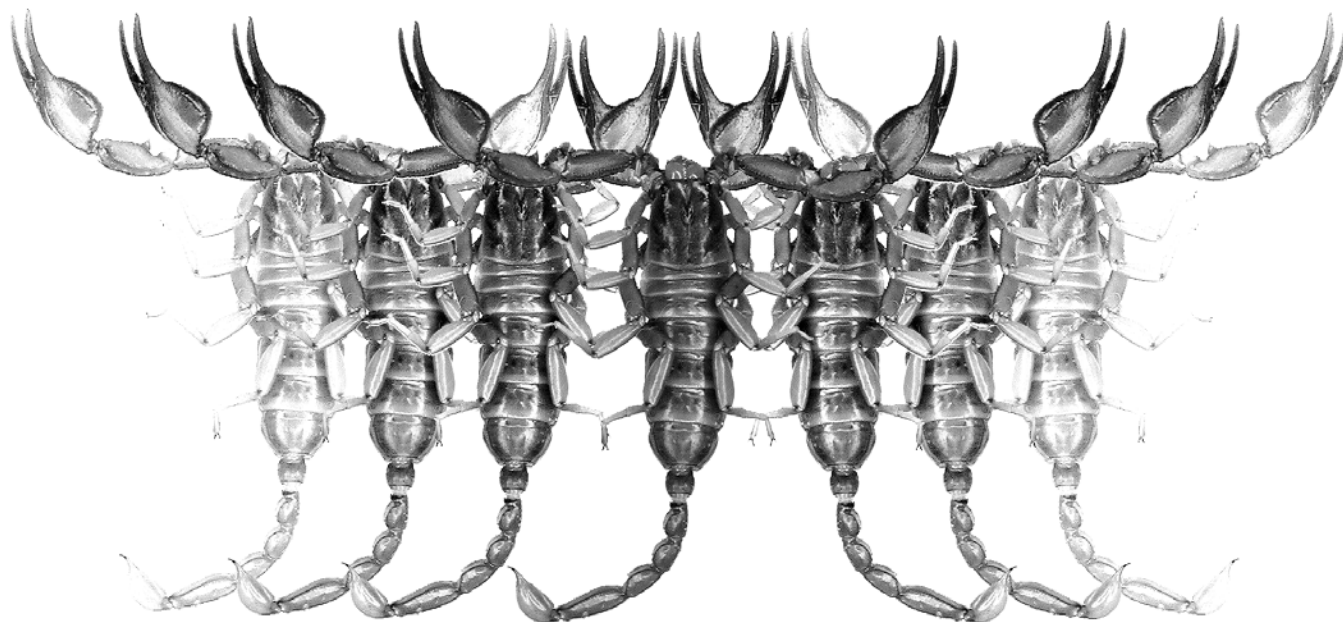


Euscorpilus

Occasional Publications in Scorpiology



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A powerful new light source for ultraviolet detection of scorpions in the field

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Summary

We describe a new portable solid-state ultraviolet (UV) light that should greatly improve the ease and effectiveness of fluorescent detection of scorpions in the field. The design is based on an array of InGaN light emitting diodes (LEDs). It is inexpensive, lightweight, simple to implement, energetically efficient and mechanically rugged. Scorpion cuticular fluorescence excited by an LED array is 13-fold brighter than excitation by previously available fluorescent tube lamps drawing the same current from the battery.

Introduction

In the past few decades, scorpion biology has been revolutionized by the use of ultraviolet (UV) lamps (“blacklights”) for fluorescent detection of these animals in the field. The chemistry of scorpion fluorescence is still not completely clarified, and more than one compound has been proposed to contribute to this phenomenon (see review and references in Frost et al. 2001). Fluorescence of the scorpion cuticle was first described by Pavan in 1954, but the phenomenon was not exploited for field studies until portable UV light sources became readily available. In 1968, Williams described the utility of fluorescent tube UV lamps for locating and studying scorpions in their natural habitats. Over the next two decades, handheld fluorescent lanterns with more convenient power sources were developed and mass produced for use in outdoor camping activities. They rapidly became standard field equipment for scorpion biologists and are currently considered the instruments of choice for blacklight detection of scorpions in the field.

