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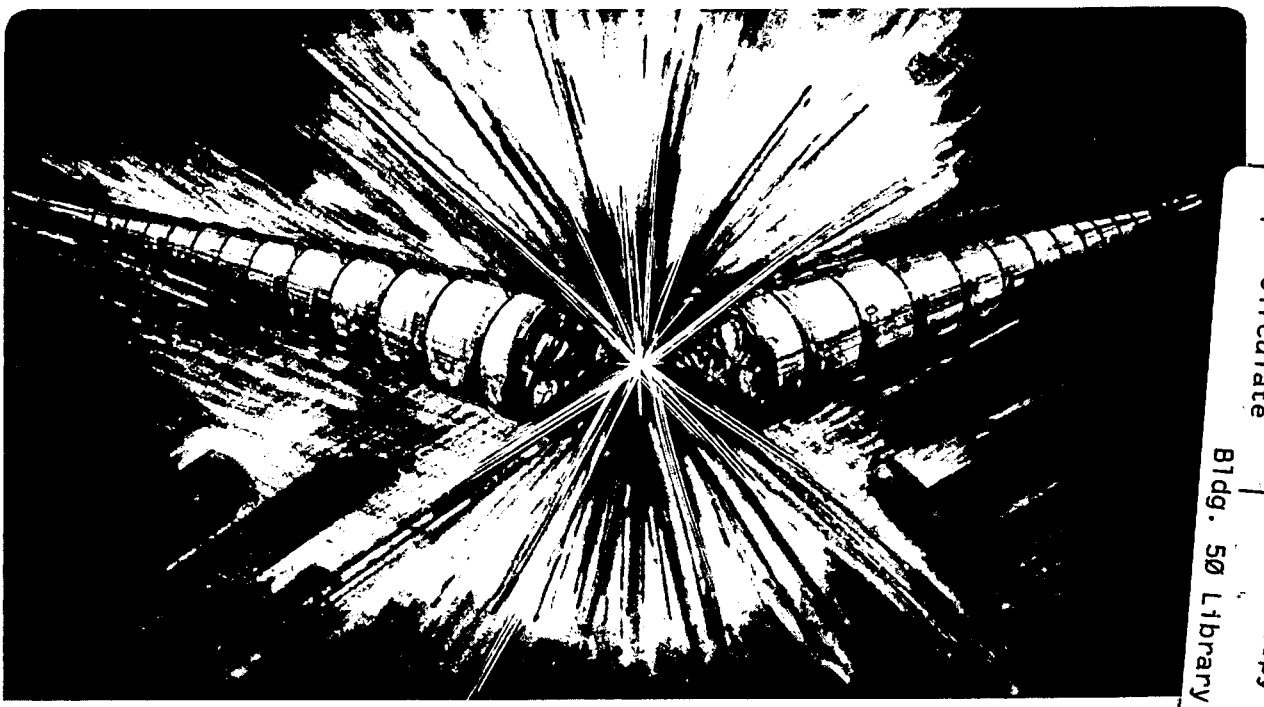

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Photoemission studies with barium and LaB_6 photocathodes and polarized laser light

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Photoemission measurements with barium and single crystal LaB_6 photocathodes are reported. The barium cathode is prepared by depositing a barium thin film onto a copper substrate. The LaB_6 cathode is a single crystal cut in the $\langle 100 \rangle$ plane. Radiation from a nitrogen laser (337 nm, 10 ns) is polarized and strikes the cathode surface at variable angles. An electron quantum yield as high as 2×10^{-3} is observed with barium. The dependence of the quantum yield on the beam polarization and angle of incidence is investigated. The results indicate that higher quantum yields are achieved when the angles of polarization and incidence are such as to minimize the reflection coefficient.

