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ABSTRACT

The light emitted when deuterium (D_2) and neon gas are bombarded with the beta particles from a tritium (T_2) source ($\sim$ 2 mCi) has been studied using tritium absorbed in a titanium backing. When an RCA 8575 phototube was used as a detector, the light from the neon produced about 30 times as much anode current as the light from the D_2. Filters were used to determine that most of the light from D_2 has wavelengths < 4000 Å, while most of the light from neon has wavelengths > 4000 Å. The phototube anode current increased by a factor of 20 when the window interior of a D_2-filled vessel was coated with a wavelength shifter, sodium salicylate. Pressure effects on the light emitted were also studied up to 150 psi, and it was determined that the light intensity does not decrease as fast as 1/pressure for either D_2 or neon. Visual observations were made with the unaided eye, an RCA 8606 image intensifier (gain $\sim 10^4$), and a far ultraviolet-sensitive image converter (gain $\sim$ 30); photographs were obtained where possible using Polaroid 3000-speed film.

I. INTRODUCTION

Knowledge of the method in which deuterium (D_2) and tritium (T_2) gases mix is of obvious importance to the technology of fusion of these materials. Presently no mixing experiments are being performed using D_2 and T_2 gas because of the difficulty in handling T_2. However, holographic techniques[1] are being used to study dynamic density variations of such gases as helium injected into nitrogen, and laser Raman spectroscopy techniques[2] are being used to measure concentrations of these gases at a given point and time. The former method is not accurate enough to be used in studying the mixing of D_2 and T_2, while the latter method is too time consuming to allow a complete study of the mixing using different pressures and nozzle sizes.

An alternative method for studying T_2-D_2 mixing is to observe the spatial and time-resolved light emission from the gas induced by the tritium beta rays. Tritium has several unique properties that make it suitable to be used for this process. The beta particles are of such low energy ($\sim$ 18 keV maximum energy with an average energy of 5.6 keV) that the average range[3] in D_2 is < 3.0 mm at one atm pressure. At higher pressures the energy deposition is even more localized, and light emission from a point is an excellent indication of the T_2 at that point. Tritium has a half-life of 12.4 years; thus, 1 cm^3 at STP is equivalent to 2.6 Ci ($\sim 9.5 \times 10^{10}$ disintegrations/sec).

In addition to studying the mixing of D_2 and T_2, the total light emission induced by T_2 beta rays can be used to indicate the presence of T_2 in D_2. Since the handling of gaseous T_2 presents tremendous safety problems, it was decided that a study of the feasibility of this method could be made using a thin layer of T_2 absorbed in titanium.

II. TOTAL LIGHT OUTPUT MEASUREMENTS

A. General

A source containing T_2 absorbed in a thin layer of titanium on a 1.5-in. diam stainless steel disk was obtained from the Health Division. The total T_2 content of the source was $\sim$ 2 Ci. However, the

effective beta-ray emission strength from the surface corresponded to a strength of ∿ 2 mCi. This estimate of the strength was based on a measurement by Battleson[4] of the current produced by the source in a sensitative ionization chamber. The source was observed in a darkroom, and after allowing ∿ 20 min for the eyes to become dark-adapted, the source could be seen faintly when viewed in air.

An RCA 8575 photomultiplier tube with a peak response at 3850 Å was then placed against the bell jar and the entire assembly was covered with black cloth. The anode current of the phototube was measured with a Keithley 602 electrometer. When the bell jar was filled with neon, the anode current was approximately 30 times the current observed when the bell jar was filled with D_2.

In order to make more quantitative measurements and to study the effect of pressure on the light emitted, a pressure vessel shown in Fig. 1 was constructed. The vessel was pressure tested to 300 psi and was considered safe for operation up to 150 psi. Figure 2 shows a photograph of the gas-filling system. The T_2 source was mounted on a holder which could be rotated from the outside of the vessel. The RCA 8575 phototube was placed against the Lucite window and measurements were made of the anode current vs the pressure for D_2 and neon. Before each filling, the vessel was evacuated to ∿ 50 μ pressure. Plots of the anode current vs pressure are shown for both gases in Fig. 3, along with a plot of 1/pressure normalized to the neon output at one atm. The anode output from the D_2 gas has been multiplied by 30, and the resulting curve is nearly identical to the neon curve. This factor of 30 difference implies only that more of the light from neon is in the spectral region to which the phototube is sensitive. Figure 4 shows a plot of the relative efficiency of the RCA 8575 phototube as a function of wavelength.[5]