Fluorescent tube lamps use elongate gas discharge tubes that are unwieldy and fragile. They require inverter and ballast circuitry, which reduces efficiency and adds weight and complexity. Moreover, the extended geometry of the tubes means that light emission is diffuse and difficult to collimate or focus, even with the aid of reflecting baffles. Here, we describe a prototype solid-state

UV lamp that overcomes these limitations. Beam collimation and efficiency of energy conversion to UV light are greatly improved, to the degree that scorpion cuticular fluorescence is enhanced by more than an order of magnitude.

Methods and Materials

We procured Indium Gallium Nitride (InGaN) light emitting diodes (LEDs) from Chi Wing Industrial Trading (HK) Ltd (Shatin, Hong Kong), via eBay (\$US 14.99/100). The UV LEDs emit light concentrated within a narrow band in the near UV wavelength range (395 nm). An array of 168 LEDs was mounted onto a 10 cm × 12 cm circuit board, and connected into 56 parallel branches each with 3 LEDs in series with a current limiting resistor (39 Ω) (Fig. 1). This assembly was housed in a small rectangular plastic enclosure (Fig. 2B). To dissipate excess heat, copper cooling fins were soldered onto the back of the circuit board and ventilated by a small fan (100 mA at 12 V) mounted on the bottom of the lamp housing. This should extend the lifetime of diodes operating in hot desert conditions. For handheld operation, a pistol grip was bolted onto the back of the lamp housing. Power was supplied to the array by a portable 12 V, 12 Ah rechargeable sealed lead acid battery (two PS-6120FP 6 V batteries in series, Power-Sonic Corporation). The total cost of all components for the LED

