基于CiADS的一个缪子催化核聚变研究设想

——探索聚变能源的独特途径

A Proposal for Muon-Catalyzed Fusion Research Based on CiADS

——Exploring a unique and promising alternative fusion

殷 雄 博士

深圳市海核安科学研究有限公司首席专家

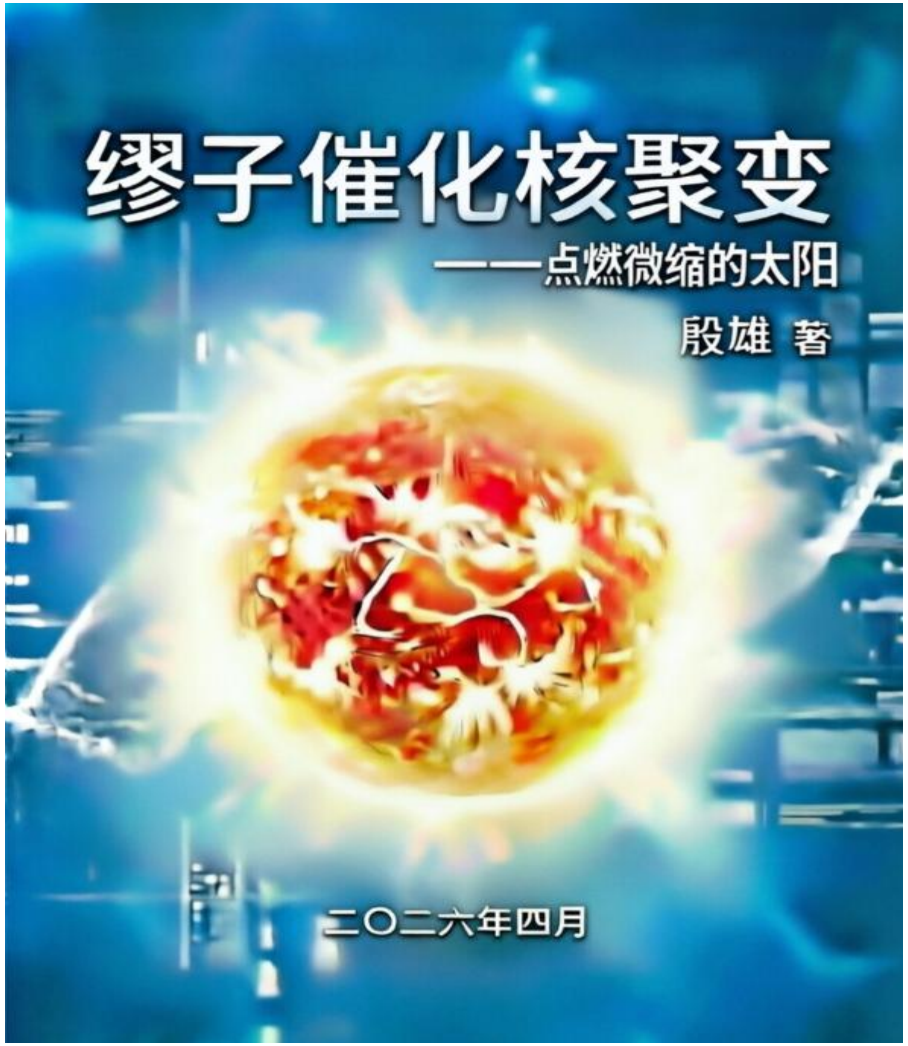
北京大学、南方科技大学、厦门大学兼职教授

Dr. Yin Xiong

Lead Researcher, **Shenzhen Haihean Scientific Research Co., Ltd.**

Adjunct Professor：Peking University, SUSTech, Xiamen University

April 25, 2026



缪子催化核聚变

——点燃微缩的太阳

殷雄 著

二〇二六年四月

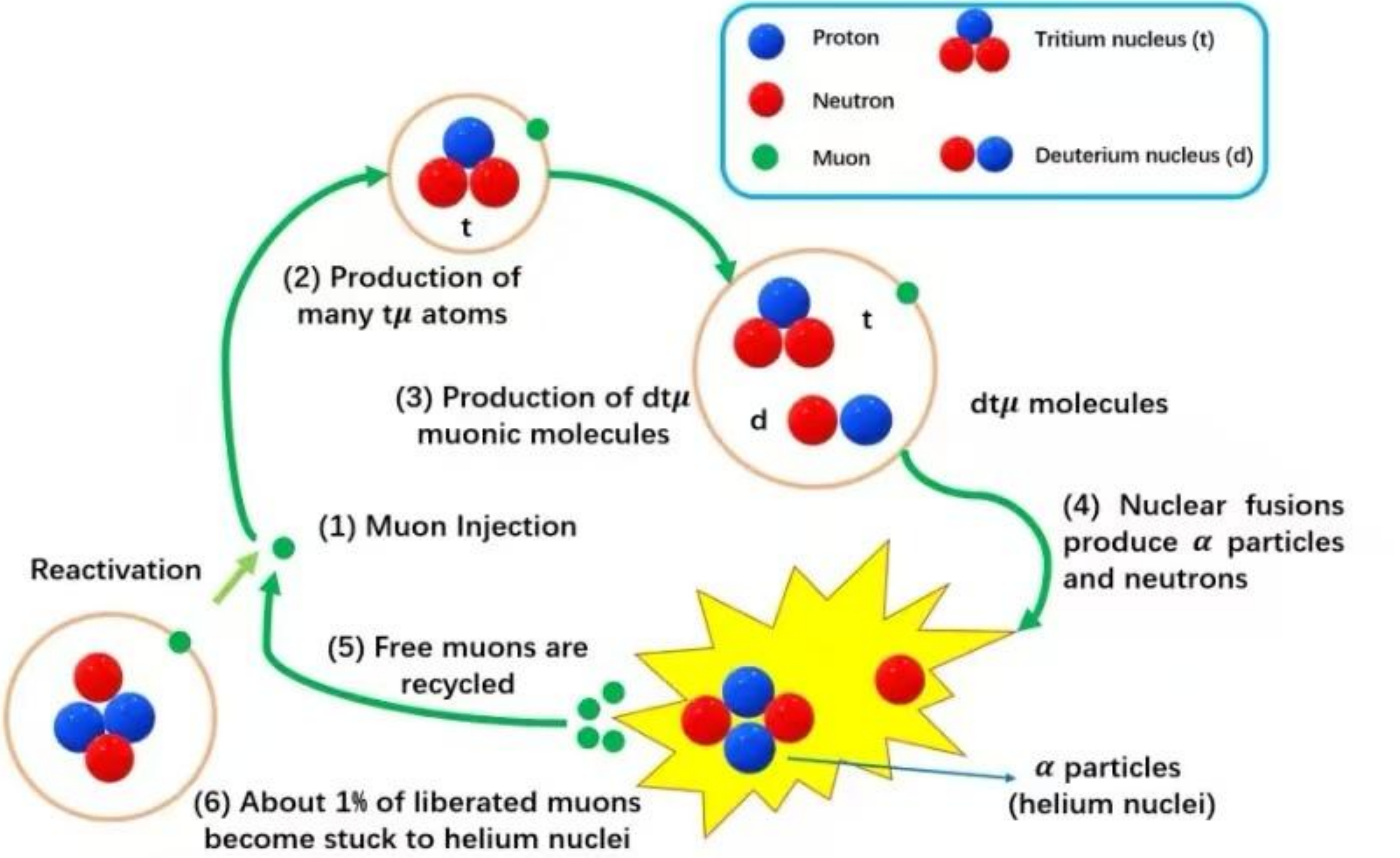
Muon-Catalyzed Fusion

——Lighting the Miniature Sun