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The laser driven RF photocathode[1-5] is a very efficient source of tightly bunched high-brightness electron beams. This is important for many accelerator applications, as well as for the generation of short-wave electromagnetic radiation. It is therefore important to improve and optimize the photocathode efficiency. It has been shown[6] that barium is an attractive candidate for use as a photocathode material. It has a low work function (~2.5 eV) and provides relatively high electron quantum yields. This paper reports work on the optimization of the performance of barium photocathodes. Studies are conducted on the dependence of the quantum yield on the polarization and angle of incidence of the laser beam. We also report studies on single crystal LaB_6 photocathodes. This material has a lower quantum yield than barium, but chemically it is much less reactive and is known to have very good thermionic emission characteristics.[5,7,8]

A schematic of the experimental setup is shown in Fig. 1. The photocathodes are installed in a 22 cm diameter stainless-steel vacuum chamber pumped by a cryosorption pump. The typical base pressure in the chamber during the barium experiments was 2×10^{-7} Torr. It was improved to 1×10^{-8} Torr for the LaB_6 photocathode measurements. Pulsed nitrogen laser radiation at 337 nm (Laser Photonics model UV24) is used to excite the photocathode. An iris limits the diameter of the beam to approximately 4 mm. The laser beam is directed through a spatial filter to improve the beam quality, polarized by a calcite Glan prism, and then attenuated to 0.05 – 1 μJ/pulse. A photodiode monitors the relative laser power, and a thermopile detector measures the absolute time-averaged power .

The barium photocathode consists of a solid copper disc (20 mm in diameter) onto which a thin layer of barium (a few microns thick) is deposited by evaporating barium from commercially available getter wires (SAES Getters).[6] The deposition is performed in vacuum, and the pressure is kept in the 10^{-7} Torr range. The anode, a graphite disc (15 mm in diameter), is located directly in front of the cathode and biased up to 6 kV. The anode and cathode are mounted on a stainless-steel shaft by means of small ceramic rods and separated by 40 mm. The rotation of the shaft allows for the variation of the angle of incidence of the laser on the cathode surface, while keeping the cathode-anode distance fixed. The time-averaged photocurrent is measured by a picoammeter connected to the cathode. The quantum yield is then calculated as the ratio between the number of emitted electrons and the number of incident photons.

Figure 2a presents the measured quantum yield for barium as a function of anode bias voltage; curves are shown for cathodes at various times after the barium deposition. The graph shows that the voltage applied to the collecting anode has to be sufficiently high to overcome the space-charge limit at the cathode. For high enough voltages the measured quantum yield is independent of the anode voltage, indicating that all the emitted electrons are collected. The voltage necessary to overcome space-charge and reach the plateau in the curves is lower for cathodes with lower quantum yields, as expected.

The dependence of the quantum yield on the age of the barium layer is shown in Fig. 2b. The initial increase in the quantum yield may be caused by formation of barium oxide on the surface, which is known to have a slightly lower work function than barium.[9] Quantum yields above 2×10^{-3} are reached three hours after the deposition time. As time goes by, however, further contamination of the barium layer leads to a degradation of the photoemission performance, and the quantum yield returns to the initial value approximately five hours after the deposition time. Also shown in Fig. 2b is the temporal evolution of the quantum yield at longer radiation wavelengths. These measurements were made using a xenon arc lamp (Oriel model 6140) and a set of narrow band-pass filters to select the wavelength of the incident radiation. We observe similar curves for the various wavelengths, with noticeably lower quantum yields at longer wavelengths.

Figure 3a shows the electron quantum yield as a function of laser beam polarization angle α (for an angle of incidence $\theta = 60°$). The quantum yield reaches a maximum value when the polarization state is such that the electric field is completely in the plane of incidence (p polarization, corresponding to $\alpha = 0°$ in Fig. 3b). Conversely, the quantum yield has a minimum value when the electric field in the laser beam is perpendicular to the plane of incidence (s polarization, corresponding to $\alpha = 90°$).

Figure 4a illustrates the dependence of the quantum yield on the angle of incidence of the laser beam. Two curves are shown, corresponding to the p and s polarizations. Measurements were obtained between 15° and 75°. The maximum quantum yield is reached for $\theta \approx 55°$, with the beam polarized parallel to the plane of incidence (p polarization).