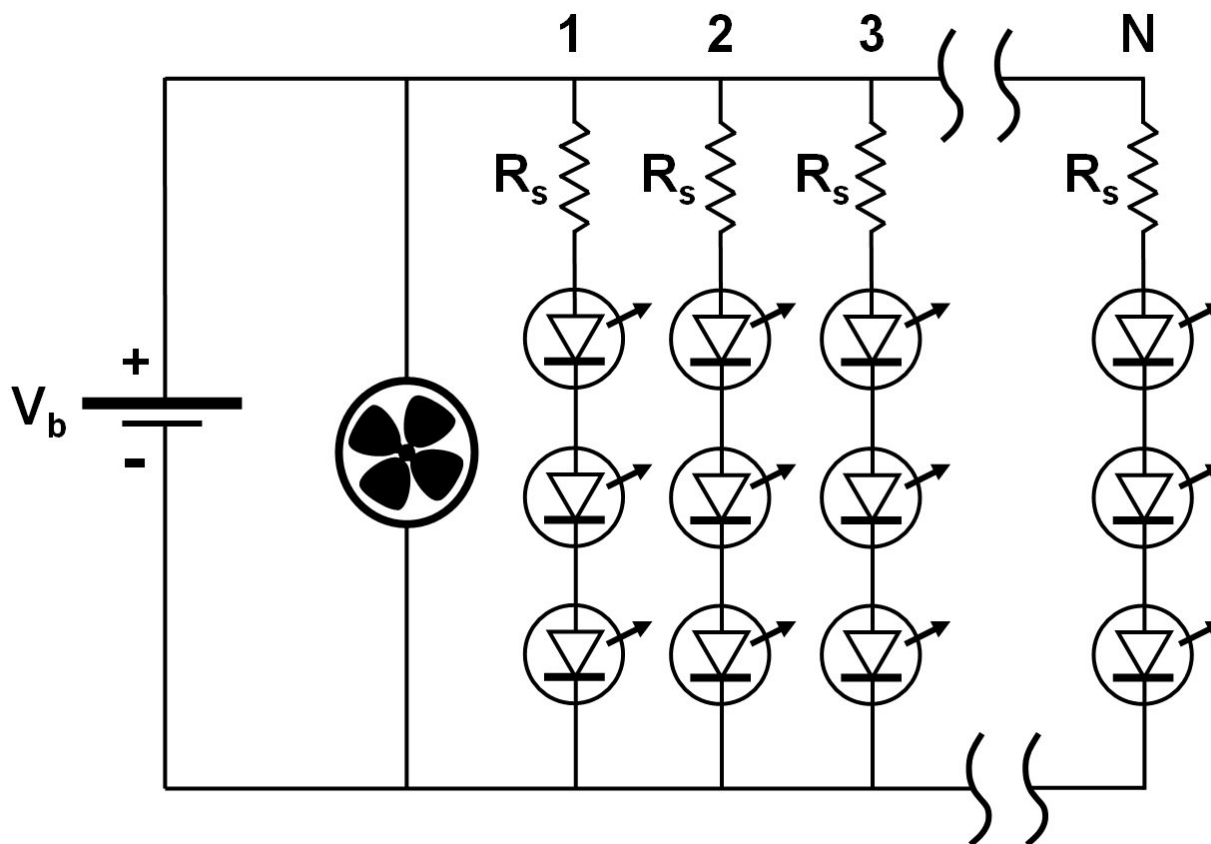


Figure 1: Circuit diagram of the prototype LED array. The array has a scalable architecture, here with $N = 56$ parallel branches. Each branch includes three LEDs in series with a single current-limiting resistor ($R_s = 39 \Omega$). Typical forward voltage drop measured across one diode was 3.4 V, giving a total diode drop of 10.2 V in each branch. During operation, voltage across the 12 V battery terminals was $V_b = 11.5$ V, so the current in each branch was $(11.5 - 10.2) / 39 \text{ A} \sim 33 \text{ mA}$. This kept the current near the maximum rating of 30 mA specified by the manufacturer for 100,000 h lifetime. Each resistor dissipates $\sim 1.3 \text{ V} \times 33 \text{ mA} = 43 \text{ mW}$; the 3 diodes in a branch dissipate $3 \times 3.4 \times 33 \text{ mA} = 337 \text{ mW}$. By using 3 diodes to maximizing total diode voltage drop, resistor power loss is kept down to about 13% of the total power. We have implemented the simplest possible circuit to drive the LEDs, one that can be easily built by biologists who have not trained in electronic engineering. More sophisticated driver circuits might be devised to regulate or balance current flow to different branches of the array, but they probably offer little additional benefit for the purposes of scorpion detection.

lamp assembly (excluding the battery and its charger) is estimated to be approximately \$US 100.00 or less.

Current and voltage measurements were made with a digital multimeter (Extech Instruments). To quantify relative differences in scorpion fluorescence, a preserved specimen of *Vaejovis confusus* (Zzyzx Rd, California, B.Hébert #6115) was attached to a dark, non-fluorescent plastic surface and imaged with a low-light charged coupled device (CCD) video camera (V-1070, Marshall Electronics) equipped with a 25 mm, 1:1.8 Computar lens, mounted on a tripod 0.8 m from the specimen. The camera automatic gain and shutter control were disabled, and gamma was set equal to 1, so that the video signal was proportional to light intensity. The video signal was digitized using an 8-bit monochrome image acquisition board (PCI-1407, National Instruments) controlled by software written in LabVIEW (National Instruments). Images were acquired when fluorescence was excited

either by the LED array or by a fluorescent tube lamp, both positioned at a distance of 1 m from the specimen. The fluorescent tube lamp was a 30 W Thin-Lite #116 (Thin-Lite Corp., California) dual tube light fixture, fitted with a pair of F15T8/BLB tubes (Sylvania), powered by the same sealed lead acid battery. A Schott GG475 long pass color filter was placed in front of the camera lens to block short wavelength light. This ensured that the camera was detecting only the fluorescence at long wavelengths ($> 475 \text{ nm}$), and not UV light from the lamps. When illuminated by the LED array, fluorescence from the specimen was sufficiently strong that the CCD chip in the camera was saturated. To bring the camera out of saturation, fluorescence was attenuated 10.5-fold by placing a 1.022 log-unit neutral density filter over the lens prior to image acquisition (Fig. 3B). In subjective testing, fluorescence was observed by eye, using yellow UV400 plastic night-driving glasses (Bruce Medical supply, Massachusetts) to block UV glare.