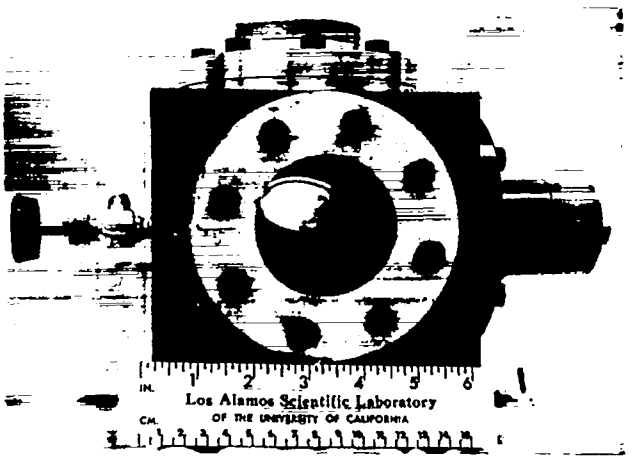

Fig. 1. Photographs of the pressure vessel showing the filling valve, the Lucite window, and the tritium source mounted on the rotating holder.

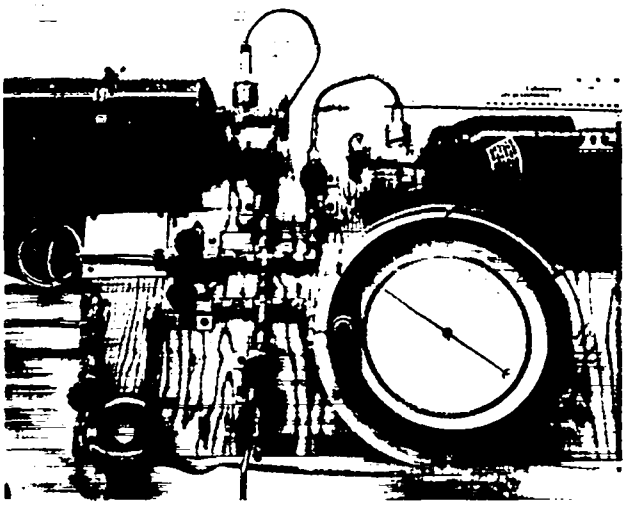

Fig. 2. Photograph of the gas-handling system showing the pressure gage and the gas bottles.

B. Spectral Distribution

Kodak gelatin filters numbers 2B, 4, and 16 were used, along with the Lucite and quartz windows, to determine the spectral distribution of the radiation emitted by the two gases. Transmission vs wavelength is plotted in Fig. 5 for these filters, as well as for the Lucite and quartz windows.[6] Table I gives the relative current readings for the neon and D_2 gases using the various filters and windows. As indicated by this table, the major portion of the light from the D_2 is below 4000 Å, while approximately half of the light from neon has wavelengths > 4000 Å. There was no apparent change in the spectral distribution with pressure for either D_2 or neon.