The dependence of the quantum yield on the laser beam polarization and angle of incidence can be attributed to changes on the reflection coefficient R of the barium surface. A smaller reflection coefficient means that a larger fraction of the incident photons interacts with the barium layer, yielding a larger num-

ber of photoelectrons. Figure 4b shows the transmission coefficient $T = 1 - R$ for polarized light incident on a barium surface, as calculated from Fresnel's equations. There is good agreement between these calculated curves and the measurements shown in Fig. 4a. The small discrepancy may be attributed to uncertainties in the values of the optical constants of barium,[10] and to the effect of the roughness of the actual cathode surface. The variation of R also explains the dependence of the quantum yield on the polarization angle α, shown in Fig. 3a. At a given angle of incidence, the reflection coefficient is expressed as $R = (R_p - R_s)\cos^2\alpha + R_s$, where R_p and R_s are the reflection coefficients for the p and s polarizations. The same dependence on $\cos^2\alpha$ is observed in Fig. 3a, where an $(A\cos^2\alpha + B)$ curve-fit shows excellent agreement with the measurements.

A large single crystal of LaB_6 (25 mm long and 6 mm in diameter) cut in the ⟨100⟩ plane is used as our second photocathode material. In order to clean the surface and "activate" the material,[11] the crystal is heated to ~1200 – 1600°C for a few minutes and then allowed to cool down to ~800 – 1000°C. The heating process is accomplished by holding the LaB_6 crystal between two graphite blocks and passing electric current through it (up to 250 A). An optical pyrometer is used to monitor the temperature. The heating power supply is negatively biased to 3 kV, thus biasing the whole cathode holder. The anode, a small graphite disc (12 mm in diameter) is spaced 16 mm from the cathode. The anode is grounded through a 50 Ω resistor, and the emitted cathode current is read as a voltage across this resistor.

Large thermionic currents (up to 300 mA) are observed when the cathode temperature is above 1200°C. To study photoemission (in the absence of thermionic emission) the temperature needs to be below ~1000°C. Unfortunately, the photoemission characteristics of the LaB_6 crystal in our chamber are very unstable at lower temperatures. Quantum yields of up to 3.5×10^{-4} are observed, but only during very short periods. We suspect that the rapid contamination of the cathode surface is the reason for this behavior.

The dependence of the quantum yield on the laser beam polarization is shown in Fig. 5. Similar to the measurements with the barium photocathode (cf. Fig. 3), the quantum yield varies as $\cos^2\alpha$, reaching a maximum value when the electric field is in the plane of incidence (p polarization). We again attribute this effect to changes in the reflection coefficient R of the cathode surface. With the LaB_6 cathodes we

actually measure R and then calculate the transmission coefficient $T = 1 - R$. Dividing the quantum yield values by T cancels the sinusoidal variation of the data, as also shown in Fig. 5.

In summary, we observe similar radiation polarization effects with both barium and LaB_6 photocathodes. The dependence of the quantum yield on the angle of incidence and polarization of the laser beam is caused by changes in the reflectivity of the cathode surface. P polarized light exhibits lower reflectivities and therefore higher quantum yields than s polarized light. For barium the difference between the two polarizations is maximized for angles of incidence of ~ 50 – 60°. We observe these polarization effects with laser power levels that differ by an order of magnitude. This suggests that the effect cannot be attributed to field-assisted photoemission, as expected for the low power levels used in our experiments.

The measured quantum yields of barium (2×10^{-3} at 337 nm) are comparable to results in similar experiments,[6] and make barium an attractive candidate for use as a photocathode material. Barium presents quantum yields much higher than the values obtained with bare copper, with vacuum requirements that are only slightly more stringent (~10^{-7} Torr). Cesiated semiconductors can achieve higher quantum yields,[12,13] but ultra-high vacuum is required for their operation (<10^{-9} Torr). LaB_6 has the advantage of being a more rugged material, which can be handled in air. Quantum yields of $\sim 3 \times 10^{-4}$ were measured, which are comparable to those reported in the literature.[7] However, these values are about an order of magnitude lower than barium, and our experiments with LaB_6 photocathodes could not achieve a stable operating condition.