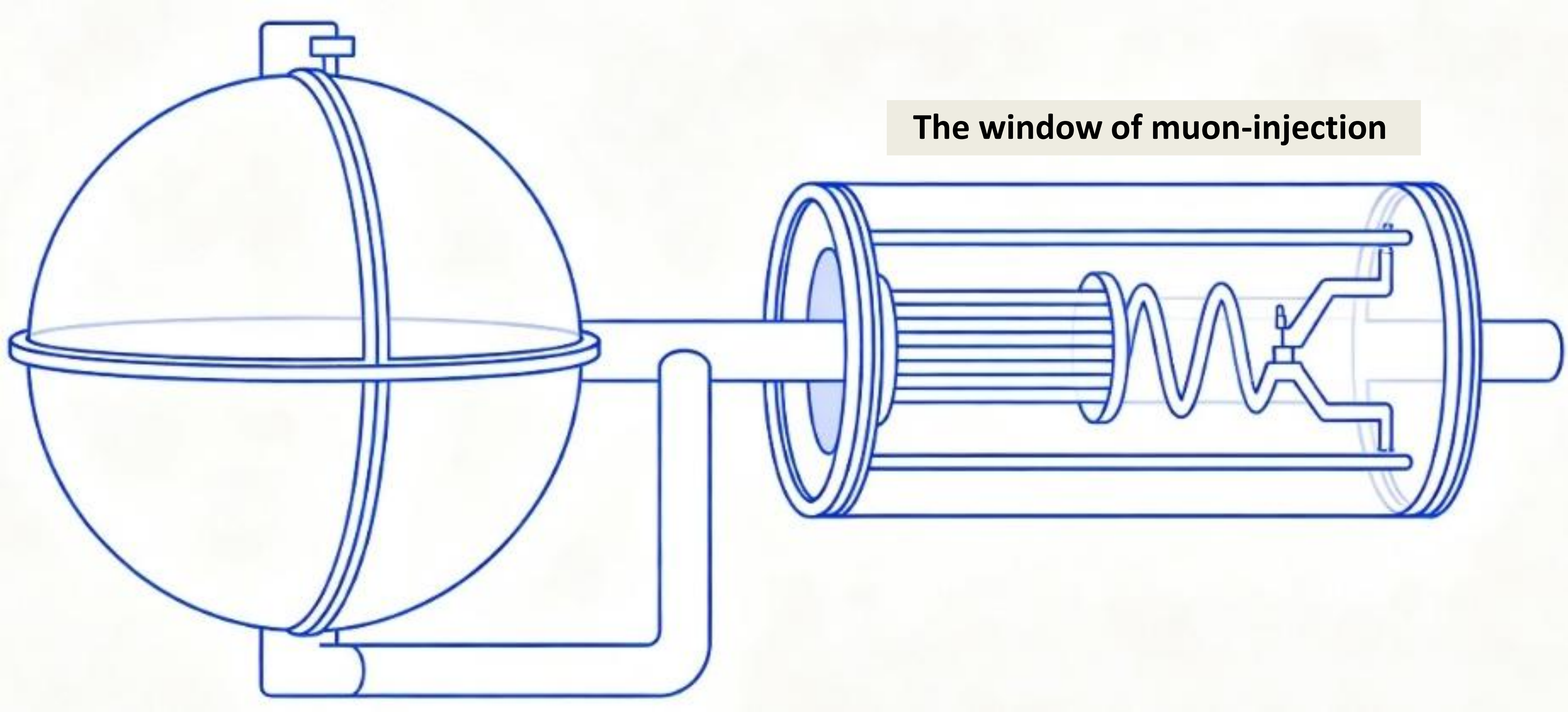
By Yin Xiong

April 2026

Principle of muon - catalyzed fusion cycle



Schematic diagram of muon-catalyzed fusion reaction vessel



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缪子催化核聚变战略定位

Strategic Positioning

阐述μCF作为一种具有独特范式优势的聚变替代路径，明确其颠覆性价值。

Elaborate on µCF as an alternative fusion path with unique paradigm advantages and clarify its disruptive value.

缪子催化核聚变（μCF）是一种逻辑自洽、物理本质深刻、工程路径截然不同的全新技术路线。

Muon-catalyzed nuclear fusion (μCF) is a brand-new technological approach that is logically self-consistent, has profound physical essence, and features a completely different engineering path.

1 磁约束（MCF）
Magnetic Confinement Fusion (MCF)

用磁场囚禁等离子体以延长约束时间，依赖高温、强磁场等极端条件。

Uses magnetic fields to confine plasma, relying on extreme conditions like high temperature and strong magnetic fields.

2 惯性约束（ICF）
Inertial Confinement Fusion (ICF)

用激光惯性压缩燃料靶丸以提升密度，同样面临极高工程难度与物理挑战。

Uses lasers to inertially compress fuel pellets, also facing extreme engineering and physical challenges.