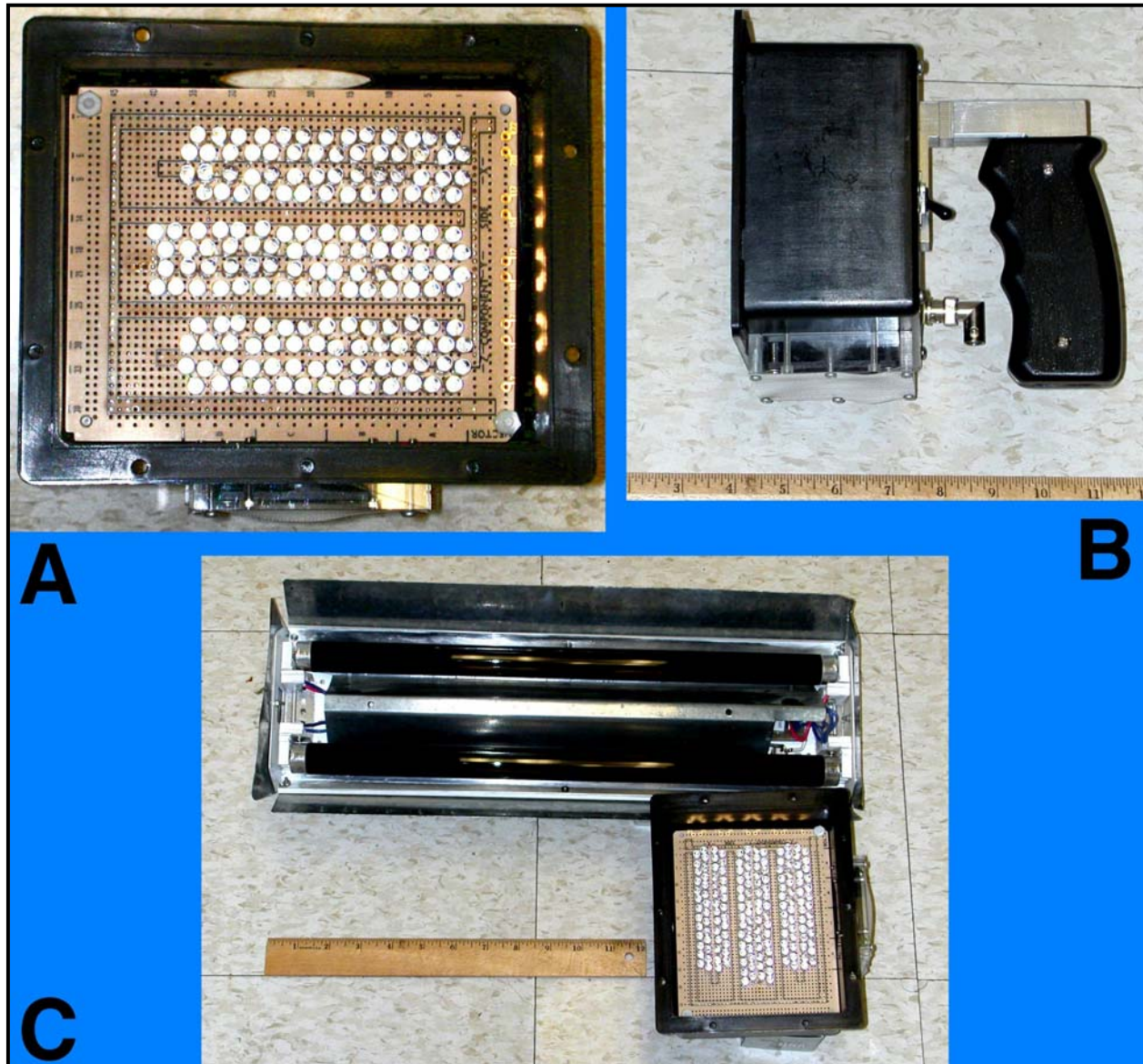


Figure 2: Photographs of a prototype LED array lamp. **A.** Frontal view showing diode array. **B.** Side view showing lamp housing. Ventilation holes were cut out of the top and bottom walls of the housing, and a small cooling fan was mounted on the bottom surface. Battery power is supplied by the BNC connection on the back. **C.** Side-by-side comparison of LED and BLB tube lamp housings, showing the substantially reduced profile of the solid-state lamp. Ruler scale: 12 inches.

Results

In subjective outdoor testing, a preserved *Leiurus quinquestriatus* (5 cm total length) was placed on a stone wall and observed at night under illumination by the fluorescent tube lamp and the LED array at a distance of 10 m. With the tube lamp, the scorpion appeared as a faint blue object without clearly discernible shape; with the LED array, the scorpion was dramatically brighter and the pedipalps and metasoma were clearly resolved.

