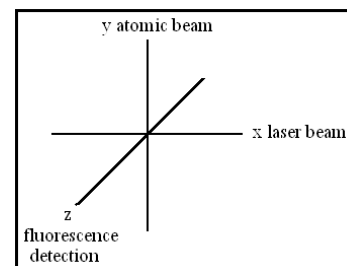


Fig.3. Details of nozzle and skimmer

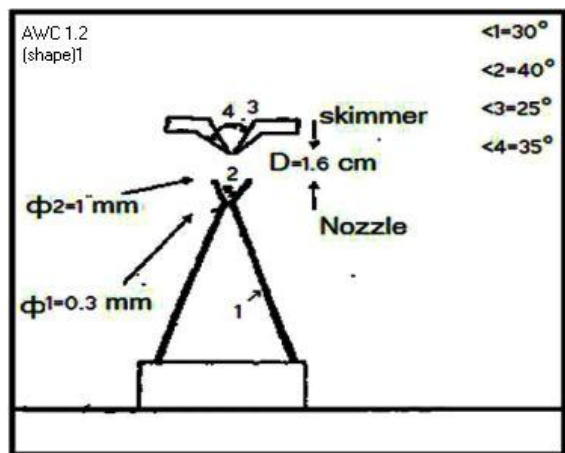


Fig. 5. Spectrum of ring dye laser interaction with Na atomic beam at beam temp of 77K showing Na-D₂ line, Ring dye laser scan 10GHz, Temp of nozzle 415°C, FWHM=0.32 GHz, Width of hyperfine structure =1.03GHz.

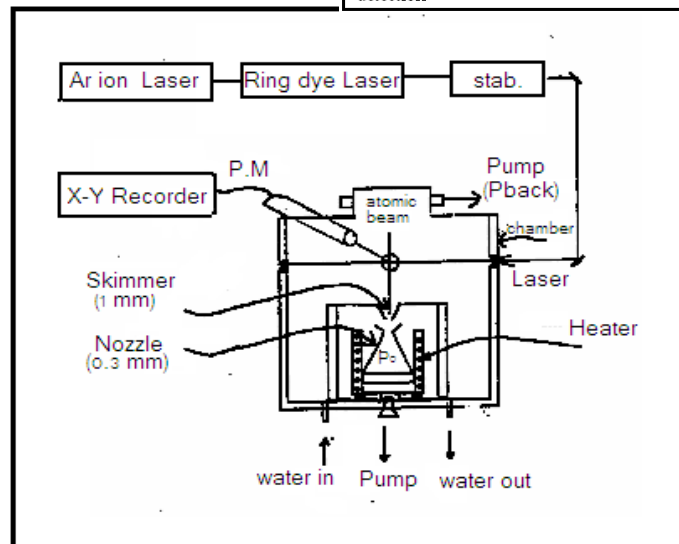
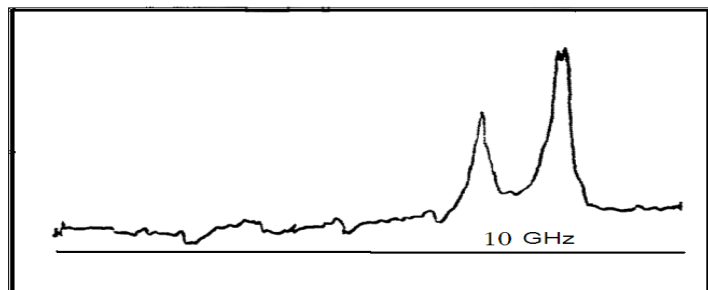


Fig.4. Ring dye laser

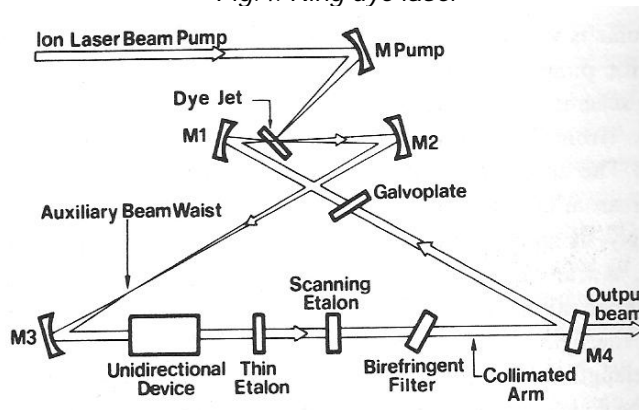
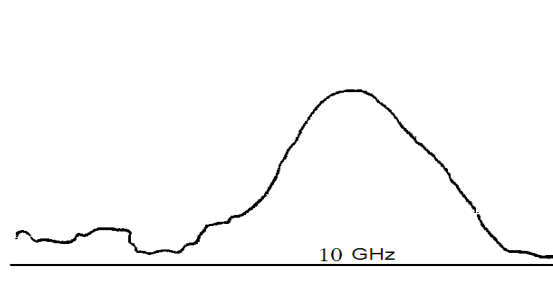


Fig. 6. Spectrum of Na-cell D₂ line with ring dye laser FWHM=2.46 GHz



The R6G dye laser was tuned to the sodium D_2 line 5895.923\AA , the wavelength was checked with a sodium reference absorption cell which show fluorescence of the self reversible sodium line.