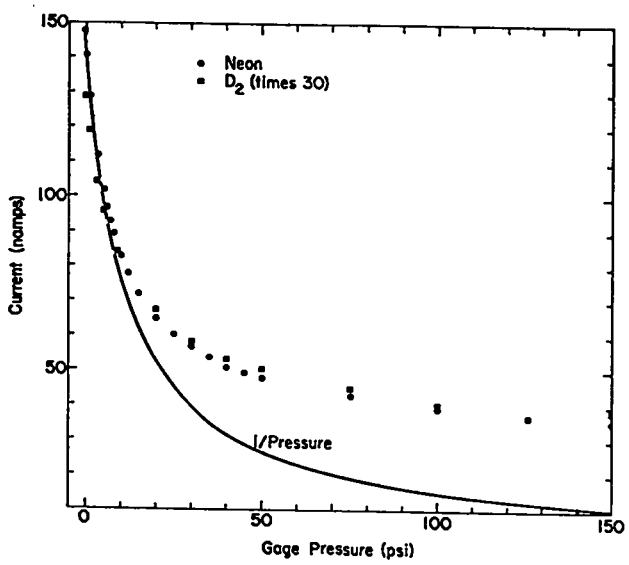

Fig. 3. Plots of the anode current in namps vs the gage pressure in psi for both neon (⊙) and deuterium (⊡). The anode current recorded when the vessel was filled with deuterium has been multiplied by 30, and it is very similar to the anode current observed when neon was used. The solid curve is a plot of pressure^{-1} normalized to the neon current at 0 psi.

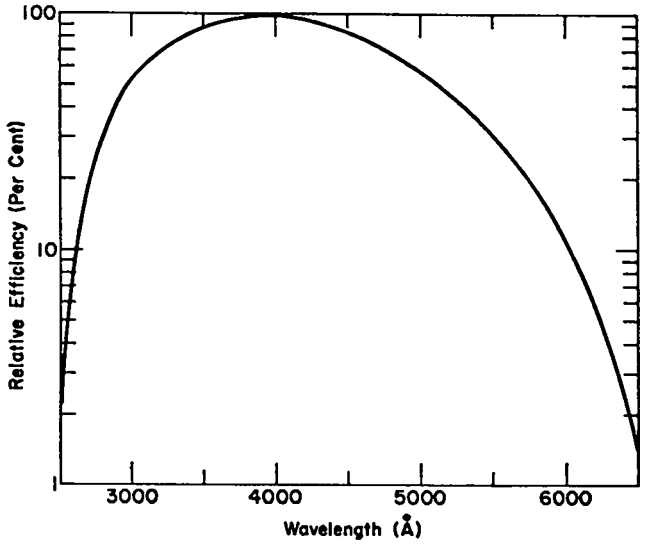

Fig. 4. Plot of the relative efficiency in percent as a function of wavelength for an RCA 8575 photomultiplier tube (from Ref. 5).

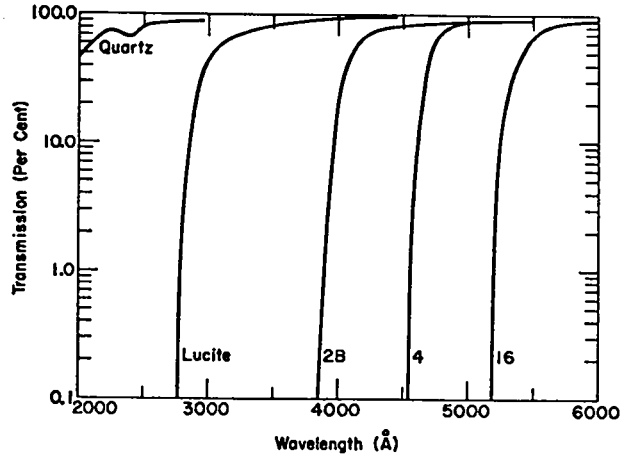

Fig. 5. Plots of the transmission of the Kodak gelatin filters numbers 2B, 4, and 16, along with the transmission curves for one-half in. of Lucite and quartz.

TABLE I

RELATIVE ANODE CURRENT FOR DIFFERENT FILTERS

Filter	Wavelength Cutoff-10% (Å)	Gas	
		D_2	Neon
1/2" Glass	2050 (50%)	100	100
1/2" Lucite	2860	70	90
2B	3970	30	50
4	4620	10	39
16	5240	2.1	36

When D_2 at atmospheric pressure was seeded by 8 to 10% neon by volume, the anode current of the photomultiplier increased by 25 to 30%. When neon at atmospheric pressure was seeded with 8 to 10% D_2 by volume, the anode current decreased by 30 to 35%. It thus appears that D_2 is a very effective quencher for neon, but that no appreciable gain (factor of 2 to 10) in light intensity can be obtained by seeding the D_2 with neon.