3 缪子催化（μCF）
Muon-Catalyzed Fusion (μCF)

用负缪子（μ^-）替代电子形成超紧凑原子/分子，在飞米尺度极大压缩原子核间距，显著提升量子隧穿概率。

Employs negative muons (μ^-) to replace electrons and form ultra-compact atoms/molecules, compressing nuclear separation to the femtometer scale and dramatically enhancing quantum tunneling probability.

范式级核心优势

Paradigmatic Core Advantages

μCF通过微观操控绕过宏观工程极限，具备温度、工程、运行及安全等方面的颠覆性优势。

μCF bypasses the limits of macro engineering through micro - manipulation and has disruptive advantages in aspects such as temperature, engineering, operation, and safety.

01

常温反应

Room Temperature Reaction

燃料靶处于近室温（300–800 K），无需维持上亿度等离子体，从根本上规避了高温等离子体不稳定性与第一壁材料热负荷极限。

Fuel target operates near room temperature (300–800 K), eliminating the need for >10^8 K plasma confinement and thus avoiding plasma instabilities and first-wall thermal load limits.

02

工程简化

Simplified Engineering

系统核心仅需“缪子发生器+反应容器”，无需超导磁体或巨型激光阵列，复杂度大幅降低。

The core of the system only requires a "muon generator + reaction vessel" and does not need superconducting magnets or giant laser arrays, significantly reducing the complexity.

03

连续运行

Continuous Operation

已实现100小时连续聚变运行，远优于ICF的脉冲式工作模式，具备持续供能潜力。

A continuous fusion operation for 100 hours has been achieved, which is far superior to the pulsed operation mode of ICF and has the potential for continuous energy supply.

04

固有安全

Inherent Safety

无临界质量、无链式反应、停堆即终止，安全特性更接近化学反应，而非核裂变系统。

No critical mass, no chain reaction, and the reaction stops once the reactor shuts down. Its safety characteristics are closer to those of a chemical reaction rather than a nuclear fission system.

当前面临的研究瓶颈

Research Bottlenecks

系统诊断μCF实用化进程中必须逾越的三道核心鸿沟：物理机制不明、能量增益不足、设计耦合困境。

Three core gaps that must be overcome in the practical process of the system diagnosis μCF: unclear physical mechanism, insufficient energy gain, and the dilemma of design coupling.

物理机制未明
Mystery of Physical Mechanism

α粘附效应是最关键的科学难题。最近有文献报告首次直接观测到共振态缪子分子（ddμ＊）的形成速率约为1.2×10^{11}/秒
而传统基态分子（ddμ）只有10^{8}/秒。这个结果为理解μCF核心机制提供了关键实验依据。

The α sticking effect is the most crucial scientific problem. Recently, some literature reported that the formation rate of the resonant state muonic molecule (ddμ＊) was directly observed for the first time, which is about 1.2×1011/s, while that of the traditional ground-state molecule (ddμ) is only 108/s. This result provides a key experimental basis for understanding the core mechanism of μCF.

01 α粘附效应
α-Sticking Effect

α粒子与缪子形成**αμ**原子，使缪子永久退出催化循环，是影响催化效率的核心因素。

The core issue affecting catalytic efficiency. Fusion-produced α particles capture muons to α particles capture muons to form **alpha-muon atoms (αμ)**, permanently removing muons from the catalytic cycle.

02 密度依赖之谜
Density-Dependent Enigma

理论预估单个缪子催化约111次，但实验发现高密度燃料下可跃升至300次以上，物理机制至今未被完全阐明。

A fundamental mystery. Theoretical predictions suggest a single muon can catalyze ~111 cycles, but experiments show this can jump to over 300 cycles at high fuel densities. The physical mechanism remains unexplained.

03 现有理论方向
Existing Theoretical Directions

一种可能的机制认为源于高密度下粘附形成的$(\alpha\mu)^+$离子与周围分子的碰撞诱导剥离过程，但理论模型尚需实验确证。

One possible mechanism suggests that it originates from the collision-induced stripping process between the $(\alpha\mu)^+$ ions formed by sticking under high density and the surrounding molecules, but the theoretical model still needs experimental confirmation.

