Seeing Radiation from Afar - A Novel Filament-Based Ionizing Radiation Sensing Technology

Traditional measurement techniques are generally restricted to the detection range of few centimeters, posing a great risk to operators.

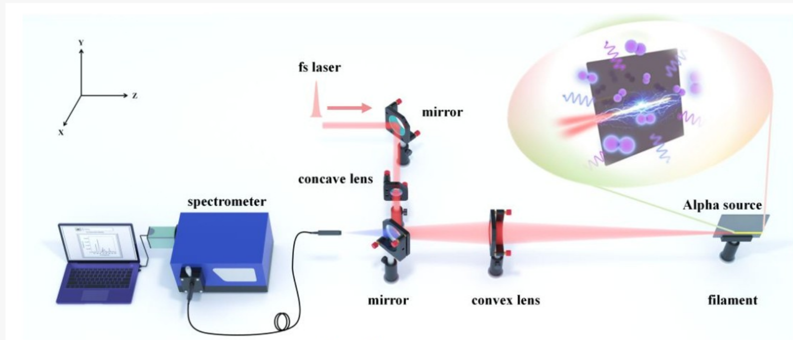

Fig 1 Experimental setup diagram of the filament-based IR sensing technique (FIRST).

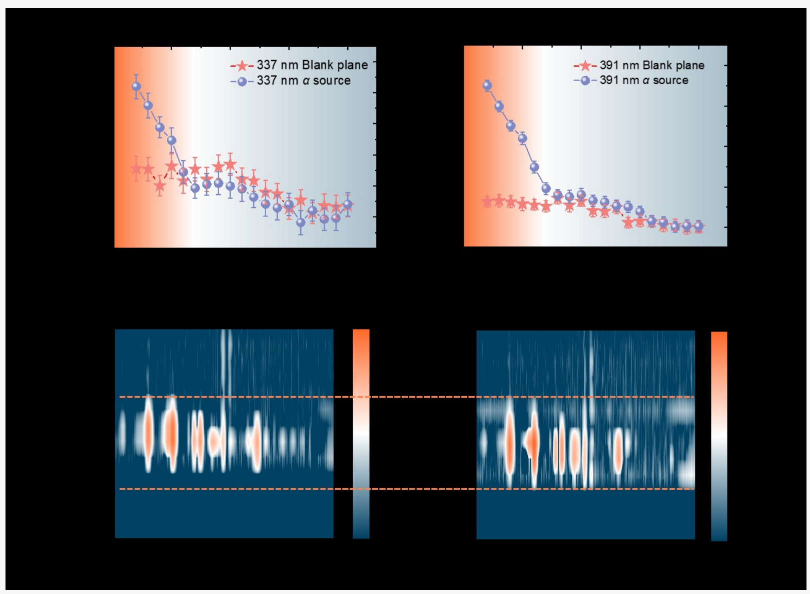

Fig 2 α-source-induced enhancement and lifetime prolongation of nitrogen fluorescence. (a) and (b) Distance-dependent nitrogen fluorescence intensity centered at 337 nm and 391 nm, respectively.

CHINA, December 5, 2025 /EINPresswire.com/ -- From the Chernobyl nuclear disaster to the release of nuclear-contaminated water from Fukushima Daiichi Nuclear Power Plant into the ocean, ionizing radiation (IR) has been continuously drawing global concerns. IR refers to particles or electromagnetic waves capable of ionizing atoms, which is widely present in nuclear power plants, medical radiotherapy and industrial radiography. Although important in medical diagnosis, cancer treatment, and scientific research, overdose exposure leads to severe biological damage. Therefore, detecting radiation sources safely, accurately, and efficiently has always been a crucial public safety issue.

Traditional IR detection techniques are mainly Geiger counters, which have only ~cm detection range and therefore pose great exposure risk. Difficulty to achieve large-scale, remote, and non-contact monitoring also greatly limits their efficiency. How to “see” weak radioactive sources from hundreds of meters away has long been an unsolved problem. With the development of ultrafast laser technology, femtosecond laser filamentation, which induces fluorescence through ionization, provides a new idea to solve the aforementioned problem.

Femtosecond laser filamentation refers to a thin and stable plasma channel formed due to the dynamic balance between optical Kerr self-focusing effect and plasma defocusing effect. The filament can maintain extremely high light intensity (about 10^{13}–10^{14} W/cm^2) over a distance ranging from meters to kilometers, which can excite substances to emit fluorescence spectra with fingerprint features. IR induces ionization background that directly affects interaction between laser-induced ionization, excitation, and relaxation of air molecules, leading to fluorescence intensity modulation. Therefore, femtosecond laser filamentation provides a new opportunity to break through the limitations of traditional IR sensing technologies.