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Figure Captions

Fig. 1: Schematic of the experimental setup.

Fig. 2: Electron quantum yield of the barium photocathodes: (a) as a function of the anode bias voltage; (b) as a function of the barium layer age.

Fig. 3: Effect of the laser polarization on the quantum yield: (a) quantum yield as a function of polarization angle; (b) diagram indicating the angles of polarization (α) and incidence (θ).

Fig. 4: Dependence on the angle of incidence: (a) of the measured quantum yield; (b) of the calculated transmission coefficient.

Fig. 5: Electron quantum yield of the LaB_6 photocathode as a function of the polarization angle.

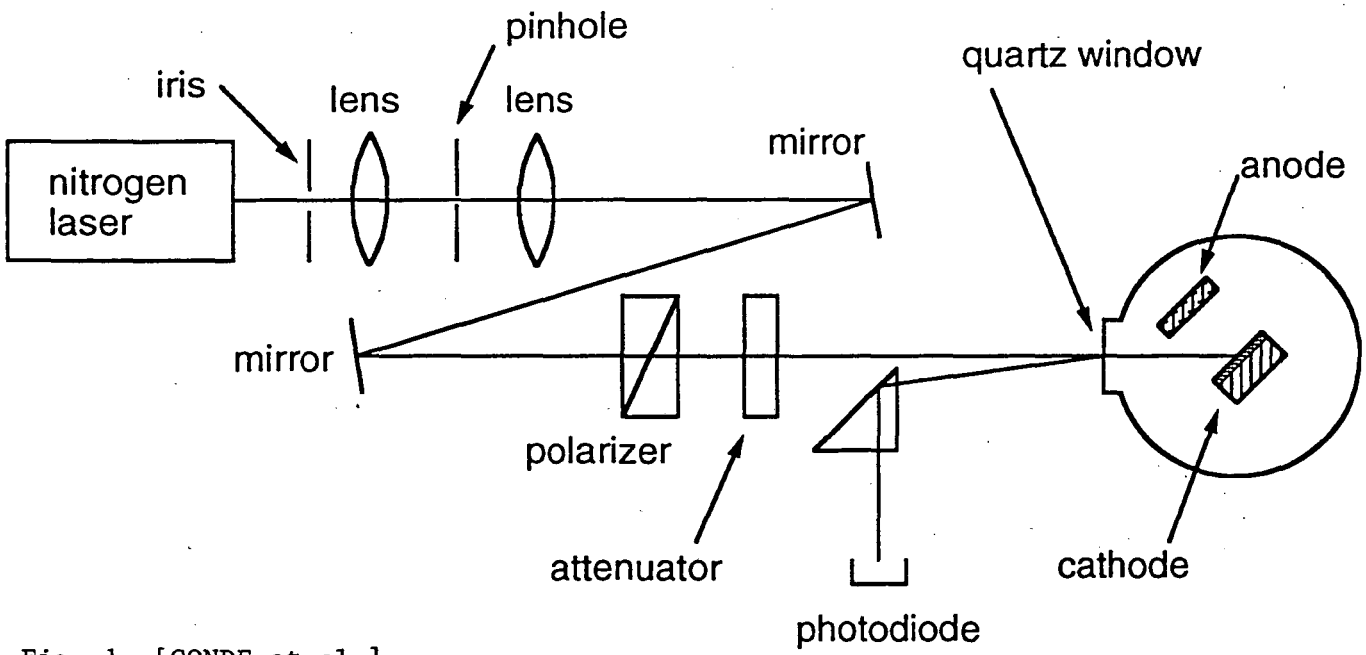


Fig. 1 [CONDE et al.]