能量增益鸿沟Energy Gain Gap

产生缪子的能耗远高于其催化聚变释放的能量，实现净能量增益是巨大的工程挑战。

The energy consumption for producing muons is much higher than the energy released by their catalytic fusion. Achieving a net energy gain is a huge engineering challenge.

1 产额与能耗

Yield and Energy Consumption

目前最先进的质子驱动器根据靶体和收集效率，每个可用μ子需要约 **0.5 - 1 GeV** 的等效能量。（DeepTech深科技，2024年12月7日）

Current state-of-the-art proton drivers require **~0.5–1 GeV equivalent energy per usable muon**, depending on target & collection efficiency.（ DeepTech, December 7th, 2024 ）

2 实现Q≥1的途径

Path to Achieve Q ≥ 1

催化150次聚变反应释放约**2.64 GeV**能量 **→ Q**值 **≈ 0.5 - 2.0**（高度依赖系统）。

Catalyzing 150 fusions releases ~2.64 GeV → Q ≈ **0.5–2.0** (highly system-dependent).

3 当前技术差距

Current Technological Gap

激光驱动等现有路径的缪子产额与能效远不足以支撑商用堆需求，面临严峻的工程平衡问题。

Existing methods like laser-driven sources are far from meeting the requirements for commercial reactors, facing severe engineering trade-offs in muon yield and efficiency.

反应容器困境

Reactor Vessel Dilemma

反应容器设计需在多重相互掣肘的目标中寻求最优解，是复杂的系统工程难题。

A complex systems engineering problem

01

尺寸矛盾

Size Paradox

缪子慢化长度要求容器尺寸大于10 cm，而中子壁负载又要求尺寸尽可能小以降低热负荷。

The muon slowing-down length requires the vessel to be larger than 10 cm, while neutron wall loading requires the vessel to be as small as possible to reduce thermal load.

02

密度与散射

Density vs. Scattering

高燃料密度可提升反应速率并抑制α粘附，但会加剧缪子的多次散射损失，形成权衡。

High fuel density boosts the reaction rate and suppresses α-sticking, but it also increases multiple scattering losses of muons, creating a trade-off.

03

增殖层布局

Breeding Layer Layout

铀-238增殖层需置于严苛位置，否则会大量俘获缪子，使催化循环直接失效。

The uranium-238 breeding layer must be placed in a stringent location. Otherwise, it will capture a large number of muons, causing the catalytic cycle to fail directly.

前瞻性创新研究思路

Innovative Research Ideas

针对前述瓶颈，提出五项具备可行性、前瞻性的创新研究路线，构成完整闭环研发体系。

Propose five feasible and forward-looking research directions to form a complete closed-loop R&D system.

破解α粘附思路

Solving α-Sticking

提出双极化协同调控技术，从根源上主动破解α粘附难题，将“黑箱”问题转化为“白箱”问题。

The bipolar collaborative regulation technology is proposed to actively solve the α-sticking problem at the root and transform the "black box" problem into a "white box" problem.

1

微观物理干预

Microscopic Physical Intervention

直接干预α粘附发生的微观物理过程本身，而非仅优化外部环境。

Instead of optimizing the external environment, directly intervene in the microscopic physical process of α-sticking.

2

双极化调控模型

Bipolar Control Model

优先极化缪子束（已实验验证），并探索燃料靶低温/高压环境对核自旋取向的间接调控，协同优化α粘附抑制。

Muon beam polarization is experimentally established; synergistic control of fuel target conditions (low-T, high-P) may indirectly influence nuclear spin alignment.

3

理论计算效果

Theoretical Calculation Effect

完全极化可使α粘附概率ω_s降幅达40-60%，直接推动单缪子催化次数从148次提升至300-350次。

Complete polarization can reduce the α-sticking probability ωs by 40-60%, directly increasing the number of catalytic cycles per muon from 148 to 300-350.

4

实施技术路线

Implementation Roadmap

分短期（实验验证）、中期（靶材开发）、长期（多维协同）三步走，目标$X_\mu > 500$次，$Q \geq 2.06$。

A three-step plan: short-term (experimental verification), medium-term (target material development), long-term (multi-dimensional synergy), aiming for $X_\mu > 500$ cycles and $Q \geq 2.06$.