The large increase in perceived scorpion fluorescence was corroborated by the results of the CCD measurement on *Vaejovis confusus* (Fig. 3). We used our software to convert pixels in acquired images to 8-bit grayscale values, and the mean value was then calculated over a region of interest covering 80% of the area of the mesosomal tergites (100 pixels). This procedure yielded mean pixel intensity values of 115 ± 3 (mean \pm SD) for the tube lamp, and 113 ± 3 for the LED array with 10.5-fold attenuation by the neutral density filter. Therefore, the LED array increased the fluorescence intensity by a

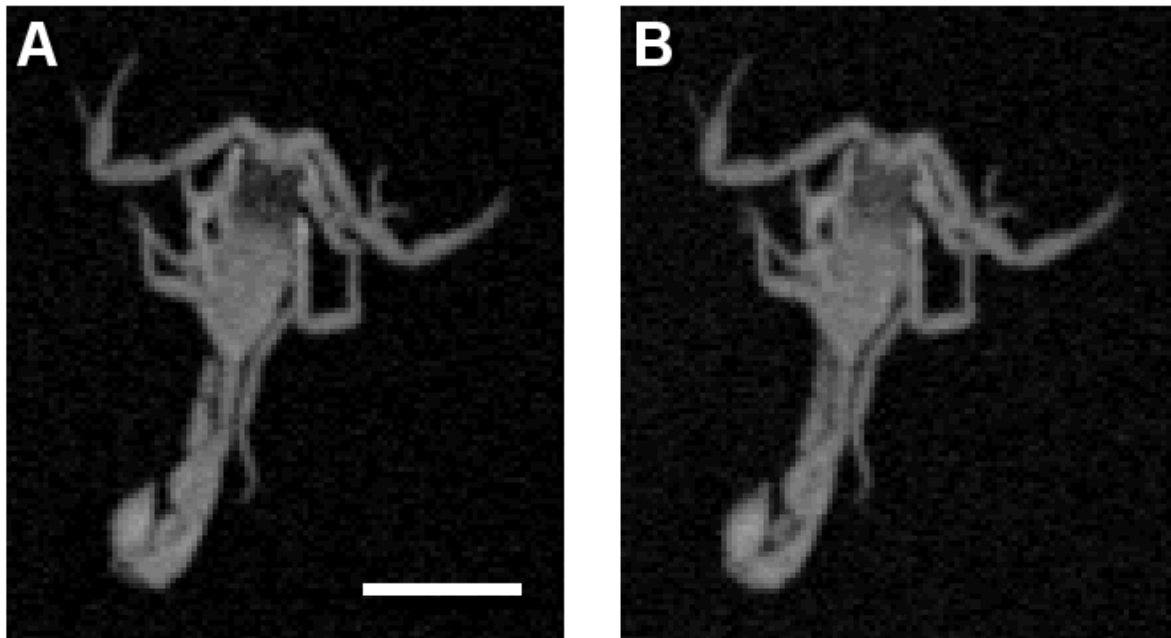


Figure 3: Comparison of scorpion fluorescence excited by different light sources. The pair of CCD camera images show a *Vaejovis confusus* illuminated by (A) a fluorescent lamp equipped with two 15 W BLB tubes (2.3 A current), and (B) a 168-diode UV LED array (1.8 A current). The scorpion fluorescence in (B) was attenuated 10.5-fold by a neutral density filter to prevent CCD saturation, so it appears equally bright in this picture. Scale bar: 15 mm.

factor of $10.5 \times 113/115 = 10.4$ over the tube lamp. The current drain on the battery was 2.3 A for the tube lamp, and 1.8 A for the LED array (excluding cooling fan current). Our 168-diode array therefore provides about 10-fold enhancement of scorpion fluorescence while extending the time between battery recharges by 35%. If the array were scaled up to $168 \times (2.3-0.1)/1.8 = 205$ diodes to draw equal net current (subtracting 100 mA of cooling fan current), then scorpion fluorescence would be around $10.5 \times 2.2/1.8 = 13$ times brighter.

Discussion

Pavan (1954) excited scorpion cuticular fluorescence using light from a high pressure mercury (Hg) arc lamp filtered through Wood's glass to isolate the 366 nm UV line. The bulky high voltage power supply and mains voltage typically required to run this type of lamp would prohibit easy field use. However, Stahnke (1972) had already observed scorpion fluorescence as early as 1945, during a demonstration of an expensive portable UV light source at a gathering of fluorescent mineral enthusiasts. At that time, affordable handheld 'mineral lights' were still too weak to be practical field tools.