The laser was aligned to orthogonally interact with the Na atomic beam, the fluorescence signal was detected with an EG & G type photomultiplier, that was placed orthogonal both to the laser and Na atomic beam as shown in Fig.2. Care was taken to reduce background in the vacuum interaction chamber.

Results and discussion

Fluorescence signal of the beam due to the 10GHz scan and interaction range of the laser with supersonic atomic beam, was detected by the photomultiplier and the signal was recorded on xy recorded as shown in Fig.5; likewise, the cell action i.e. broader interaction region of the laser with the Na particles was also recorded and show in Fig.6.

The results indicate a supersonic atomic beam of mach 4.855 and beam velocity 10.5×10^4 cm/sec (as calculated from equations (1) and (4)), where details of the nozzle shown in Fig.3. The width of nozzle at FWHM=0.32 GHz as compared to the cell action of 2.46GHz.

The beam diverge by 5.15° as calculated from Doppler interaction of the laser beam with the supersonic atomic beam of sodium (Streeter 1975).

$$\frac{\Delta v}{v} = \frac{v \sin \theta}{c} = \frac{\Delta v}{c/\lambda}$$

$$v \sin \theta = \Delta v \lambda$$

where:

v =beam velocity, 10.5×10^4 cm/s

c = speed of light

$v \sin \theta$ =component of beam velocity in the direction of the laser

Δu = half width of beam profile =0.32/2GHz

λ = 5895.923\AA

θ = 5.15°

The flux of the beam was measured by collecting the Na atoms adsorbed on a glass plate for a certain. The measured flux 6.98×10^{15} part/sec. as compared to the calculated rate 9.44×10^{14} part/sec. (equation 6.), the overall results listed in Table 1.

The shift in the hyperfine structure of the Na D_2 line 5895.923\AA of transition $3^2p_{3/2} - 3^2s_{1/2}$ as shown in Fig.5

Fig. 7. Part of the level scheme of sodium showing the hyperfine splitting of the $3^2p_{3/2}$ and the ground state $3^2s_{1/2}$.

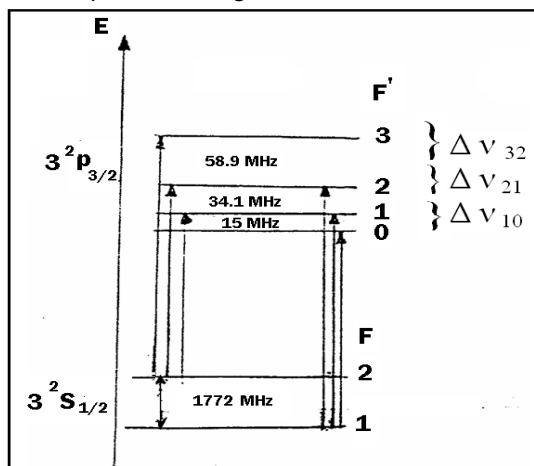


Table1. Results with sodium

Mach=4.85
Flux rate (measured)= 6.98×10^{15} part/sec
Flux rate (calculated)= 9.44×10^{14} part/sec
Φ =0.3mm
λ_{mfp} =0.148mm
line (FWHM)=0.32GHz
Laser of a Na line = 5895.923\AA
Temp. (T_0)= 415°C
T =77K
Hyperfine structure = 1.03GHz
P_0 =0.7 Torr
P_s = 3×10^{-3} Torr , P_b = 1×10^{-5} Torr

been measured 1.03GHz of the fluorescence laser supersonic atomic beam interaction. The shift in the hyperfine structure is the splitting of $^2s_{1/2}$ ground state of the sodium D_2 -line as shown in Fig.7 (Alhasan & Fiutak, 2002).

The hyperfine shift in sodium have been measured by many authors being 1.7GHz as measured from fluorescence of laser effusive type atomic beam interaction (Zalic *et al.*, 1993).The main difference between supersonic beams and effusive type beams (a part from the difference in flux and width

of the beam), are the temperature of the atoms or molecules in the beam. The temperature calculated being 77K as compared to room temperature (300°K) in case of effusive type beam. This effect causes sharper lines and narrower broadening. The high resolution obtained allows calculated the splitting of state in term of electronic, nuclear & total angular momentum.

Where $F=I+J$

The energy of the hyperfine structure is (Zalic, 1993)

$$W_F = W_J = \frac{C}{2} A_J + \frac{3C(C+1) - 4I(I+1)J(J+1)}{8I(2I-1)J(J+1)} B_J$$

where $C=F(F+1)-I(I+1)-J(J+1)$

W_J = Energy of fine structure term.

A_J =Magnetic splitting factor

B_J =Nuclear quadruple coupling const.

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