动态反应容器设计

Dynamic Reactor Design

超越静态设计范式，构建“缪子-燃料共演化”的动态智能反应容器，实现精准协同。

Transcend the static design paradigm, construct a dynamic intelligent reaction vessel of "muon - fuel co - evolution", and achieve precise synergy.

1

共演化系统理念

Co-evolution System Concept

将燃料状态与缪子过程视为一个实时反馈、动态耦合的统一系统。

Regard the fuel state and the muon process as a unified system with real-time feedback and dynamic coupling.

2

梯度燃料区设计

Gradient Fuel Zone Design

容器内部分区，燃料压力梯度递增，让缪子始终处于催化效率最优的密度区间。

Internal partitioning of the container, with an increasing gradient of fuel pressure, keeps muons within the density range with the optimal catalytic efficiency at all times.

3

智能液滴流技术

Intelligent Droplet Flow Technology

液滴表面集成传感器，实时反馈状态，并通过外部电场进行毫秒级轨迹修正。

The integrated sensors on the droplet surface provide real-time feedback on the status, and the trajectory is corrected at the millisecond level through an external electric field.

4

原位诊断闭环

In-situ Diagnosis and Control Loop

利用内壁FBG阵列监测状态，数据直接反馈至燃料注入系统，形成控制闭环。

Use the inner wall FBG array to monitor the status, and the data is directly fed back to the fuel injection system to form a control closed-loop.

5

平台建设规划

Platform Construction Plan

依托CSNS二期升级质子束，2027年前完成首套原型机测试。

Relying on the proton beam upgrade in the second

缪子源

Muon Source

依托CiADS/HIAF等大科学装置构建高强度缪子源，为缪子催化聚变研究提供实验条件，实现大科学装置的“二次赋能”。

Rely on large scientific facilities such as CiADS and HIAF to construct a high-intensity muon source, provide experimental conditions for μ CF research, and realize the "secondary empowerment" of large scientific facilities.

01

具有潜力路径

The Potential Path

探索依托国内大科学装置（如CiADS升级束流）建设高通量缪子源的可能性，同时持续评估国际前沿路径（如激光驱动、等离子体加速缪子）。

Investigate feasibility of high-flux muon sources using upgraded domestic facilities (e.g., CiADS proton beam), while monitoring global advances (laser-driven, plasma-based muon generation).

02

三大工程创新

Three Engineering Innovatio

采用旋转梯度复合靶分散热负荷、超导螺线管收集提升效率、脉冲压缩与极化调控。

Adopt a rotating gradient composite target to disperse heat load, use a superconducting solenoid to improve collection efficiency, and implement pulse compression and polarization control.

03

产额提升目标

Muon Yield Goal

CiADS二期规划产额达10^{10} μ^{-}/s，理论极限可达10^{16} μ^{-}/s。

Phase II of CiADS plans to achieve a yield of 10^{10} μ^{-}/s, with a theoretical limit of 10^{16} μ^{-}/s.

04

战略价值升维

Strategic Value Dimension Upgrade

将国家巨额投入的基础设施，转化为具备全球领导力的核心技术输出平台。

Transform the nation's huge investment in infrastructure into a globally leading core technology output platform.

铀层功能再定义
Redefining the Uranium Layer

01

传统功能局限
Traditional Functional Limitations

传统设计中，铀层主要作为屏蔽系统的"第一道防线"，功能单一。

In traditional designs, the uranium layer serves solely as the "first line of defense" for shielding, with a single function.

02

重构为核心引擎
Redefinition as a Core Engine

将其重新定义为多功能、多阶段的能量与物质转化中心，成为系统战略引擎。

Reconceptualize it as a multi-functional, multi-stage center for energy and material conversion, becoming the strategic engine of the system.

将铀-238增殖层从单纯的防护盾重构为系统的能量与物质转化中心，重塑核能格局。

Reconstruct the uranium-238 breeding layer from a simple shield into the energy and material conversion center of the system, and reshape the nuclear energy landscape.

03

三阶段价值
Three-Stage Value Realization

聚变期吸收中子释放裂变能；停堆期提取钚-239支撑裂变电站；终极形态实现闭式燃料循环，铀资源利用率从<1%提升至>90%。

During the fusion phase, it absorbs neutrons to release fission energy. During the shutdown phase, it extracts plutonium-239 to support fission power stations. In the ultimate form, it enables a closed fuel cycle, boosting uranium resource utilization from <1% to >90%.