However, by the mid 1960's UV lamp technology had progressed to the stage where it could be applied to field biology. Honetschlager (1965), Williams (1968) and Stahnke (1972) described the use of the Burgess 'Safari Lite' to locate scorpions. This lamp was powered by two 69 V non-rechargeable batteries, and it was adapted to scorpion hunting by replacing the visible-light fluorescent tubes with UV emitting 'BLB' fluorescent tubes. In these tubes, ionized Hg ions emit UV radiation primarily at the 366 nm spectral line, supplemented by a broad-band phosphor emission centered around 360 nm (~75 nm peak width; Fig. 4). Visible light output from the plasma tube is blocked by tinting the glass a deep purple color. An inverter circuit converts direct current (DC) from a portable battery to alternating current (AC), and a magnetic or solid-state ballast circuit is included to regulate the flow of current through the plasma.

Since their introduction, portable fluorescent tube blacklights have enjoyed widespread use by scorpion biologists engaged in taxonomic surveys and discovery of new taxa (e.g. Lamoral, 1979; Levy & Amitai, 1980; Williams, 1980; Lowe, 2001; Prendini, 2001), and in ecological (e.g. Hadley & Williams, 1968; Polis, 1979; Polis & Farley, 1979; Sissom et al. 1990) and toxicological (Honetschlager, 1965; Zahl, 1968) investigations. Although they have been employed effectively, these

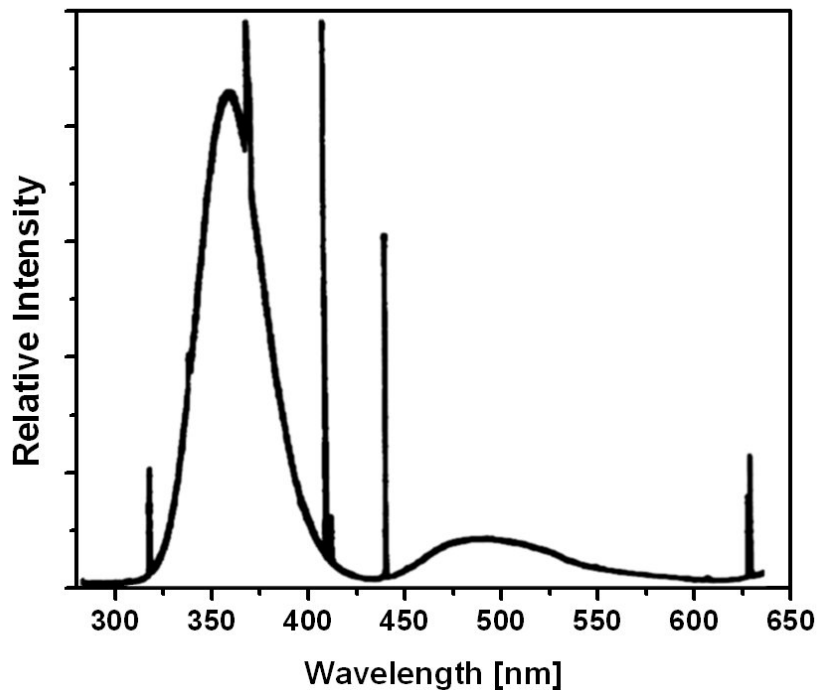


Figure 4: Excitation spectrum of a blacklight tube and fluorescence spectrum of the scorpion cuticle. The data were recorded with a scanning spectrometer during blacklight illumination of *Hadrurus obscurus* (Iuridae). The broad peak below 400 nm and the discrete Hg lines correspond to the tube emission (F6T5/BLB, Sylvania), and the broad peak in the visible region (450-550 nm) corresponds to the blue-green fluorescence of the scorpion. This visible peak disappeared when the scorpion was removed and only light from the BLB tube was scanned. Identically shaped 450-550 nm fluorescence spectra were obtained from *Paruroctonus silvestrii* and *Paruroctonus becki* (Vaejovidae), which suggests that the chemistry of fluorescence is conserved across different scorpion families. We therefore expect that UV detection results presented here will be applicable to a wide variety of scorpion taxa. We did not record the UV LED spectrum. Typical published spectra for these devices peak sharply at the rated wavelength of 395 nm, with 50% peak widths of only about 20 nm.

lamps suffer from several limitations. Fluorescent lights convert energy stored in a battery to UV photons more efficiently than incandescent lights, but significant losses are still incurred by the AC inverter and ballast circuits. Additional losses include heat dissipation in the electrodes and plasma of the gas discharge tube, and the emission of visible wavelength photons which must be blocked out. In contrast, the UV LED only requires a simple resistive circuit to run directly off a DC power supply. Under forward bias, electrons in the conduction band of the semiconductor enter the pn -junction and recombine with holes in the valence band, thereby releasing photons by a much more direct process. The energy bandgap in the InGaN material determines the 395 nm photon wavelength, so light emission is narrowly concentrated around this wavelength, with only about a 25 nm peak width. There is minor visible emission in the green range caused by autofluorescence of the clear epoxy casing of the LED, but this is much weaker than the UV emission, and may even be useful for background illumination to assist the operator in traversing rough terrain and avoiding encounters with venomous snakes.

