Preliminary Study of a Photoionized-Barium Plasma Source for the W II a Stellarator

S. Ishii and W. Ohlendorf

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Die nachstehende Arbeit wurde im Rahmen des Vertrages zwischen dem Max-Planck-Institut für Plasmaphysik und der Europäischen Atomgemeinschaft über die Zusammenarbeit auf dem Gebiete der Plasmaphysik durchgeführt.

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S. Ishii+) and W. Ohlendorf

ABSTRACT

A source of photoionized barium plasma from metastable atoms is developed for study on the W II a stellarator.
An ion flux of 2×10^{12} sec^{-1} is obtained.

I. INTRODUCTION

It was proposed that a photoionized barium plasma should be used for the W II a stellarator to avoid an ambiguity arising from contact of the plasma with solid materials (1). The direct photoionization of barium with light from a cascade arc (2,3) was attempted but the yield of photoionized plasma was too low for study on the stellarator. Normal photon sources, such as cascade arcs and xenon high-pressure lamps, provide insufficient photon flux in the ultra-violet region to which the ionization energy of the barium corresponds. Likewise, there are not tractable lasers in this spectral region.

A most promising method was proposed by one of us, making use of metastable states (4,5) which ionization energy is lowered by 1.1 $\sim$ 1.5 eV; normal photon sources are available for the ionization of metastable barium. The yield of metastable atoms in the case of calcium has been reported to be about 20 % (6).

The purpose of the present work is to develop a photo-ionized-barium plasma source from metastable atoms. Excitation of the metastable barium was performed by means of an electric discharge in barium vapor in a manner similar to that of ref. 6. Population densities of states of the barium were determined by the resonance fluorescence method (7,8,9) and an extremely large

+) On leave from Rikagaku-Kenkyusho (the Institute of Physical and Chemical Research), Honkomagome, Bunkyo, Tokyo

fraction of the atoms was found to be in the metastable states (10).

The photoionization of this metastable barium was carried out under experimental conditions similar to that of the stellarator. The yield of photoionized plasma was somewhat larger than the theoretically-predicted value based on the quantum-theoretical cross-section of the metastable barium (11).

In the course of this work several technical difficulties have to be conquered:

1) there is at hand no insulator which is not reduced to metal by high temperature in the presence of barium vapor;

2) the restricted size and shape of the stellarator ports demanded an extremely compact metastable-barium source assembly, which was constructed with much effort;

3) the form of the orifice of the barium oven had to be improved to avoid condensation of the barium on undesirable plaees in the discharge component.

The conquest of these problems should be seen occasionally in the experimental procedures.

II. ELECTRIC DISCHARGE IN BARIUM VAPOR

In order to design the discharge component of the metastable-barium source, some characteristics of the barium discharge were investigated. In this stage of the work the barium oven of ref. 9 was used, partly because it has been elaborately calibrated. The naked discharge electrodes (seen in Fig. 4) were placed 10 mm above the oven and spaced 5 mm apart. Figure 1 shows (a) the emission current of the tantalum cathode versus cathode-heating current at an accelerating potential of 500 V and (b) the discharge current in barium vapor of 2×10^{-4} Torr versus the cathode-heating current at a fixed discharge voltage of 500 V. The maximum base pressure was 3×10^{-5} Torr. The peak of the discharge current at a cathode-heating current of $3.5 \sim 4$ A prevails in all ranges of attainable barium pressure. To obtain the maximum discharge-plasma density the cathode-heating current was fixed at the value which gives this peak discharge current. A slight increase of the barium pressure changes the discharge condition a great deal, as seen in Fig. 2; one can see an extremely large difference between the discharge voltages, comparing Fig. 1- (b) and Fig. 2- (a). At the barium pressure 2.5×10^{-4} Torr (Fig. 2 (b)) one can see the glow-to-arc transition according to the general classification of electric-discharge modes. In the negative voltage-current characteristic region of the curve (b) in Fig. 2 the state of the discharge was much noisier.

III. PRODUCTION OF METASTABLE BARIUM

In the atomic energy states of barium one can see one singlet and three triplet metastable levels (Fig. 3). Restricted to only simple transitions the singlet term is enriched through excitation of the energy levels 6p $^1P_1^o$, 6p, $^1P_1^o$, and 7p $^1P_1^o$; the triplet terms through 6p $^3P_1^o$. A number of other multiple/cascade transitions (not shown in Fig. 3) may participate in the enrichment of these metastable terms. The physical process for the excitation of the upper levels in electric discharges is considered to be principally collisions with plasma electrons.

In order to design the electric discharge component for the excitation of barium one must first study the excitation probability of barium. The cross section for collisional excitation of barium by electrons is, however, experimentally unknown. If it can be considered of the same order as that of cesium ($\sim 10^{-14}$ cm^2)[12], and a plasma of electron density

$\sim 10^{12}\,cm^{-3}$ and electron temperature $\sim$ 5 eV can be obtained, the mean free path for excitation is smaller than 1 mm.

The assembly of the discharge electrodes and the barium oven is shown in Fig. 4. The barium oven, designed to give much more barium flux to the stellarator, is modified at the orifice so as to be compatible with the discharge component. The density of barium vapor between the electrodes is of the order of $10^{13}\,cm^{-3}$ at the maximum temperature of the oven in the absence of the discharge; the density at the measuring point, 60 mm above the electrodes, is reduced by the factor 3×10^{-2}. The cathode is a 0.3 mm diameter tantalum wire spiralled to 3 mm diameter, 10 mm length. The discharge current can be varied up to 1 A; the discharge voltage is of the order of 10 V and decreases with increasing barium vapor pressure. The discharge space is surrounded by a thin stainless-steel wall (see Figs. 4,5) and this wall may be highly heated by the discharge so as to prevent barium atoms from condensing on it. This reflection effect of the hot wall can clearly be seen in a following experimental result (Fig. 8).

The barium vapor jetting out of the 4 mm diameter orifice of the oven is collimated with an aperture limiter of 7 mm diameter and forms an atomic beam of 10 mm diameter at the measuring point (Fig. 6). Since the lifetime of the metastable barium atoms is as long as 10 $\sim$ 100 sec (5,11), these atoms remain lossless in the atomic beam. The brighter core of the barium beam seen in Fig. 6 contains the main fraction of metastable atoms according to the measurements. The outer glimmering (green) part is the dispersed vapor which scatters the light of the discharge at a resonance wavelength of 5535 Å.

IV. MEASUREMENT OF METASTABLE BARIUM

1) Method of the measurement.

The population densities of metastable barium were determined by the resonance fluorescence method (7,8,9). The block diagram of the measurement is shown in Fig. 7. The modulated light from a xenon high-pressure lamp (XBO 900 W) illuminates the barium beam and the resonance emission perpendicular to both the illuminating light and the barium beam is received with a monochromator. The electric signal from a photomultiplier mounted on the monochromator is recorded through a narrow-band amplifier tuned at the modulation frequency. The holder of the receiving optics is installed with a helical potentiometer to observe the spatial distribution of the density. The large slit width of the monochromator (1 mm) was employed to obtain a sufficiently large signal at the expense of resolution.

The intensity of the resonance emission $J_{\lambda'}$ is given in terms of the illuminating light intensity I_λ under the condition that the scattering medium is optically thin:

$$J_{\lambda'} = p_{\lambda'} q_{\lambda'} t_{\lambda\lambda'} \frac{\Omega}{4\pi} I_\lambda \frac{\pi e^2 \lambda^2}{m c^2} f_\lambda n_s M W \qquad \frac{\text{photons}}{\text{sec}\cdot\text{cm}^2\cdot\text{ster}} \qquad (1)$$

where M is the magnification of the illuminating optics; W is the effective breadth of the lamp; n_s is the density of the atoms which absorb the photons at the resonance wavelength λ ; f_λ is the oscillator strength (13) for the resonance excitation; $q_{\lambda'}$ is the branching ratio for the resonance emission at λ' ; $p_{\lambda'}$ is the anisotropy factor due to polarization of the emission; $t_{\lambda\lambda'}$ is the transmittance of the optics; Ω is the solid angle subtended by the exit pupil of the illuminating light at the barium.

In the emission spectrum of the excited barium are observed four predominant peaks close to the wavelengths 5500 Å, 5800 Å, 6000 Å, and 6500 Å, each arising from each group of several transitions tabulated in Table 1. The poor resolution power of the monochromator requires only a somewhat laborious summation of contributions from all relating transitions for each peak; for each peak one equation is obtained for the response of the photomultiplier at λ' by summing up the right hand side of eq. (1) with respect to λ .

One then obtains four simultaneous equations with five unknown n_s's: the densities of $^1S_0$, $^1D_1$, $^3D_{1,2,3}$. Considering that the densities of the triplet terms are nearly equal (Boltzmann's law), we determined these densities from three of the four equations, checking the compatibility of the rest with the resulting values.

