New high-efficiency rare earth micronuclear battery

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With the rapid advancement of the Internet of Things, intelligent manufacturing, and medical devices, there is an escalating demand for miniaturization, high performance, and low power consumption in various applications. Micro-electro-mechanical systems (MEMS) are tiny devices that integrate mechanical and electrical components at a microscale, typically ranging from 1 to 100 micrometers. MEMS has emerged as a crucial solution, enabling real-time data monitoring and feedback, thereby enhancing system performance and reliability. Recognized as a transformative technology of the 21st century, MEMS are integral to the development of next-generation devices. According to market and technology trends of Yole Development, the global market for MEMS devices is projected to experience substantial growth between 2023 and 2029, increasing from \$13.6 billion to \$20 billion.[1] This underscores the scientific and practical significance of advancing efficient MEMS technologies in supporting innovative energy solutions.

MEMS is comprised of three integral components: energy sources, sensors, and actuators. The energy sources component is vital to the functionality of MEMS. Currently, various micro-energy technologies have been developed, including micro-internal combustion engine batteries, micro-lithium-ion batteries, micro-fuel cells, micro-solar cells, and micro-nuclear batteries. Micro-internal combustion engine batteries provide robust energy outputs but are less efficient and generate emissions. Micro-lithium-ion batteries are known for high energy density, ideal for portable electronics, yet have limited lifespans and disposal challenges. Micro-fuel cells convert hydrogen into clean energy quickly but rely on hydrogen infrastructure, which can hinder adoption. Micro-solar cells harness renewable energy but depend on sunlight, limiting efficiency and requiring larger surface areas. In contrast,