If a substantial number of photons from D_2 had wavelengths < 4000 Å, then a wavelength shifter coated on the inside of the Lucite window should result in a marked increase in the anode current of the photo-tube. Sodium salicylate has an efficiency of ∿ 65% for converting light with wavelengths from 300 to 3400 Å into light peaked at 4200 Å with a half-width

of ∿ 350 Å (see Ref. 7, p 214). When the inside of the Lucite window was coated with a thin layer of sodium salicylate, the anode current increased by a factor of ∿ 20. The anode current decreased with pressure in approximately the same manner as before.

III. SPATIAL RESOLUTION EXPERIMENTS

A. General

From the measurements described previously it is apparent that most of the light from D_2 is in the ultraviolet (uv). At pressures less than ∿ 1/3 atm, various experiments[7-9] show that H_2 emits a continuous spectrum between 1600 and 4000 Å with a broad peak around 2300 Å. Other experiments[7,10-12] at low pressure also show that H_2 emits a line spectrum between 1100 and 1600 Å. The continuous spectrum is due to $a^3\Sigma_g^+ \rightarrow b^3\Sigma_u^+$ transitions where $b^3\Sigma_u^+$ is an unbound state that dissociates into two ground state hydrogen atoms. The line spectrum around 1600 Å is due to $B^1\Sigma_u^+ \rightarrow X^1\Sigma_g^+$ transitions (Lyman band), while the line spectra around 1200 Å is due to $C^1\pi_u \rightarrow X^1\pi_g^+$ transitions (Werner band). (Lasing transitions have been observed in the Lyman band[10,11] and more recently in the Werner band[12,13] and are the most energetic lasing lines definitely observed.)

Measurements by Berlman et al.[8] indicate that flash tubes filled with D_2 emit ∿ 65% more photons than H_2-filled tubes in the spectral region from 1800-3500 Å. This is due partially to the higher density of vibrational levels within a given electronic state for D_2. This higher density of states gives rise to a larger total excitation cross section, as well as a more rapid radiative decay because of larger Franck-Condon factors.

Experiments on mercury vapor discharge lamps up to 285 atm indicate that the line character is replaced by a continuum as the pressure is increased.[14]

B. Apparatus and Procedure

Polaroid 3000-speed film and an oscilloscope camera with an f/1.8 lens were used to photograph the light from the tritium beta rays. Initial photographs were obtained using a Lucite window in the pressure vessel. Figure 6 shows a photograph of a front view of the source in one atm of neon gas obtained with a 15-min exposure. This source had previously been placed on an O-ring and bombarded with deuterons. The position of the O-ring, as

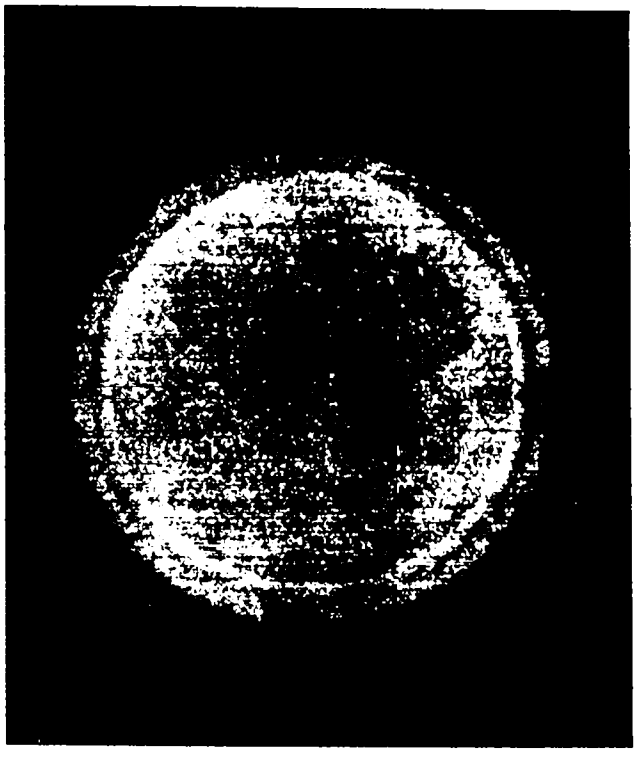

Fig. 6. A front view of the tritium source in one atm of neon obtained using a Polaroid scope camera with an f/1.8 lens and 3000-speed film. The exposure time was 15 min (see text).

well as other details, are obvious in the photograph. A similar exposure for 14 h when the vessel was filled with D_2 yielded a completely dark photograph. When the Lucite window was replaced with quartz and the source viewed edge-on to increase the intensity, a 3-h exposure gave a faint picture using D_2 gas.