2) Experimental Result

The measured population densities at a moderate temperature of the barium oven versus the discharge current is shown in Fig. 8. The density n_3 of the metastable state reaches a maximum value at a discharge current of about 0.3 A and is considered to be saturated at larger currents. This saturation suggests a high population of the metastable states; the plasma density increases with increasing discharge current. (At this current the discharge is in the stable mode, as mentioned in section II). At the maximum temperature of the oven with the discharge current of 0.3 A the population densities of various states were determined to be:

$n_0 = 1.4 \times 10^{10}\ cm^{-3}$ for the ground state,
$n_1 = 6 \times 10^{9}\ cm^{-3}$ for the single term,
and $n_3 = 3 \times 10^{10}\ cm^{-3}$ for each triplet term,

while the density in the absence of the discharge was $n_0 = 3.3 \times 10^{10}\ cm^{-3}$. It is noted that the sum of those densities in the presence of the discharge is three times as large as this density in the absence of the discharge. This discrepancy obviously arises from the reflection effect of the hot wall of the discharge space, as mentioned in section III. Assuming that the discharge space is in thermal equilibrium with the oven, the total density with the discharge should be:
$n_0 = 4.3 \times (3.3 \times 10^{10}) = 1.4 \times 10^{11}\ cm^{-3}$ according to a rough theoretical estimation; the yield of metastable atoms then should amount at least to 68 %.

3) Some remarks.

If the scattering medium is optically thin, only the light polarized perpendicular to the plane containing both the direction of the illumination and that of the scattering can be observed (8,14). In order to check this effect we illuminated the barium with plane-polarized light. The experimental result is shown in Fig. 9, in which $I_{\perp}$ and $I_{\parallel}$, respectively, are the intensities of the scattered light when the illuminating light is polarized perpendicular and parallel, respectively, to the plane containing the directions of both the illumination and the observation. It can clearly be seen that the polarizability is getting weaker by the larger density.

The condition of thin optical thickness is formulated (9) as

$$n_s \ell \lesssim 2 \times 10^6 (\Delta \bar{V} + 10^3)/f_\lambda \quad cm^{-2} \tag{2}$$

where ℓ is the geometrical thickness of the medium, $\Delta \bar{V}$ is the spread of the mean thermal speed of the atoms and f_λ is the oscillator strength of the relevant transition. In the present case this turns out to be $n_s \lesssim 5 \times 10^{10} cm^{-3}$ for the transition λ 5535 Å in good agreement with the polarization experiment. The value of n_o shown above thus amounts to the marginal value of the validity of the measurements. In other cases this problem does not arise because of the small values of f_λ.

The barium discharge brightens very strongly. In order to investigate the possibility of photoexcitation by this light we measured the absolute photon intensity of the discharge. The spectrum has large line peaks at 4554 Å, 4726 Å, and 4947 Å in addition to 5535 Å, along with many other lines. The absolute intensities are 1×10^{25} at 5535 Å, 2×10^{24} at 4554 Å etc., in unit of photons/sec x cm^2 x cm($\Delta\lambda$) x ster, where the Doppler broadening of the barium is employed as $\Delta\lambda$. Using a classical value of photoexcitation cross-section (14), one obtains 25 cm as the excitation length of atoms for the transition λ 5535 Å if the discharge space forms a large cavity. This means that photoexcitation is negligible for enrichment of the metastable states.

V. PHOTOIONIZATION OF THE METASTABLE BARIUM

1) Theory

When photons with energy higher than the ionization energy of a gas travel in the gas, they are absorbed for ionization, giving their excess energy to the released electrons. The increase dI_λ of photon intensity at the wavelength λ within the absorption band in the course of travelling in a gas of density n is given by

$$dI_\lambda = -\sigma_\lambda n I_\lambda dx \qquad \frac{\text{photons}}{\text{sec} \cdot \text{cm}^2 \cdot \text{unit}\Delta\lambda \cdot \text{ster}} \qquad (3)$$

where σ_λ is defined as the photoionization cross-section of the gas atom and dx is an infinitesimal distance in the gas. If the gas is homogeneous and the thickness ℓ of the gas layer is small compared with $(\sigma_\lambda n)^{-1}$, the total photon flux Φ absorbed for photoionization is given by

$$\Phi = n \ell \Omega \int_{\Delta\lambda} I_{o\lambda} \sigma_\lambda d\lambda \qquad \frac{\text{photons}}{\text{sec} \cdot \text{cm}^2} \qquad (4)$$

where $I_{o\lambda}$ is the irradiating photon intensity; Ω is the solid angle subtended by the exit pupil of the irradiating optics at the absorbing gas; the integration is carried out over the absorption band $\Delta\lambda$ of the photoionization cross-section.

If secondary ionization by the released electrons can be neglected, eq. (4) gives the ion flux produced by the photons.

2) Experimental arrangement.

The setup of the photoionization experiment is depicted in Fig. 10. Light from a xenon high-pressure lamp (XBO 6500 W) irradiates, through a quartz focusing system, the metastable-barium beam arranged in a stainless-steel vacuum vessel immersed in a magnetic field. An intense photon flux is released from the restricted volume of the lamp and its intensity amounts to 1.3×10^{25} photons/ sec · cm^2 · cm ($\Delta\lambda$) · ster at 3200 Å. In the arrangement of this experiment the diameter of the effective photon beam at the barium is 15 mm; the effective solid angle at the barium is 0.04 steradians, being combined with concave mirror on the back side of the lamp. (The best arrangement, in which the distance between the lamp and the barium is smaller, could not be fulfilled because the leakage magnetic flux disturbed the lamp discharge a great deal). Taking into account the loss factor arising from transmittance of the optics and shadowing of the setting, the ion flux is given by $\Phi_i = 3\ n cm^{-2} sec^{-1}$ where the value of σ_λ is employed from a quantum-theoretical calculation (11) under the assumption that the photoionization cross-sections of the singlet and the triplet terms are equal. With the obtained metastable barium the ion flux predicted to be $3 \times 10^{11}\ cm^{-2}\ sec^{-1}$.

The magnetic field is not dispensed with because the detection of the photoionized plasma has to be performed outside the irradiated space; this is only possible by measuring the ions along the magnetic field. Another reason for using it was to prevent the discharge plasma from diffusing to the irradiated space.

This suppression of the plasma was, however, not sufficient, probably due to the large ion Larmor radius: the ion current of the discharge plasma diffusing across the magnetic field was detected with an end plate put on the end of the barium beam (Fig. 10). The discharge component was, for this purpose, arranged outside the magnetic field in order not to change with changing magnetic field. Figure 11, being thus obtained, suggests that the enhanced diffusion occurs when the Larmor radius is equal to that of the vacuum vessel.

As the magnetic field could not be strengthened, a negatively-biassed grid was arranged on the top of the discharge component as shown in Figs. 10, 12, resulting together with the magnetic field in sufficient suppression of the discharge plasma.

The ion detector for the photoionized plasma, shown in Fig. 12, consists simply of a gridded plate and a naked plate arranged on both ends of the plasma column which elongates along the magnetic field lines. When the plate is contaminated with barium secondary electrons are easily produced by incident ions and photons from parasitic light. The grid, negatively biased with respect to the base plate, is therefore employed to repel the secondary electrons. The diameter of the grid is 18 mm. The whole measuring system is electrically insulated from both the discharge electrodes and the vacuum vessel.

3) Experimental result

From the ion saturation current to the ion detector (Fig. 13) we obtained $\Phi_i = 8 \times 10^{11}$ $cm^{-2}sec^{-1}$. This is about three times larger as the predicted value.

When there was no discharge, a photoionization signal could not be observed with the same measuring sensitivity. In addition, when the irradiating light was filtered with an optical test glass whose transmission characteristic is expressed as $\log_{10} (I_\lambda / I_{0\lambda}) = \lambda / 550 - 6.36$ for $\lambda < 3500$ Å, the ion flux was lowered to about onethird. This means that the photoionization is performed principally by the photons in the wavelength range of 3000 Å ~ 3500 Å, which covers the photoionization band $\Delta\lambda$ of all metastable states.

It was proved by changing the lamp discharge current that the produced ion flux is proportional to the photon intensity which is proportional to the square of the current.

4) Some remarks

The discrepancy between the predicted and the measured value of the ion flux may arise from other complex processes;

(1) ionization of metastable atoms by released electrons,
(2) enrichment of metastable atoms by released electrons and ionization by photons and/or the electrons.

The determination of the ion flux was carried out under the assumption that all ions are collected by the ion detector. If the large Larmor radius is taken into account (5 mm), the value determined above is corrected to a larger value.

If the second concave mirror is arranged on the other end of the irradiating light, the system forms an optical cavity and the number of produced ions will be multiplied.

Some improvement of the barium oven will give a further increase.

VI. CONCLUSION

It is concluded that we can obtain practically a sufficient amount of photoionized plasma for study of the W II a stellarator although several ambiguities remain as to physical interpretation. Only technical improvements give a further large amount of photo-ionized plasma.

The present geometrical form is proper to the W II a stellarator. Apart from special limitations the photoionized plasma source can find a general application to study of plasma physics.