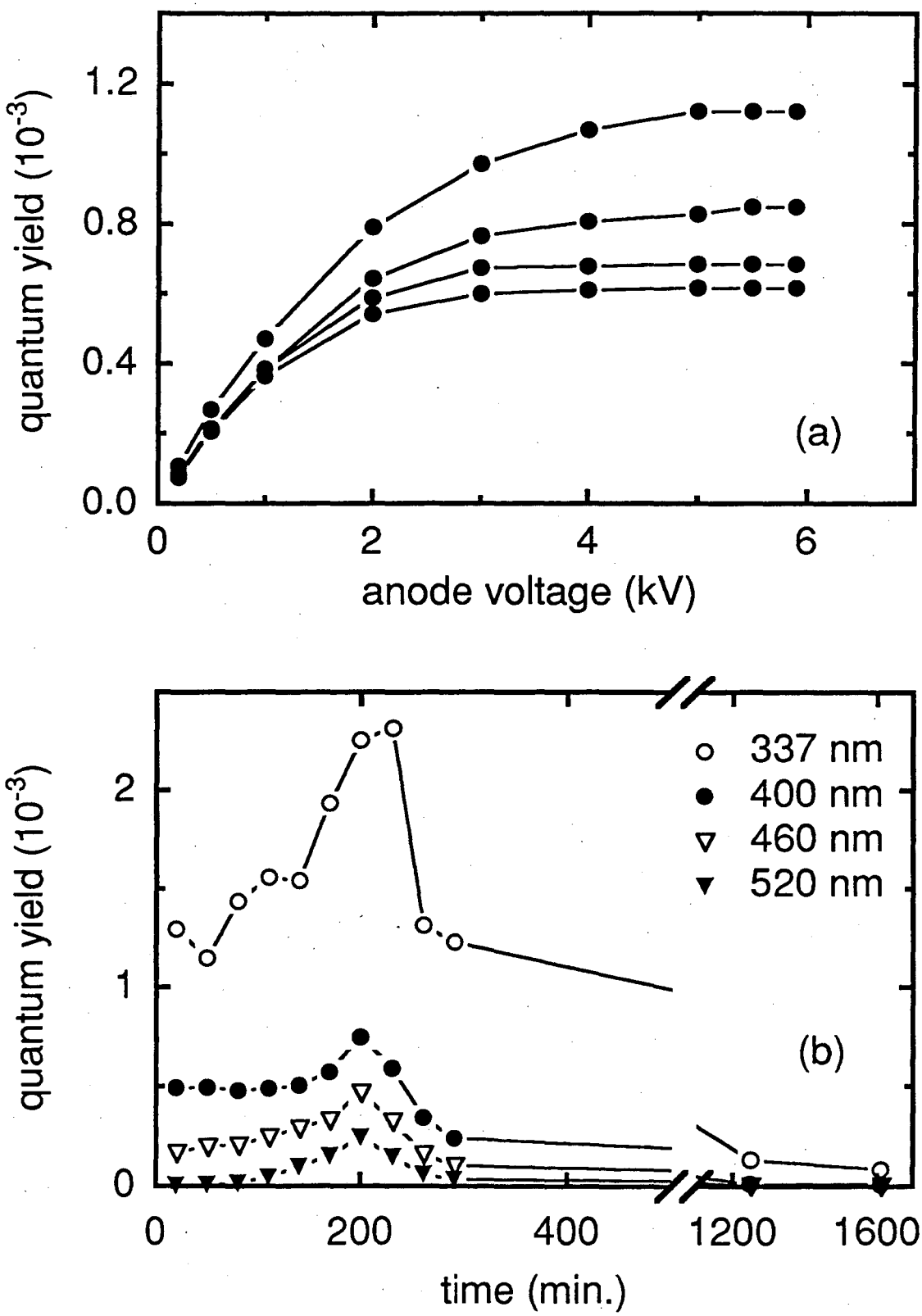