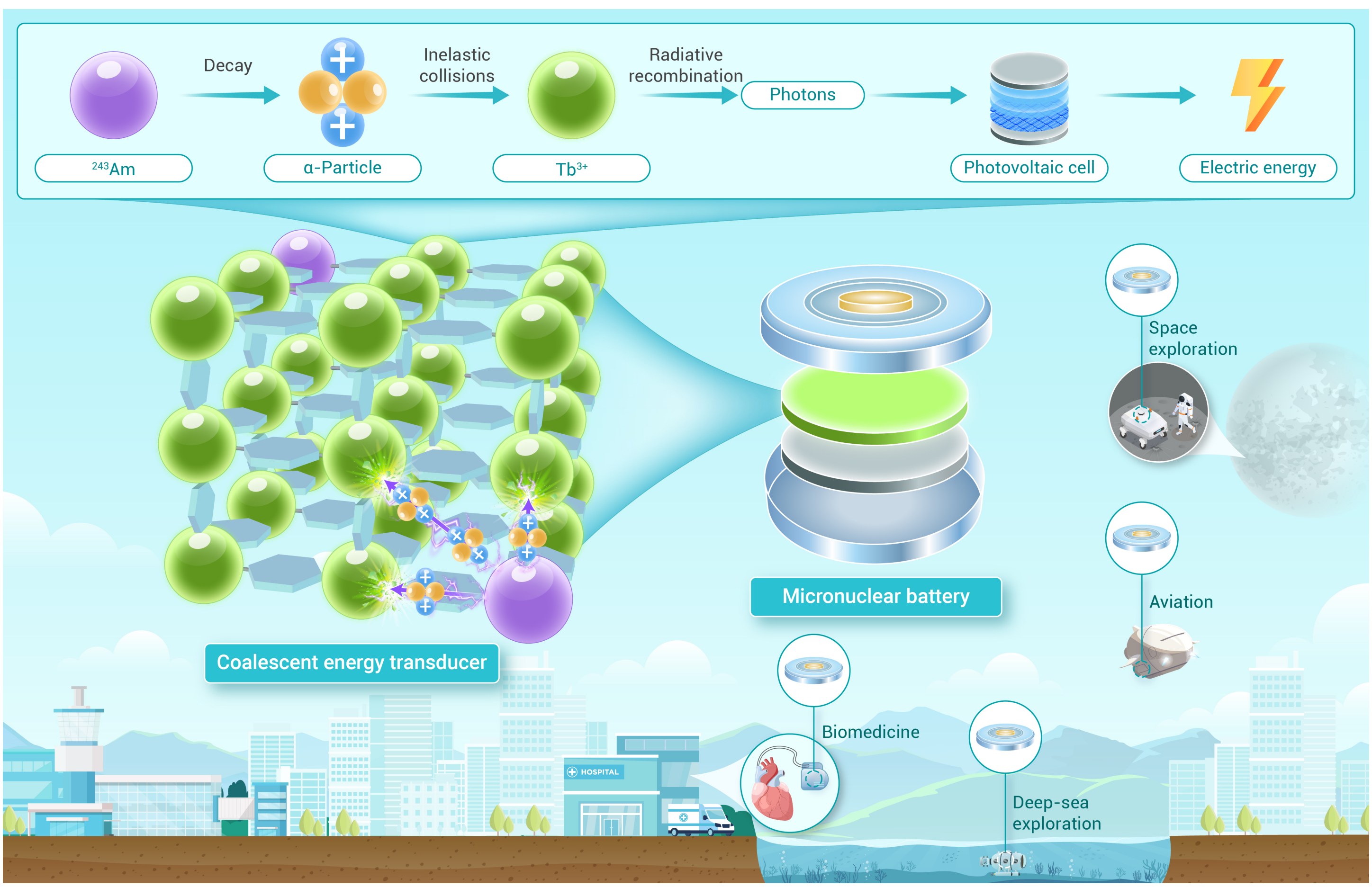

Figure 1. Schematic diagram of micronuclear battery with a coalescent energy transducer.

micronuclear batteries offer exceptional longevity, lasting decades with minimal maintenance, making them suitable for critical applications like medical implants and remote sensors. Thus, while each micro-energy technology has strengths and weaknesses, micro-nuclear batteries stand out for specialized applications requiring reliability and long-term performance.

A nuclear battery is a sophisticated device that generates electricity by converting high-energy alpha (α) and beta (β) particles, as well as gamma (γ) rays emitted by various radioactive isotopes.[2] These nuclear batteries demonstrate exceptional environmental adaptability, possess an extended operational lifespan, and eliminate the need for charging and discharging, while also being unaffected by light conditions. This makes them particularly suitable for the long-term, stable operation of autonomous MEMS. In particular, in the realms of space exploration, medical applications and wearable technology requiring long-lasting micro-electromechanical systems, micronuclear batteries emerge as an ideal power source for independent microenergy solutions within MEMS. Therefore, the development of micronuclear batteries is of great significance to promote the rapid development of MEMS.

Since the early 20th century, nuclear batteries have piqued the interest of researchers in the field of energy conversion. The initial development can be traced back to H.G.J. Moseley and J. Harling, who constructed and tested a device utilizing radium decay to release energy in 1913.[3] It wasn't until 1953 that $^{90}Sr/^{90}Y$ released β particles to bombard silicon-based p-n junction semiconductor devices for power generation.[4] This breakthrough laid the groundwork for significant progress in nuclear battery research, leading to the development of thermoelectric conversion nuclear batteries, radio-voltaic batteries, and radiophotovoltaic batteries. A radiophotovoltaic battery is a device that converts the energy released by radioactive decay directly into electricity through the photovoltaic process. Recently, the rapid advancements in semiconductor materials and solar cell technology have reignited interest in radiation-induced photovoltaic effect nuclear batteries. These innovative devices harness the decay energy of radioactive isotopes, converting it into light energy using fluorescent materials, which is then transformed into electrical energy through semiconductor devices. The ongoing research and development of long-lived, high-power-output radiation-photoelectric conversion nuclear batteries is a key way for advancing practical micronuclear batteries, particularly for applications in MEMS where miniaturization and efficiency are paramount.