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FIGURE CAPTIONS

Fig. 1: a) Dependence of emission current on cathode-heating current, accelerating voltage = 500 V;

b) Discharge current versus cathode-heating current, discharge voltage = 500 V, barium pressure = 2×10^{-4} Torr

Fig. 2: Voltage-current characteristics of barium discharge with cathode-heating current of 3.5 A at barium pressure of a) 2.3×10^{-4} Torr and b) 2.5×10^{-4} Torr.

Fig. 3: Energy level diagram of barium, related to metastable levels.

Fig. 4: Assembly of metastable-barium source.

Fig. 5: Discharge component.

Fig. 6: Excited barium beam, running from bottom to top. The outer glimmering part is thin barium vapor which scatters light of the discharge.

Fig. 7: Block diagram of measurement of barium density.

Fig. 8: Dependence of population densities on discharge current. n_o and n_3 are the population densities of $6s^2\ {}^1S_o$ and $5d\ {}^3D$, respectively.

Fig. 9: Effect of polarization of illuminating light on the resonance scattering of the barium. $I_\perp$ and $I_{\parallel}$, respectively, are the intensities of the scattered light when the illuminating light is polarized perpendicular and parallel, respectively, to the plane containing the directions of both the illuminating light and the observation.

FIGURE CAPTIONS (continued)

Fig. 10: Set-up of the photoionization experiment. Magnetic field is applied perpendicular to both the barium and the irradiating light.

Fig. 11: Magnetic-field dependence of ion current of the discharge plasma reaching the end plate across the magnetic field. r_i is the Larmor radius of the barium ion. The metastable-barium source is placed outside the magnetic field so that the discharge state remains unchanged with changing magnetic field.

Fig. 12: Scheme of measurement of the photoionized plasma.

Fig. 13: Characteristic of the ion detector current. The broken curve was taken with an optical test glass as a filter of the irradiating light.

Table 1: Transitions for determination of metastable barium

Absorption lines (Å)	Transitions	Emission lines (Å)	Observed peaks (Å)
5535	$6s^2\ {}^1S_o$ — $6p\ {}^1P^o_1$ — $6s^2\ {}^1S_o$	5535	5500
5806	$5d\ {}^3D_3$ — $6p'\ {}^1F^o_3$ — $5d\ {}^3D_3$	5806	
6483	$5d\ {}^1D_2$ — $6p'\ {}^1F^o_3$ — $5d\ {}^3D_3$	5806	5800
5826	$5d\ {}^1D_2$ — $6p'\ {}^1P^o_1$ — $5d\ {}^1D_2$	5826	
5997	$5d\ {}^3D_1$ — $6p'\ {}^3P^o_1$ — $5d\ {}^3D_1$	5997	
3889	$6s^2\ {}^1S_o$ — $6p'\ {}^3P^o_1$ — $5d\ {}^3D_1$	5997	6000
6063	$5d\ {}^3D_2$ — $6p'\ {}^3P^o_1$ — $5d\ {}^3D_2$	6063	
3889	$6s^2\ {}^1S_o$ — $6p'\ {}^3P^o_1$ — $5d\ {}^3D_2$	6063	
6483	$5d\ {}^1D_2$ — $6p'\ {}^1F^o_3$ — $5d\ {}^1D_2$	6483	
5806	$5d\ {}^3D_3$ — $6p'\ {}^1F^o_3$ — $5d\ {}^1D_2$	6483	
6498	$5d\ {}^3D_3$ — $6p'\ {}^3D^o_3$ — $5d\ {}^3D_3$	6498	
6595	$5d\ {}^3D_1$ — $6p'\ {}^3D^o_1$ — $5d\ {}^3D_1$	6595	6500
4132	$6s^2\ {}^1S_o$ — $6p'\ {}^3D^o_1$ — $5d\ {}^3D_1$	6595	
6675	$5d\ {}^3D_2$ — $6p'\ {}^3D^o_1$ — $5d\ {}^3D_1$	6675	
4132	$6s^2\ {}^1S_o$ — $6p'\ {}^3D^o_1$ — $5d\ {}^3D_2$	6675	

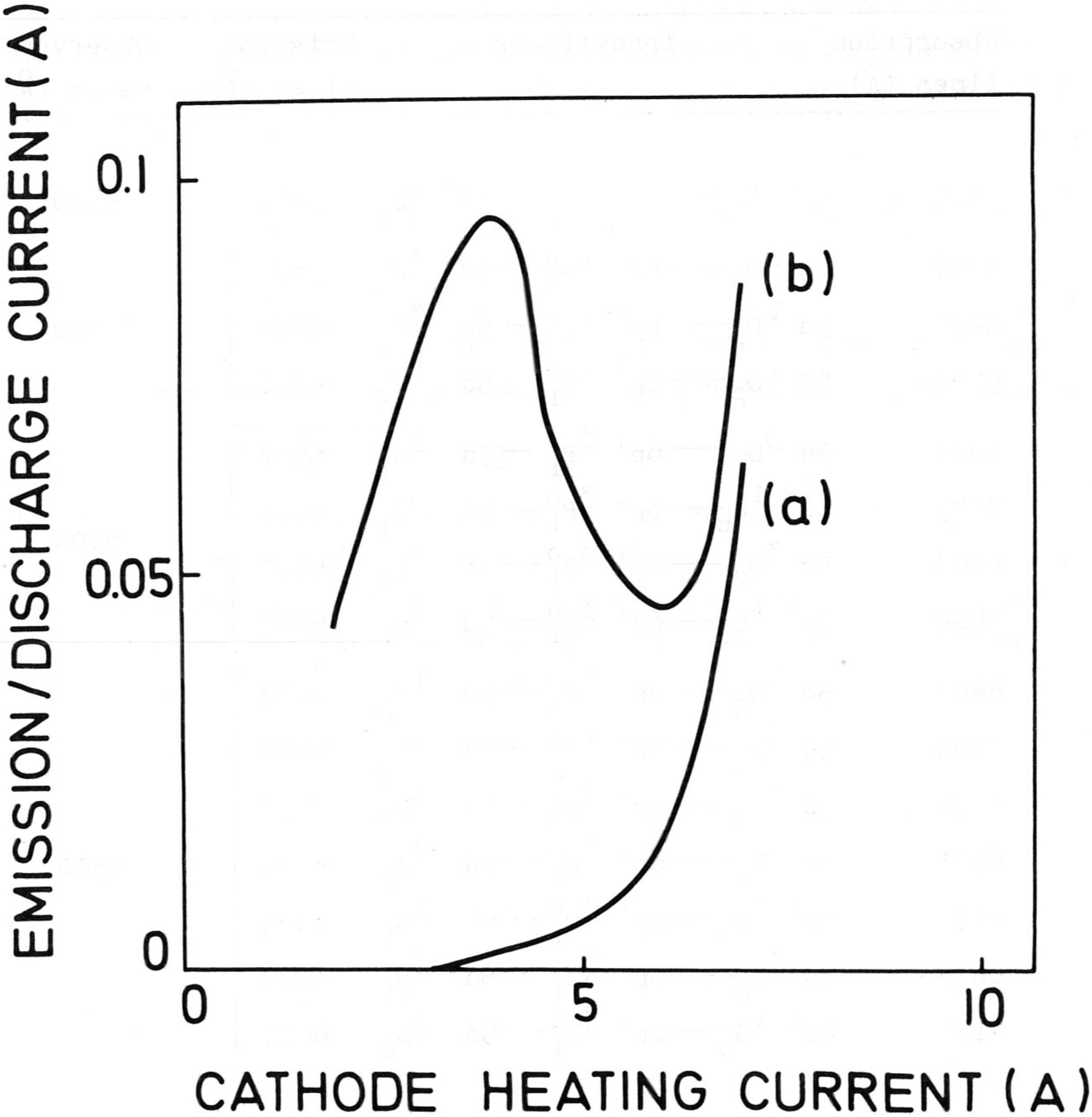

EMISSION / DISCHARGE CURRENT (A)
0.1
0.05
0
(b)
(a)
0
5
10
CATHODE HEATING CURRENT (A)