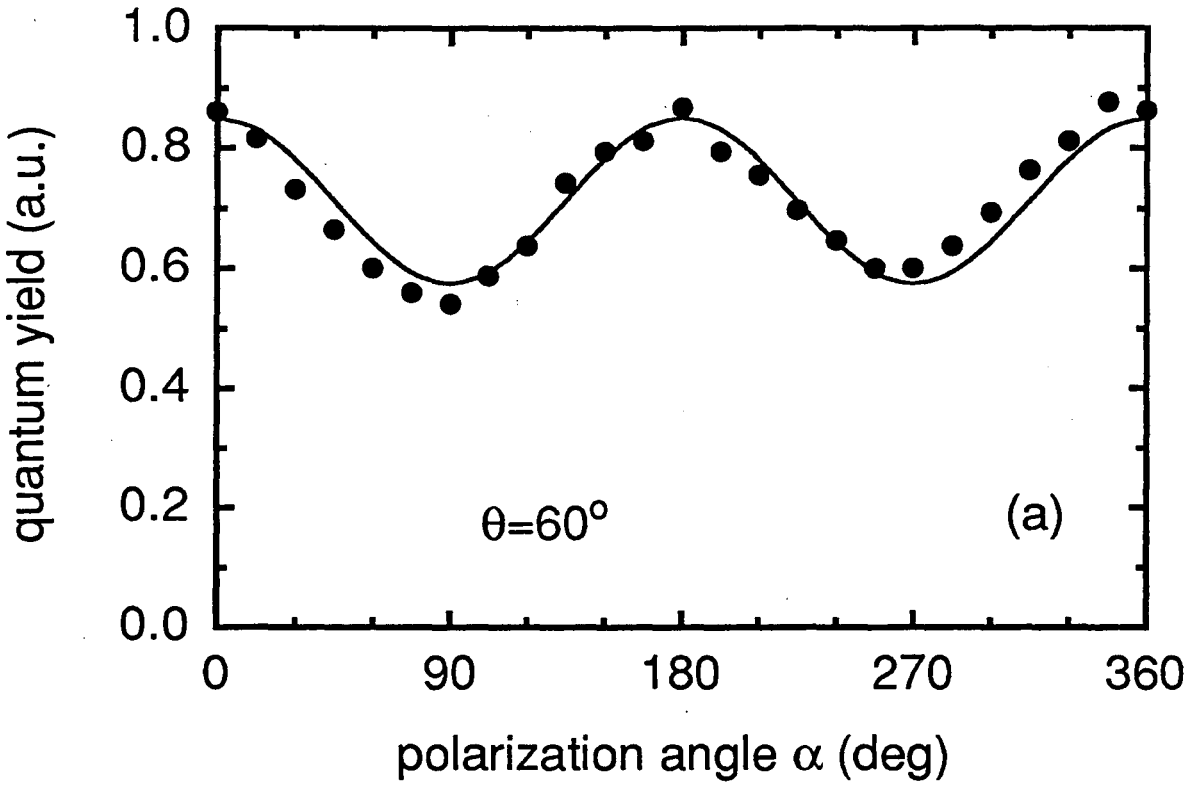