Another drawback of the fluorescent tubes is their diffuse radiation pattern, a consequence of the extended geometry of their light emitting surfaces. Partial collimation can be achieved by attaching a metallic reflector to the lamp housing to direct the light forward and away from the operator, but this increases the weight of the lamp. Diffuse lighting facilitates the scanning of large areas of habitat at close range, but the wide angular divergence of the beam combined with the inverse square

law greatly diminishes the intensity of light incident on surfaces at moderate to long ranges (10-40 m). In the LED array, the pn -junction inside each LED approximates a point source and the clear epoxy casing is cast into a hemispherical lens which focuses the light into a highly directional radiation pattern with a narrow divergence angle of ca. 25°. The result is a collimated beam capable of intense illumination of surfaces at moderate to long distances. The range of scorpion UV detection is therefore greatly extended, and remote sensing of scorpion populations becomes a real possibility. Conversely, if short range, wide field illumination is desired, the LED beam can be easily made to diverge simply by tilting individual elements of the array.

Our lamp also addresses a well known problem faced by scorpion collectors – the loss of fluorescence contrast in the presence of ambient nocturnal illumination from moonlight or nearby artificial lights. In the past, this problem has restricted blacklighting activities to darker phases of the lunar cycle because fluorescent tube lamps were too feeble to compete with moonlight. The much higher intensities attainable by LED lamps should provide some relief from this problem. The scalable architecture of our LED array makes it very convenient to ramp up the intensity by increasing the number of branches. The intensity may also be raised by decreasing the values of the current limiting resistors, which increases the branch current. Exceeding the 30 mA maximum rated current of the diodes would be expected to shorten their total life, but this may not be an important factor given their high rated lifetimes and the

intermittent blacklighting schedules of many scorpion researchers. Fluorescent tubes become less efficient over time, having typical rated lifetimes in the range of 9,000 h, whereas LEDs are rated for 100,000 h.

Fluorescent tubes are fragile and prone to breakage in the harsh environments where field scorpologists work. Most researchers can probably recall expeditions that were hindered or cut short by such incidents. In order to ensure the success of expensive and time consuming field trips to remote locations, multiple backup tubes must be carried and protected in sturdy containers. Lamp housings need to be strengthened and the tubes shielded, which adds weight and may block off some UV light output. The LED array is very rugged and easily withstands sharp impacts that would shatter the tubes of a fluorescent lamp. The small, compact profile is more convenient to transport in the field. Damage or malfunction of a single tube may render a fluorescent blacklight useless, but the cascaded parallel architecture of the LED array means that damage to, or burnout of, a few LEDs only slightly reduces the total light output.

The order of magnitude boost in UV power provided by the LED array, and the longer emission wavelength (395 nm vs. 360 nm) have one undesirable side effect. The violet-blue haze perceived by blacklight operators is noticeably stronger and is more likely to interfere with night vision, and the intense UV radiation can harm the eyes if the array is viewed directly. We therefore strongly recommend that scorpologists using this new generation of high power blacklight should wear commercially available night-driving glasses (or 'shooting glasses'). These optics incorporate a yellow filter material to block short wavelength radiation, while passing most of the colors of the scorpion fluorescence spectrum (440-540 nm). Users will need to exercise strict safety protocols in the field, and refrain from shining the beam into the eyes of their fellow researchers.

Solid-state light sources hold considerable promise for field biologists. For example, entomologists can construct more efficient and durable light traps. The narrow band quasi-monochromatic emission of LEDs offers versatility in scientific applications. For example, the UV array may be augmented with an auxiliary bank of red LEDs, allowing an operator to switch rapidly between UV detection and red light observation of invertebrate behavior. We have little doubt that many other creative applications will emerge.

Acknowledgements

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