FIG. 1

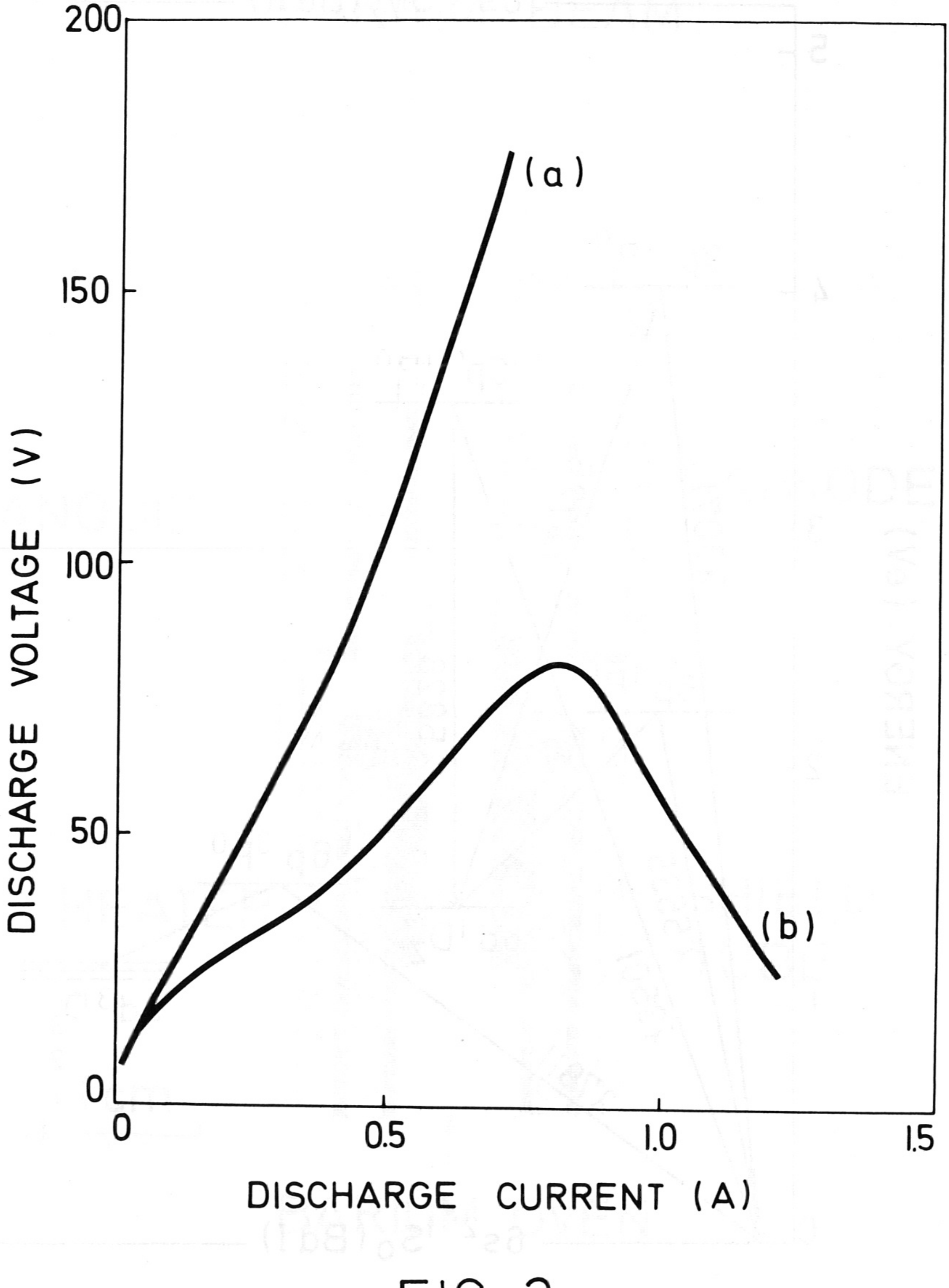

200
150
100
50
0
DISCHARGE VOLTAGE (V)
(a)
(b)
0
0.5
1.0
1.5
DISCHARGE CURRENT (A)

FIG. 2

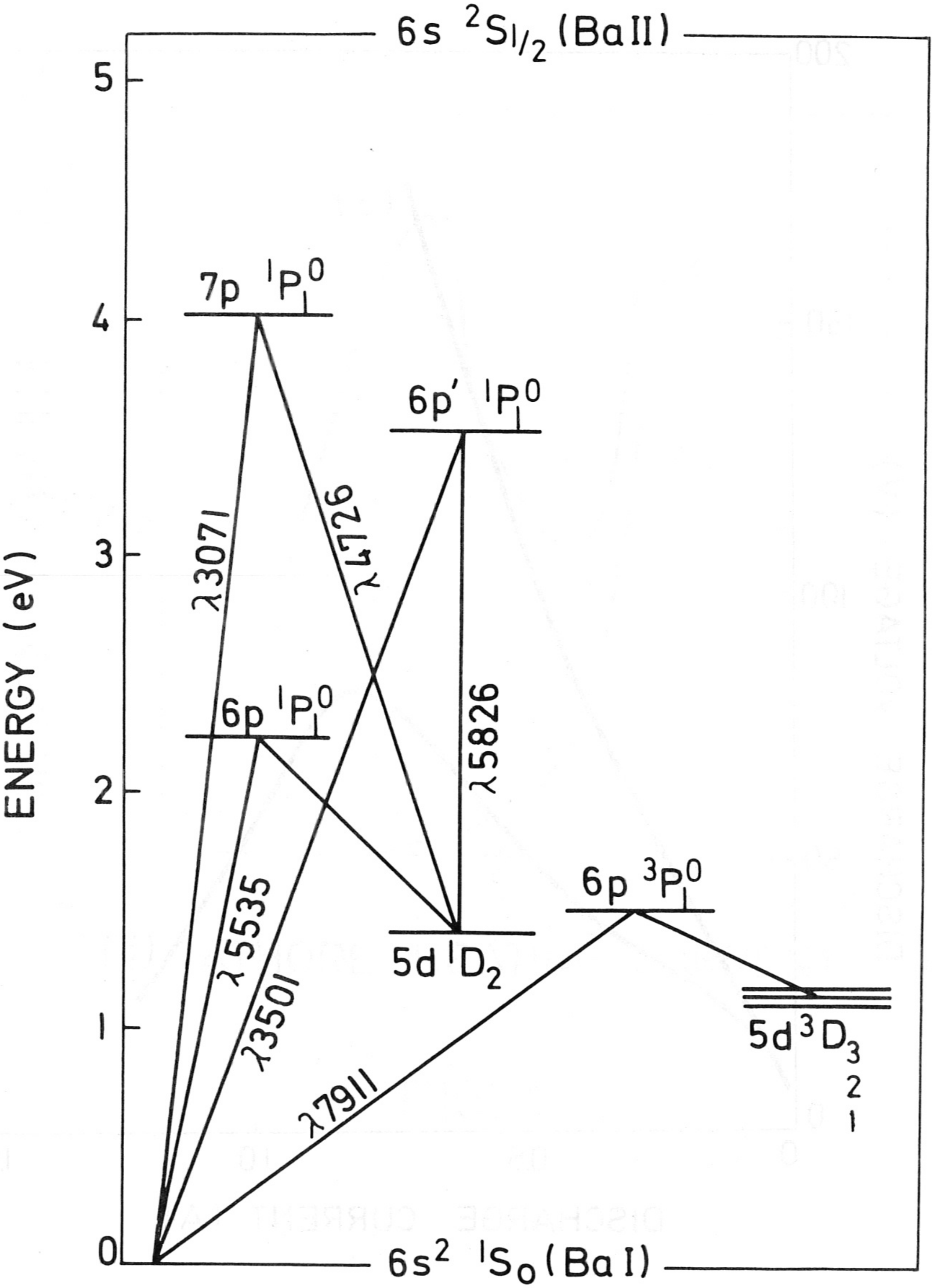

6s ²S1/2 (Ba II)
5
4
3
2
1
0
ENERGY (eV)
7p ¹P₁⁰
6p′ ¹P₁⁰
6p ¹P₁⁰
6p ³P₁⁰
5d ¹D₂
5d ³D₃
2
1
λ3071
λ4726
λ5826
λ5535
λ3501
λ7911
6s² ¹S₀ (Ba I)