In order to obtain photographs using shorter exposure times and with better contrast, an RCA 8606 image intensifier and a 2-1/2-in.-diam f/0.85 lens were used. The image intensifier had a luminous gain[15] of ∿ 30,000 and a photon gain of ∿ 10,000, but the input fiber optics would not transmit light below 3900 Å. The f/0.85 lens was placed against the quartz window of the pressure vessel and used to focus the light onto the intensifier. The same Polaroid scope camera with 3000-speed film was used to photograph the output of the intensifier. Figure 7 shows a photograph of an edge view of the source in one atm of neon obtained with a 1/30-sec exposure. Figure 8 shows a similar photograph of the source in one atm of D_2 obtained using a 10-sec exposure. Two

Fig. 7. An edge view of the tritium source in one atm of neon obtained during a 1/30-sec exposure. A 2-1/2-in.-diam f/0.85 lens and an RCA 8606 image intensifier were used in conjunction with a Polaroid scope camera and 3000-speed film to obtain this photograph.

Fig. 8. An edge view of the tritium source in one atm of deuterium obtained during a 10-sec exposure. A 2-1/2-in.-diam f/0.85 lens and an RCA 8606 image intensifier were used in conjunction with a Polaroid scope camera and 3000-speed film to obtain this photograph. Notice the spots due to the large dark current and the range of the beta rays compared with those in Fig. 7.

differences to be noted are the greatly increased noise for the 10-sec exposure and the increased range of the beta rays in D_2. The difference in exposure times by a factor of 300 is partially due to the fact that the intensifier will not transmit below 3900 Å.

In order to see what light could be observed from D_2 in the uv, an EMR image converter tube with a photon gain of $\sim$ 30 was obtained. This tube had a curved faceplate of lithium fluoride (transmission to 1040 Å) and a cesium iodide photocathode with a peak quantum efficiency of 29% at 1219 Å decreasing to 0.6% by 1800 Å. In order to focus light at these wavelengths a Cassegrain-type reflecting lens ($\sim$ 4-cm diam) was designed using spherical surfaces and the construction was carried out by group M-5. The aluminum surfaces of the mirrors were coated with MgF_2 as described by Hutcheson et al.[16] in order to reflect $\sim$ 85% of the light down to 1200 Å. An intense mercury uv source was used to aid in focusing the light onto the EMR tube. Figure 9 shows a photograph of the mirrors and supports used in the lens, and Fig. 10 shows the entire lens system with the EMR tube mounted on the end. The complete system out to the EMR tube was evacuated and filled with D_2. A 14-h exposure resulted in no visible photograph. It appears that the integrated intensity of the light in the 1200 to 1800 Å region of the spectrum is not very large. However, the solid angle of this lens is $\leq$ 10% of that of the f/.85 lens and the response of the EMR tube cuts off rather sharply. The EMR tube was removed and replaced with a quartz window, and the RCA 8606 was placed at the focus of the lens. As expected, a poorer picture resulted than obtained previously with the source in D_2 because of the decrease in solid angle.

IV. CONCLUSIONS

From these measurements it appears that most of the photons from D_2 bombarded with T_2 beta rays are between 1600 and 4000 Å. Special optics are needed in this spectral region, but because of solid-angle and field-of-view problems in the reflecting optics, a dichromatic doublet of fused silica and either sapphire, lithium fluoride, or MgF_2 would probably be more useful.[17]