α- particles possess higher decay energies than β-particles, with energies ranging from a few keV to tens of keV. This characteristic suggests that developing α-radioisotope micro-nuclear batteries could yield more durable and efficient power outputs. Currently, α- thermoelectric conversion nuclear batteries have seen successful applications in space exploration equipment. However, the traditional structure of radioactive photovoltaic cells is mainly designed for β-particle radiation cells, featuring a conventional architecture that includes a radioactive source, scintillator, and photovoltaic cell. When α-particles or β-particles are incident on the scintillator, the scintillator will absorb part of the energy. The luminescence process after absorbing high-energy photons can be divided into three stages: conversion, transfer and luminescence. In the first stage, high-energy photons have a series of complex interactions with the crystal lattice of the scintillating material. During this process, the scintillating material forms many electron hole pairs in the conduction band and valence band and is excited. The second stage is then entered, where electrons and holes migrate through the material and are captured by traps in the forbidden band. In the third stage, electrons and holes are continuously trapped in the luminescent centers and undergo radiation transitions, forming a scintillation luminescence. The resulting luminescence acts on the photovoltaic device to produce electrical energy. In this battery configuration, the radiation source module and the transducer module are typically positioned independently. The penetration depth of α-particle is short, which allows the alpha particles released by the radioisotope to transfer energy to neighboring particles. The non-transducer unit inelastic collides electrons with the extranuclear nucleus, and this energy is lost through non-radiative recombination, which impedes the effective conversion of actinide α-particles decay energy. Therefore, a critical challenge in advancing α-particles radioisotope micro-nuclear batteries is the design of an optimized configuration of converter/radiosource systems that minimizes self-absorption and maximize energy conversion efficiency.

In 2024, Li et al. innovatively broke through this problem of reducing the effective conversion of actinide α-particles decay energy due to non-transducer unit inelastic collides electrons with the extranuclear nucleus.[5] A new architecture of α-radioisotope radiophotovoltaic batteries that integrates a condensed energy converter with a peroxide thin film photovoltaic cell is proposed (Figure 1). The condensed energy converter links a radioactive isotope to a luminous center at the molecular level, allowing the energy from α-particle decay to be efficiently transferred to the surrounding high-Z converter unit. This minimizes unnecessary energy loss due to energy transfer to non-converter atoms during α-particles transport. Due to the similar ionic radius, charge density and coordination chemistry of rare earth Tb^{3+} and Am^{3+}, ^{243}Am as α-particles decay emitters with half-lives longer than hundreds of years successfully is incorporated into the crystal lattice of a crystalline terbium-bearing coordination luminescent polymer ($Tb_2(C_{12}O_{12})\cdot(H_2O)_8\cdot 2H_2O$), the energy conversion efficiency from α decay energy to continuous self-luminescence is increased by 8000 times, which is the most efficient micronuclear battery at present.

Micronucleus batteries can operate at high temperatures, making them suitable for industrial applications and spacecraft exposed to the heat of the sun. Micronucleus batteries also perform well in high-radiation environments, making them ideal for nuclear facilities or space missions, where conventional batteries degrade rapidly. Micronucleus batteries can withstand extreme humidity, making them effective for tropical climates or underwater sensors. The resilience of micronucleus batteries at low temperatures also facilitates deployment in polar regions or high altitudes, where other batteries may fail. This work not only provides a new direction for the development of micronucleus batteries, but also new energy solutions for future applications in extreme environments.

Despite the abovementioned achievements, there are limitations to consider, including regulatory hurdles related to the use of radioactive materials, public safety concerns, and the high initial costs associated with production. Furthermore, the complexity of the technology and the need for safe disposal methods for radioactive components can pose challenges for widespread adoption. With further optimization and integration, this new type of micronucleus battery is expected to play an increasingly important role in a variety of fields that require a long-term, stable power supply.

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AUTHOR CONTRIBUTIONS

C. Rao, L.Y. Guo wrote the draft. M. Y. Qian helped draw the figure. X. G. Yang helped polish the language. L. J. Han, Y. B. Zhang, W. P. Liao supervised and revised the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.