FIG. 3

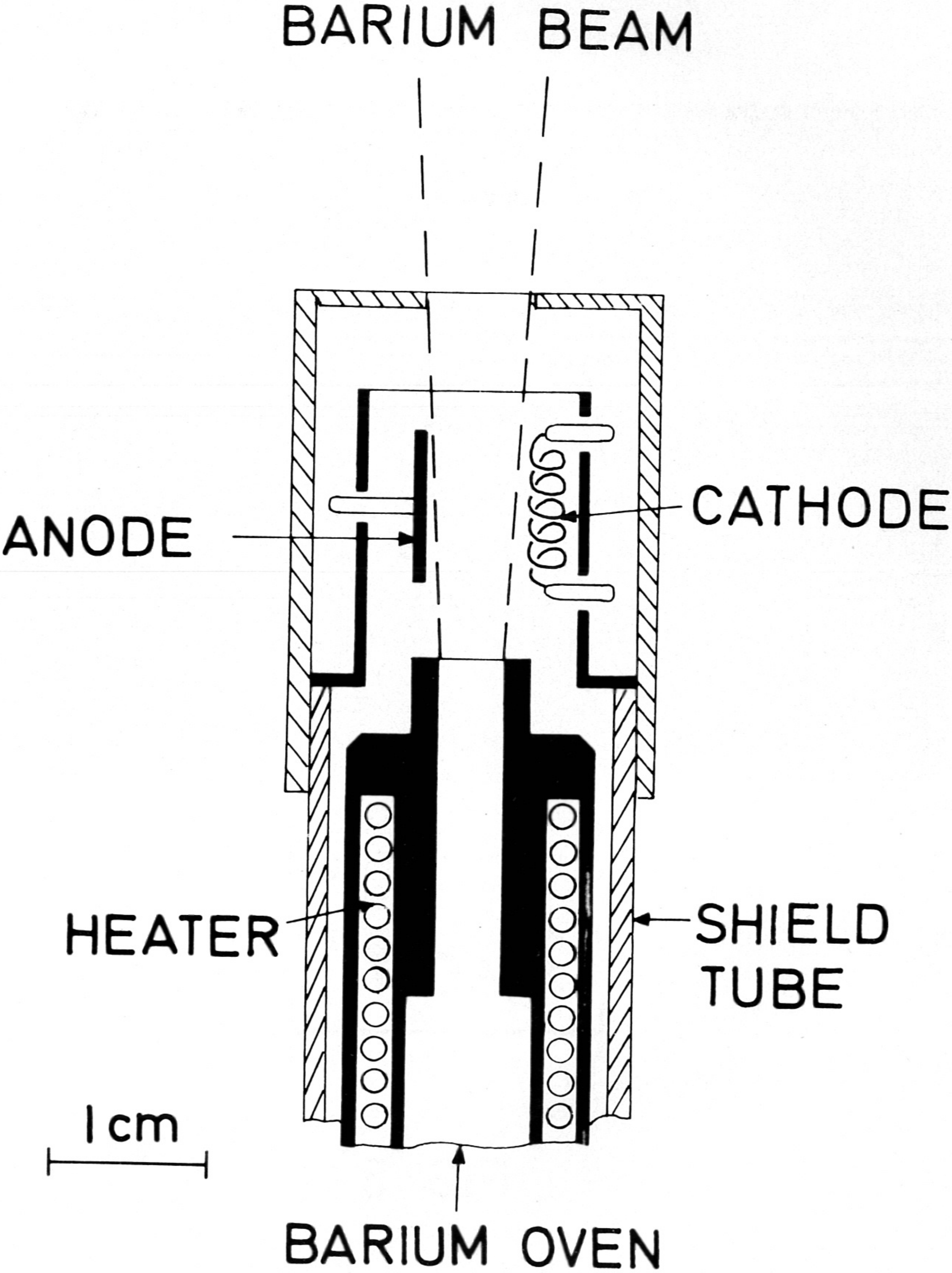
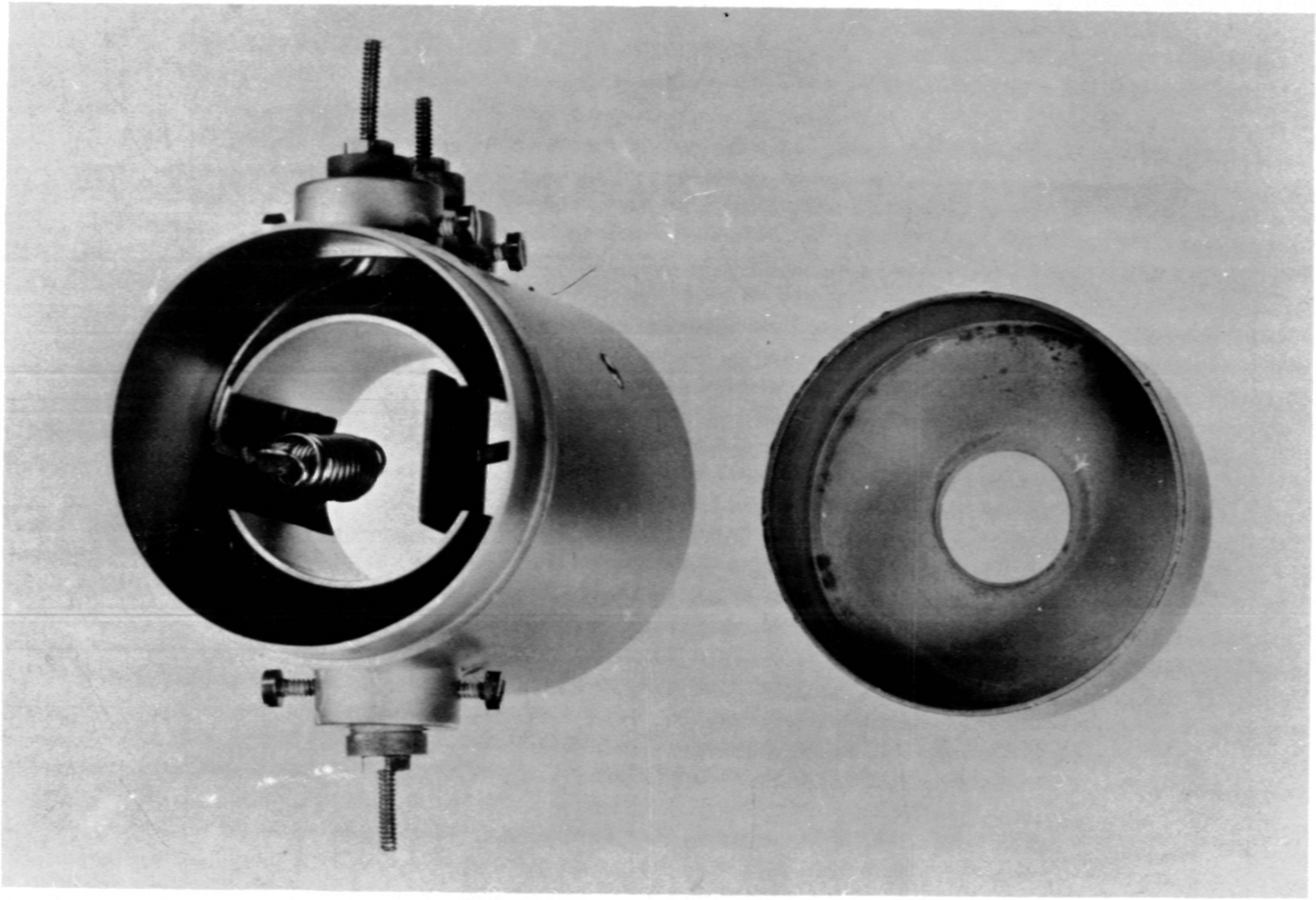