Fig. 2 [CONDE et al.]



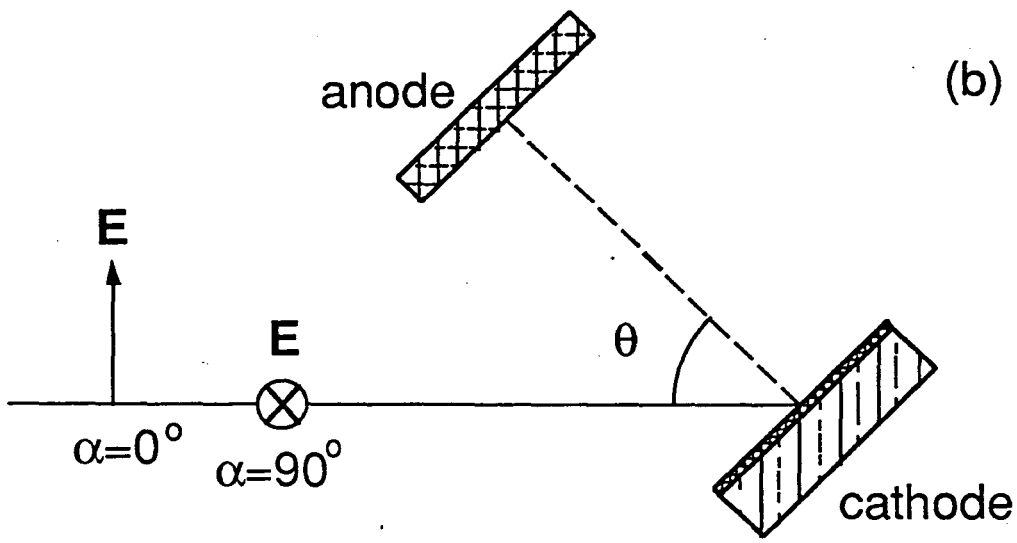


Fig. 3 [CONDE et al.]