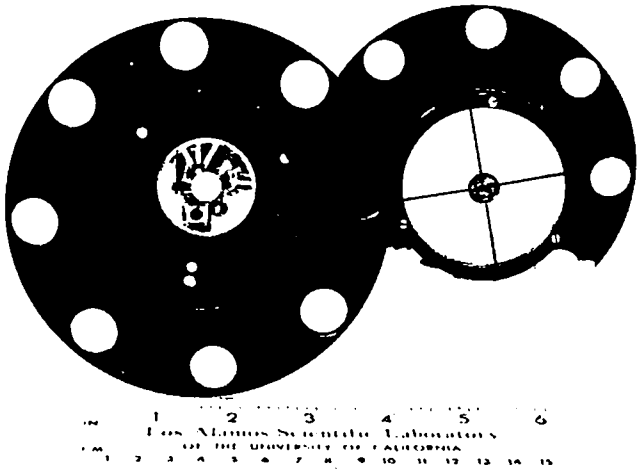

Fig. 9. Photograph of the MgF_2-coated mirrors and supports used in the reflecting optics system.

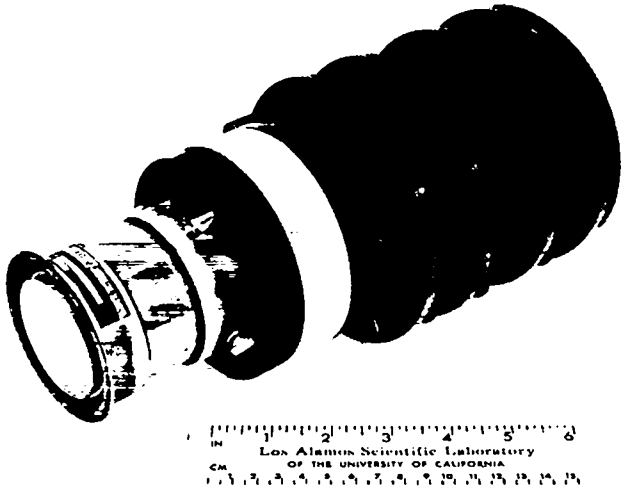

Fig. 10. The assembled lens system with the EMR image converter tube mounted at the focal plane. The output fiber optics of the tube can be seen.

If one assumes that the photon emission from gaseous T_2 varies inversely as the pressure, then the "effective" disintegration rate of T_2 for light production is independent of the pressure. The calculations of Miles et al.[18] indicate that for electrons with energies > 0.1 keV, 33 eV are required to produce an ion pair; therefore, each cm^3 of T_2 at STP produces an average of 1.7×10^{13} ion pairs/sec. If one assumes that one photon results from each ion pair produced, then 1.7×10^{13} photons/sec will be produced from each cm^3 of T_2. For a lens system accepting 0.1% of the total light (1-in.-diam lens 8 in. away) with no reduction in size and with a 50% transmission, 8.5×10^9 photons/sec would be focused onto 1 cm^2. For an image tube with a photon gain of only 10^3 and for 5500 Å (∿ 2.3 eV) output light, the output would be 31 ergs/cm^2/sec. If film with a sensitivity similar to that of Polaroid 3000-speed (5×10^{-3} erg/cm^2 to produce a reflection density of 0.5 in the print) were used, then exposure times of ∿ 1/6 msec could be used. Dilute concentrations of T_2 (< 1%) could be observed using msec framing rates if image intensifiers with gains of 10^5 were used.

The above discussion assumes that the film was placed against the output fiber optics of the image tube. If an additional lens were used to focus the output of the intensifier onto the film, the light intensity would be reduced by a factor of 10 to 100. The above discussion also assumes 1 photon per ion pair. The results of the phototube measurements indicate that in the region above 2800 Å, there are 12 to 120 photons emitted per disintegration, or 0.07 to 0.7 photons emitted per ion pair. However, in view of the measurements with sodium salicylate, a more reasonable estimate of the number of photons per ion pair with wavelengths > 1600 Å is between one and ten.

For gaseous tritium each beta decay would result in a $^3He^+$ ion recoiling with ∿ 3 eV. Additional photons would result from the recombination of this ion that would probably not be observed when using T_2 absorbed in titanium. In a discharge tube at a pressure of 600 torr, helium emits a continuous spectrum between 1600 and 4000 Å (see Ref. 7, p 103). Contributions from this effect may be observed by Battleson of Sandia, Livermore[4] when he performs some of his planned experiments using gaseous T_2 in a chamber with a sapphire window.

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