BARIUM BEAM
ANODE
CATHODE
HEATER
SHIELD
TUBE
1 cm
BARIUM OVEN

FIG. 4



2 cm

FIG. 5

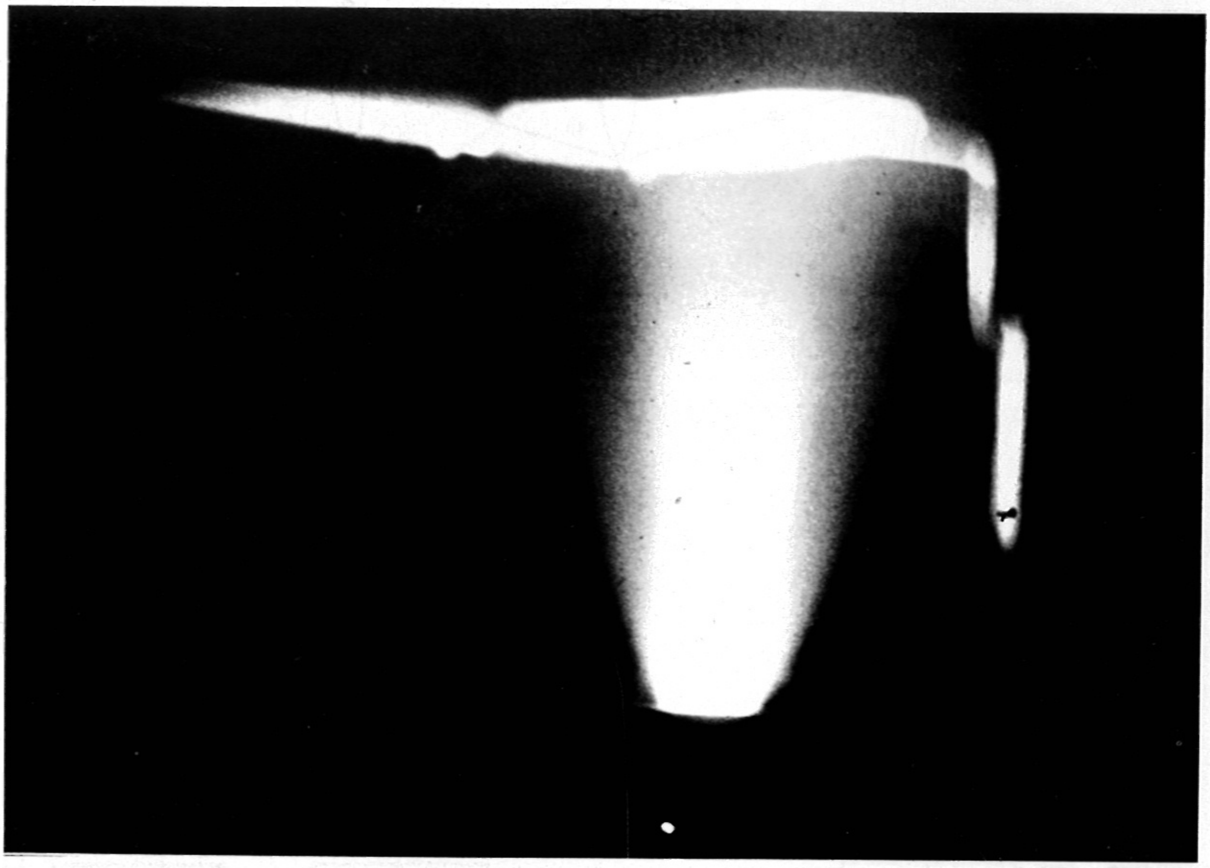


FIG. 6

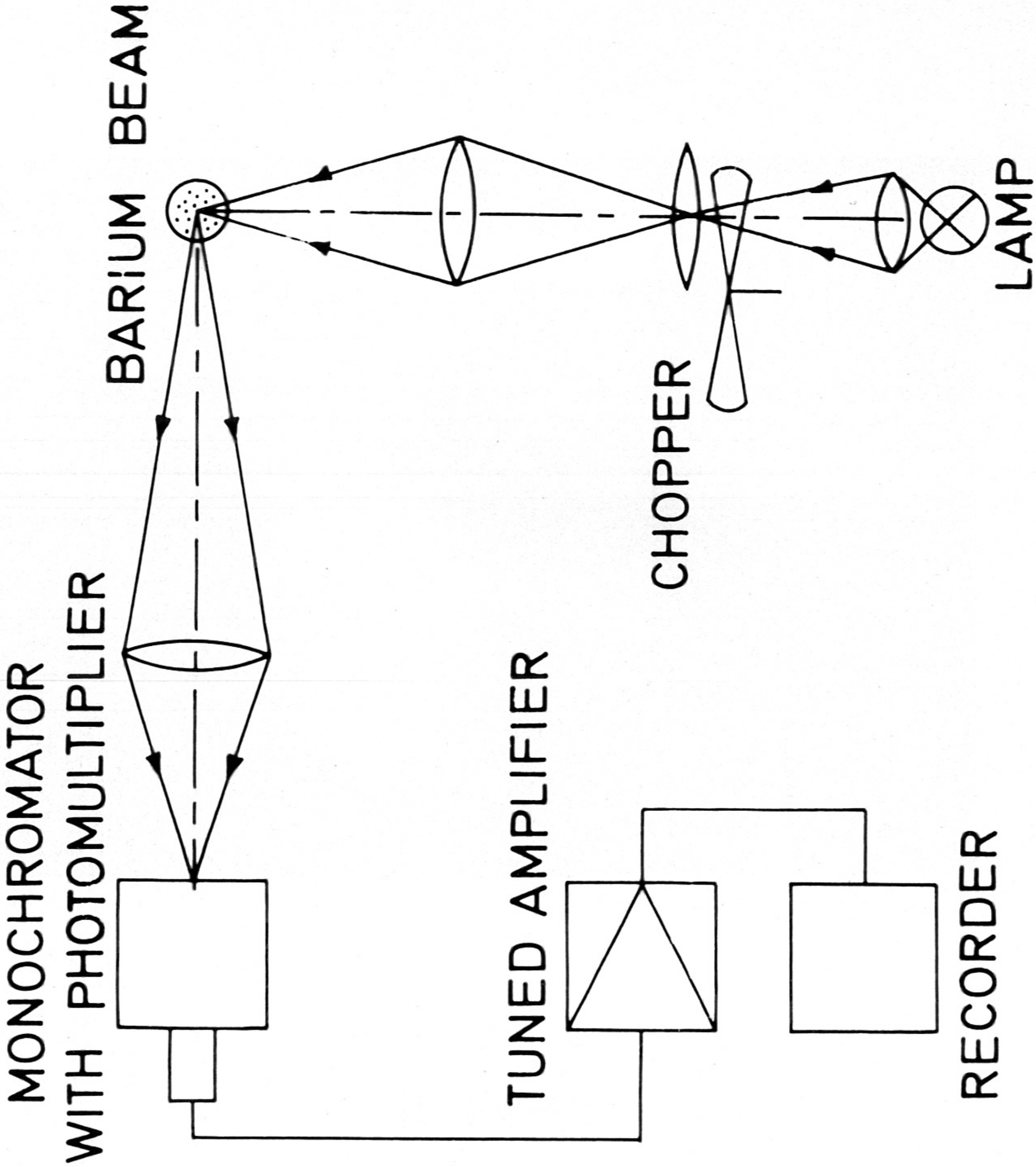
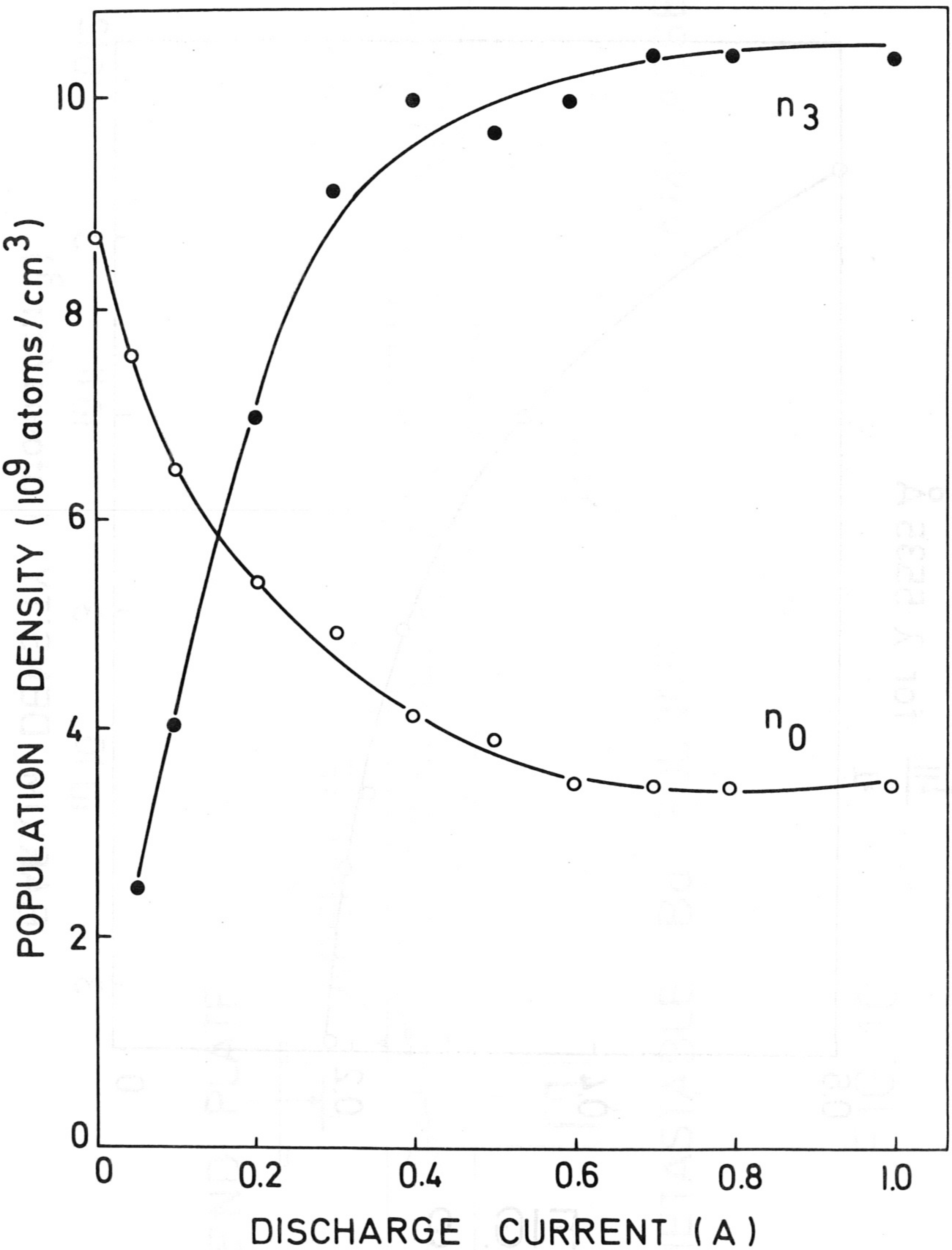
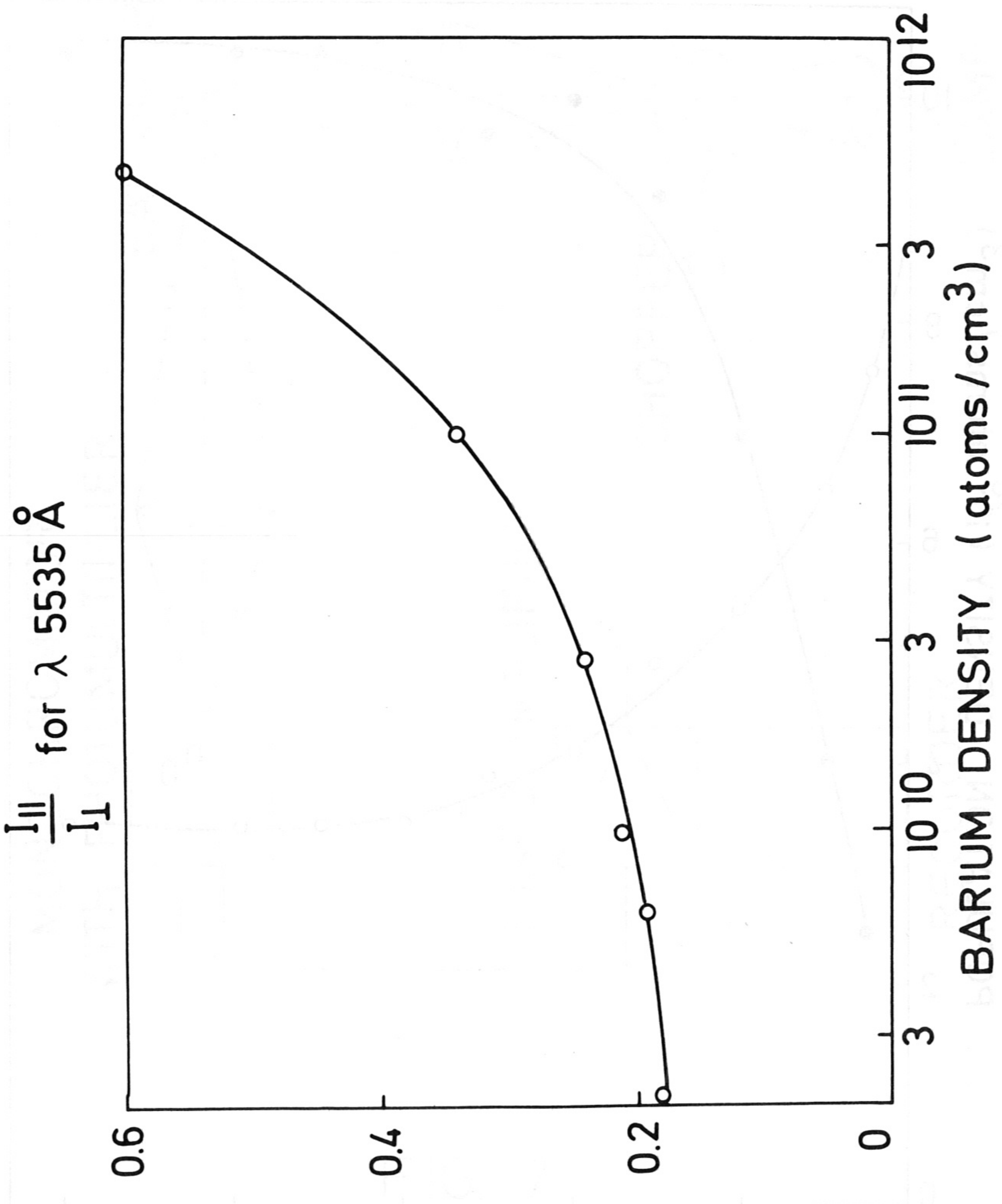