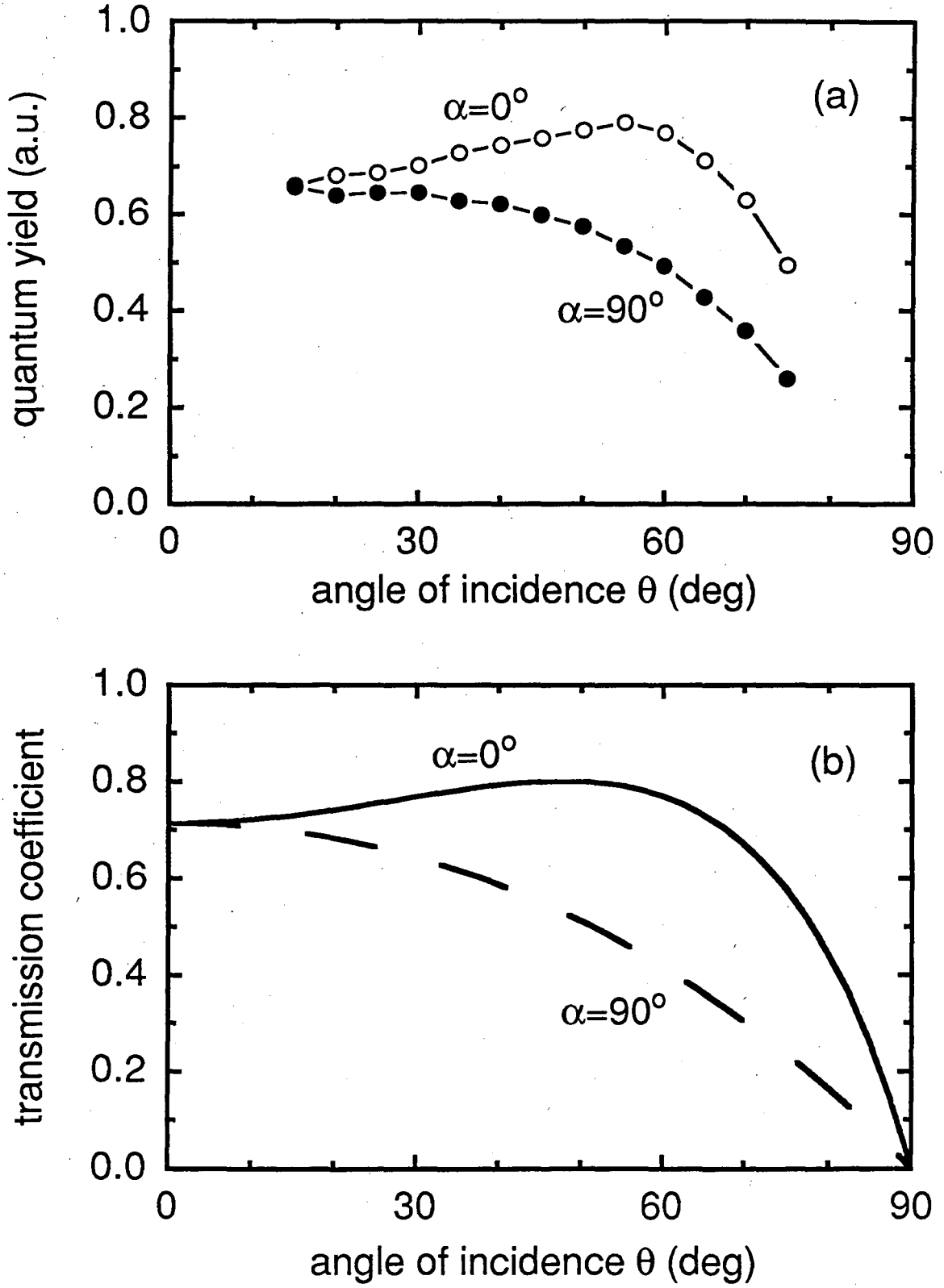


Fig. 4 [CONDE et al.]

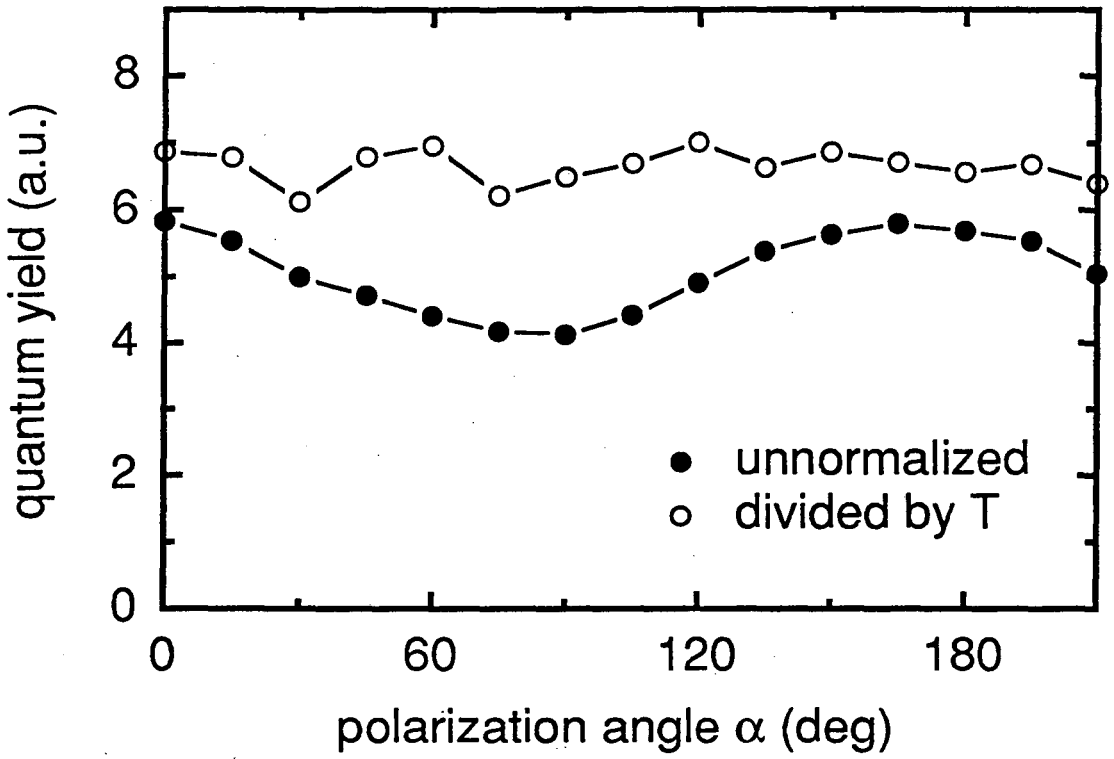


Fig. 5 [CONDE et al.]

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