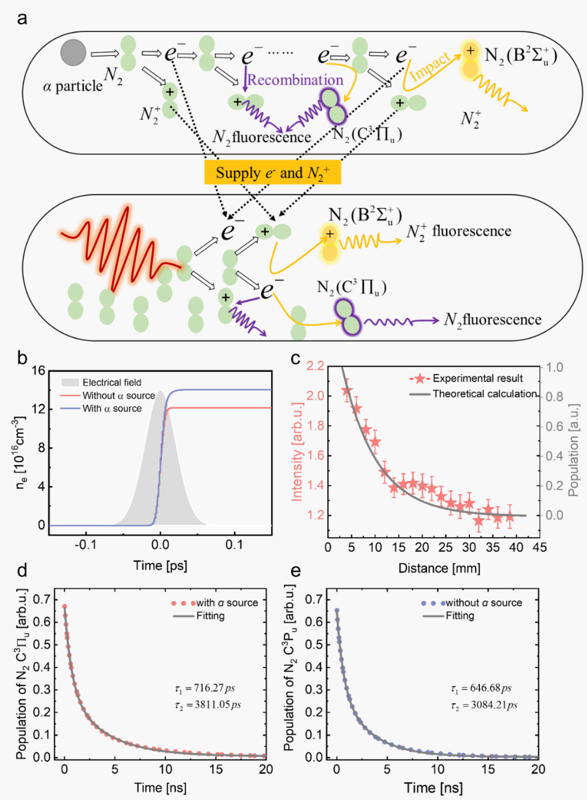

Fig 3 (a) Mechanism of modulated nitrogen fluorescence emission by α particles; (b) Calculated dynamic of total electrons density with/without α-generated free electron;

In light of this background, the research group led by Prof. Weiwei Liu from the Institute of Modern Optics, Nankai University, proposed and demonstrated a filament-based IR sensing technology (FIRST). The team systematically studied how IR affects filament-induced nitrogen fluorescence spectra and their dynamics in air, and built a quantitative model describing the interaction among IR, plasma and femtosecond laser. Because filaments can induce and detect fluorescence over kilometers, the technology is expected to realize large-area, remote and non-contact IR monitoring.

The experimental setup is shown in Fig. 1. Femtosecond laser pulses (center wavelength 800 nm, repetition rate 500 Hz, pulse duration 60 fs, single-pulse energy 3.5 mJ) pass through a telescope system made of a concave and a convex lens and form a 15 mm-long stable filament 1 m behind the convex lens (the position can be tuned by adjusting the lens pair). A 1 kBq α planar source is placed parallel to the filament. Backward nitrogen fluorescence is collected by fiber and sent to an iCMOS time-resolved spectrometer. The results show that the α source increases the nitrogen molecular/ionic fluorescence intensity at 337 nm/391 nm by more than 30 % (Figs 2a,b) and prolongs the fluorescence lifetime by about 1 ns (Figs 2c,d). The team then built a microscopic model of radiation-enhanced filament-induced nitrogen fluorescence (Fig 3a) that couples the α-generated free-electron density, electron acceleration and collisional ionization, and the population and relaxation of excited nitrogen states.

The calculation shows that α-generated electrons are accelerated by light field and induce collisional ionization, raising the number of excited nitrogen molecules and the electron density by ~20 % (Fig 3b). This leads to the observed ~30 % increase of backward fluorescence (Fig 3c) and ~0.8 ns extension of fluorescence lifetime (Figs 3d,e), in good agreement with experiment. Noted that the α source activity in this study is only 1 kBq, far below the 10 kBq exemption level given in IAEA Safety Standards Series No. GSR Part 3, which proves the potential for low-dose radiation detection. Furthermore, the core mechanism is universal and can, in principle, be extended to all IR types. By combining solar-blind UV detection and time-gating technique, background can be further suppressed for real-world deployment. The technology is expected to serve in nuclear-plant inspection, radioactive-material tracking and nuclear-accident emergency response, constructing a safe, intelligent and sustainable nuclear-security system. Furthermore, the revealed physical mechanism of radiation-modulated filament-induced fluorescence dynamics will deepen understanding of the interplay among IR, plasma and strong laser fields, and promote the integration of strong-field laser and radiation detection.

About the research group:

The research group on extreme-scale optoelectronic detection technology and equipment (https://imo.nankai.edu.cn/femto/cdefault.html) is led by professor Weiwei Liu, a distinguished professor of the Ministry of Education. The team's research is centered on ultrafast optics, towards the major national needs in aerospace, biomedicine, integrated circuits and other fields. It integrates the cutting-edge technologies of micro-nano optoelectronic manufacturing and intelligent perception in a space-air-ground system. The group is engaged in novel mechanisms and methods such as quantum probes, ultra-precision laser processing, and optoelectronic interaction and detection. It aims to overcome the performance limitations of present ultrafast laser technologies and provide unique and superior tools for advanced laser detection and processing.
The team has led more than forty national and provincial projects, including the National Key R&D Program, the CNSF and Tianjin key projects, with an on-going budget of forty million yuan. The group developed China's first on-orbit hazardous-gas analyzer deployed on Tiangong-1 and Tiangong-2 space station, and led the full-chain optical simulation for the atmospheric environment detection satellite, supporting the approval of China's first atmospheric satellite "Atmosphere-1". The team's achievements have been selected as one of the Top Ten Advances in Chinese Optics and have been highlighted by journals such as Light, JPCL, AOM, and Chinese Optics and China Central Television.

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