BARIUM BEAM
LAMP
CHOPPER
MONOCHROMATOR
WITH PHOTOMULTIPLIER
TUNED AMPLIFIER
RECORDER

FIG. 7



10
8
6
4
2
0
POPULATION DENSITY (10^9 atoms / cm^3)
n_3
n_0
0
0.2
0.4
0.6
0.8
1.0
DISCHARGE CURRENT (A)

FIG. 8



I_II / I_⊥ for λ 5535 Å
0.6
0.4
0.2
0
3
10 10
3
10 11
3
10 12
BARIUM DENSITY (atoms/cm3)

FIG. 9

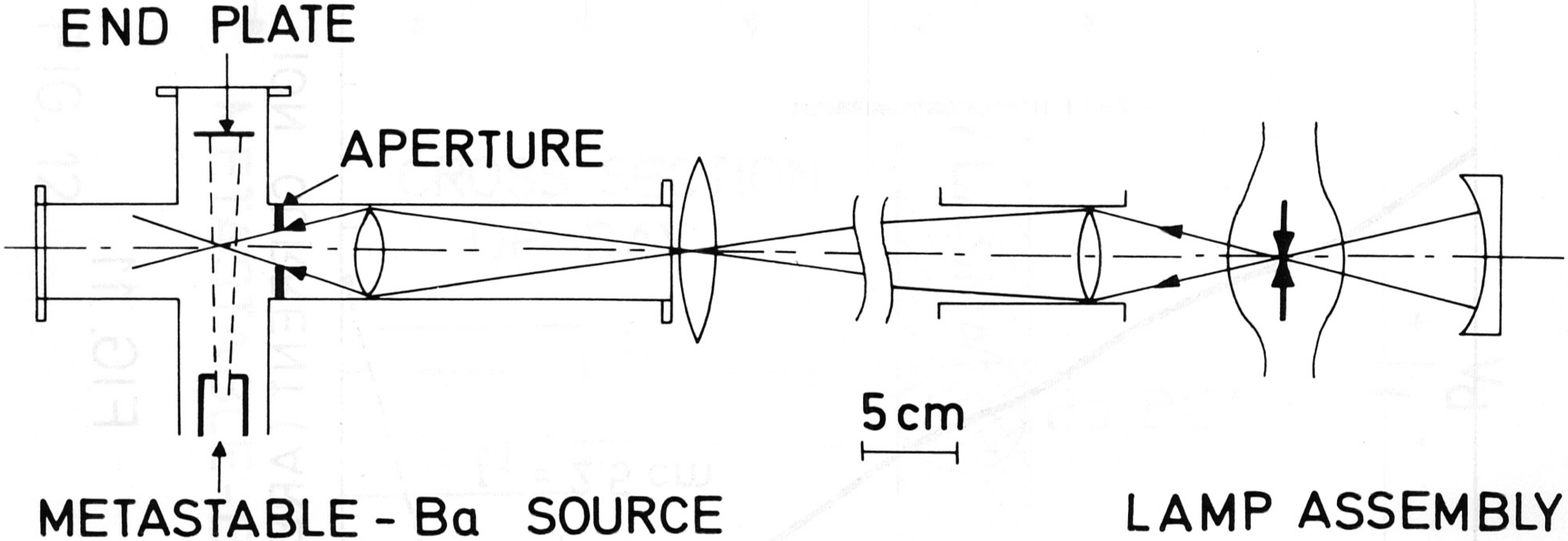


FIG. 10

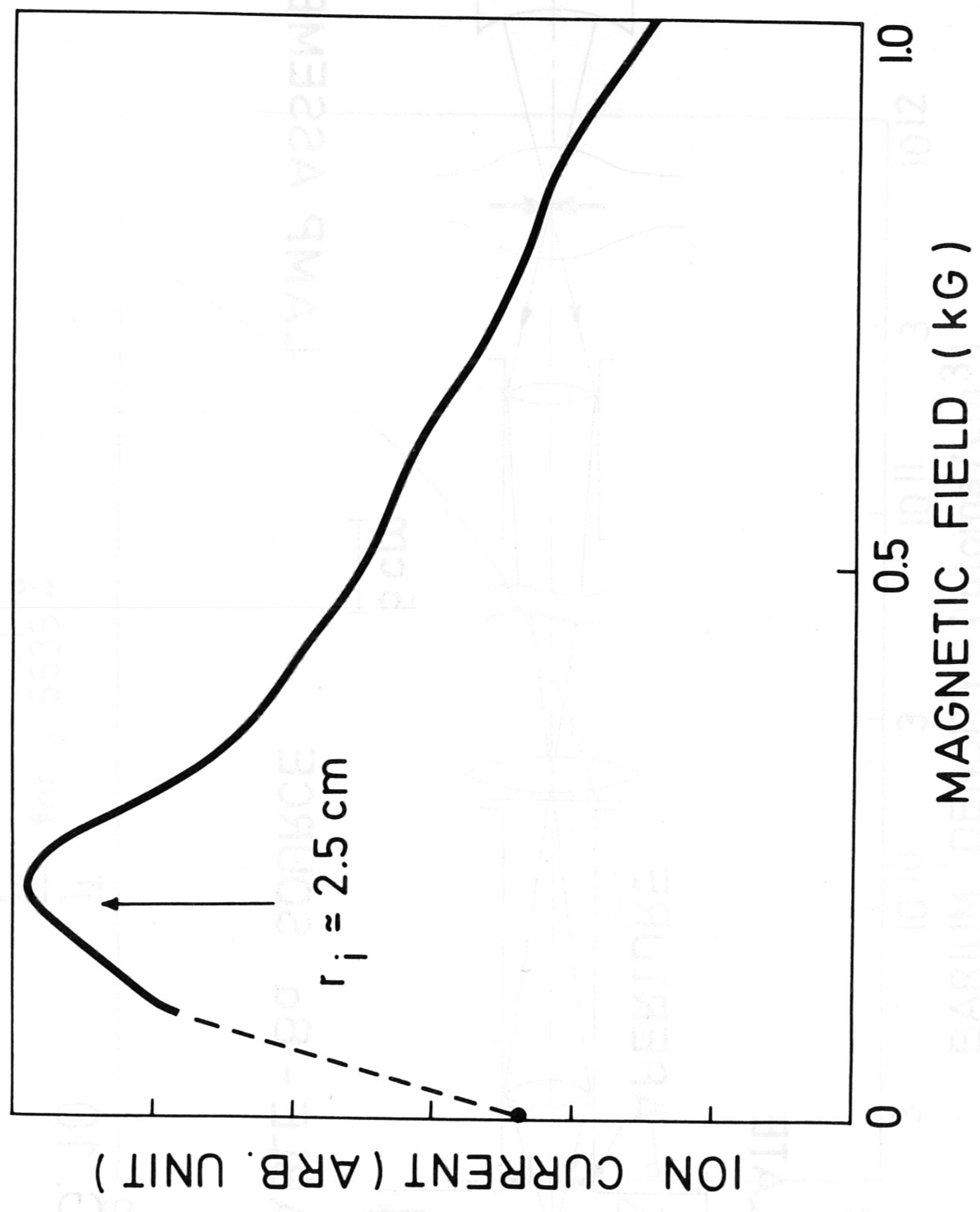
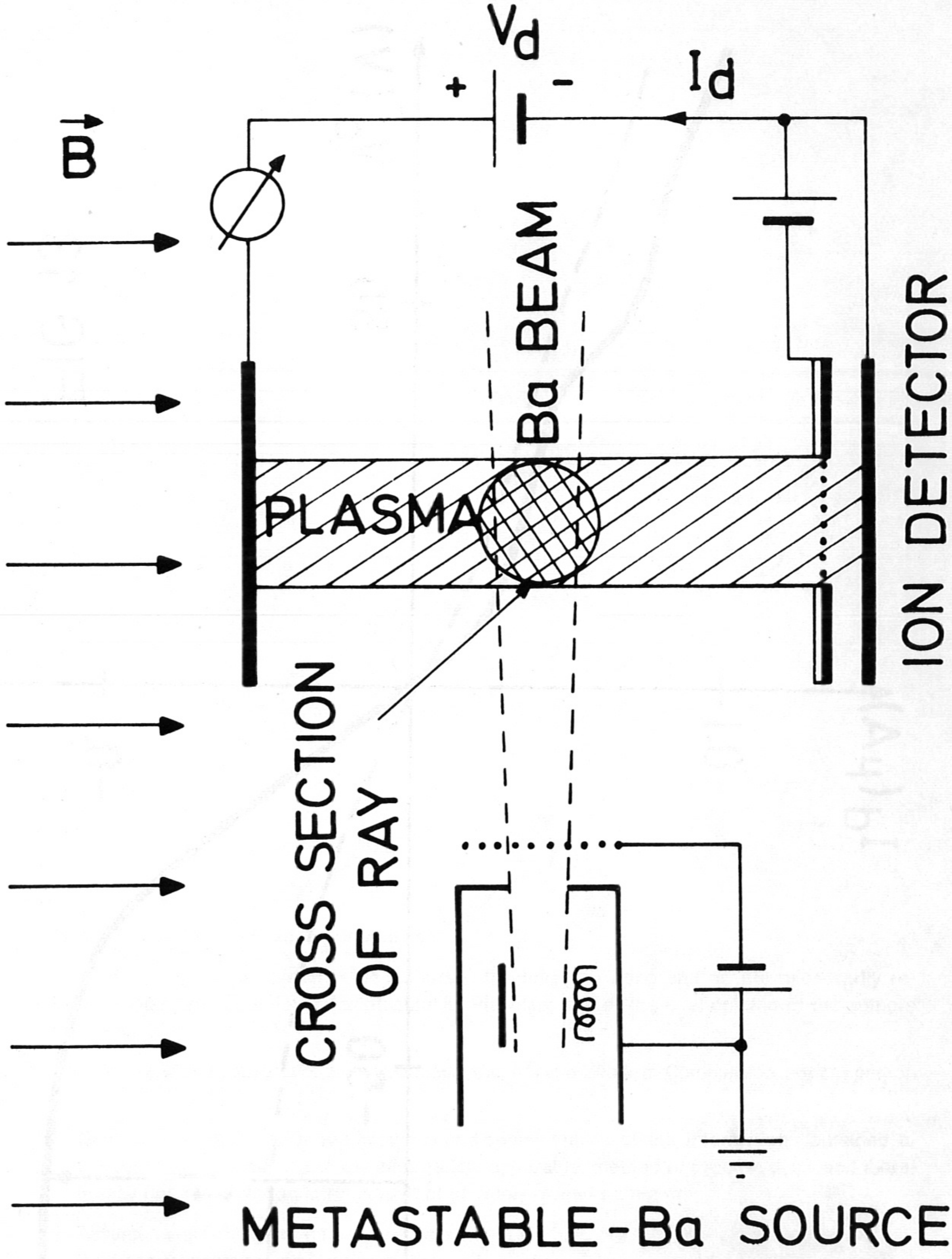


FIG. 11



V_d
+
-
I_d
$\vec{B}$
Ba BEAM
PLASMA
ION DETECTOR
CROSS SECTION
OF RAY
METASTABLE-Ba SOURCE

FIG. 12

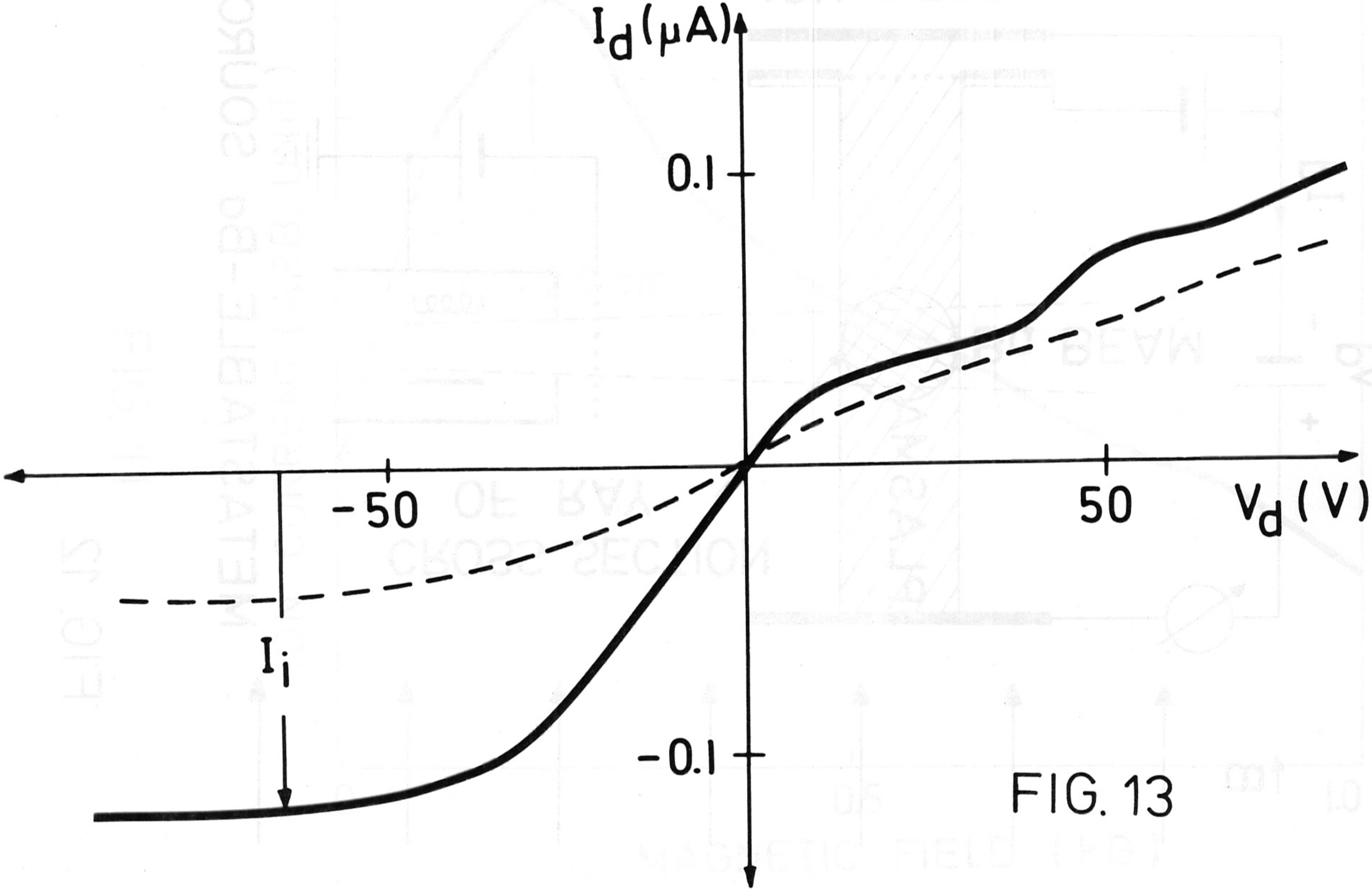


FIG. 13