04

验证与推广
Verification and Promotion

2026-2028年在大科学装置上验证性能，后续建成供热堆打通全链条工艺。

Validate performance on large-scale scientific facilities from 2026-2028, and then build a heat supply reactor to complete the entire process chain.

构建数字孪生体

Building a Digital Twin

构建覆盖全系统的“缪子催化数字孪生体”，驱动研究范式从经验驱动迈向AI驱动。

Constructing a "Muon Catalysis Digital Twin" to drive the research paradigm shift

01

传统模拟极限
Limitations of Traditional Simulation

面对多尺度、多物理场强耦合过程，传统模拟方法已接近极限。

Facing multi-scale, multi-physics strongly coupled processes, traditional simulation methods have reached their limits.

02

超级仿真平台
Super Simulation Platform

融合DFT、GEANT4、CFD与机器学习（ML）的超级仿真平台。

Develop a platform that integrates DFT, GEANT4, CFD, and Machine Learning (ML).

03

核心特征
Core Features

以全球实验数据为训练集校准参数，可接收实时数据流并更新状态，用强化学习算法寻找全局最优解。

Calibrate parameters using global experimental data as a training set. It can receive real-time data streams and update states, using reinforcement learning algorithms to find global optimal solutions.

04

发展路线图
Development Roadmap

2026年启动联盟，2027-2029年完成子系统孪生体开发，2030+年作为所有设计与实验的“中央大脑”。

Launch the alliance in 2026, complete subsystem twin development from 2027-2029, and become the "central brain" for all design and experiments by 2030+.

结语与展望

Conclusion and Outlook

总结μCF的核心价值，强调当前正站在工程化突破的关键门槛，呼吁共同创造未来。

Summarize the core values of μCF, emphasize that we are currently standing at the critical threshold of engineering breakthrough, and call on everyone to jointly create the future.

从微缩太阳到文明之火

From Mini Sun to Civilization

缪子催化核聚变不是技术备胎，而是一条具备独特范式优势的独立聚变能源技术路线。

Muon-catalyzed nuclear fusion is not a technical backup option, but an independent fusion energy technology route with unique paradigm advantages.

01

独立的第三条路

An Independent Third Path

其核心价值在于用微观物理的巧劲绕过了宏观工程的极端条件挑战，提供了战略选项。

Its core value lies in using the subtle force of microscopic physics to bypass the challenges of extreme conditions in macroscopic engineering, thus providing strategic options.

02

核心价值所在

The Core Value

它的核心任务是解决工程技术问题，而非攻克基础物理难题，这正是其根本信心来源。

Its core task is to solve engineering and technical problems, rather than tackle fundamental physical challenges. This is precisely the source of its fundamental confidence.

03

从原理验证到工程突破

From Proof-of-Principle to Engineering Breakthrough

我们已经走完“原理可行性验证”阶段，现在正站在“工程化突破”的关键门槛上。

We have completed the "principle feasibility verification" stage and are now at the critical threshold of "engineering breakthrough."

迈向创造者的时代

Towards the Age of Creators

本书提出的五大创新思路构成了一个完整的闭环研发体系，每一步都有清晰的理论支撑与可验证的里程碑节点。

The five major innovative ideas proposed in this book constitute a complete closed-loop R & D system, with each step supported by clear theories and verifiable milestone nodes.

01

闭环研发体系

A Closed-Loop R&D System

从被动接受物理限制，转向主动设计物理过程；从孤立优化单一环节，转向系统级多目标协同；从依赖国家单项投入，转向激活国家大科学装置的网络化赋能。

Shift from passively accepting physical limitations to actively designing physical processes; from optimizing single isolated links to multi-objective collaboration at the system level; from relying on single national inputs to activating the networked empowerment of national large-scale scientific facilities.

02

历史性的门槛

A Historic Threshold

我们正站在一个历史性的门槛上，缪子点燃的“微缩太阳”有望在有生之年成为现实。

We are standing on a historic threshold. The "mini sun" ignited by muons could become a reality in our lifetime.

03

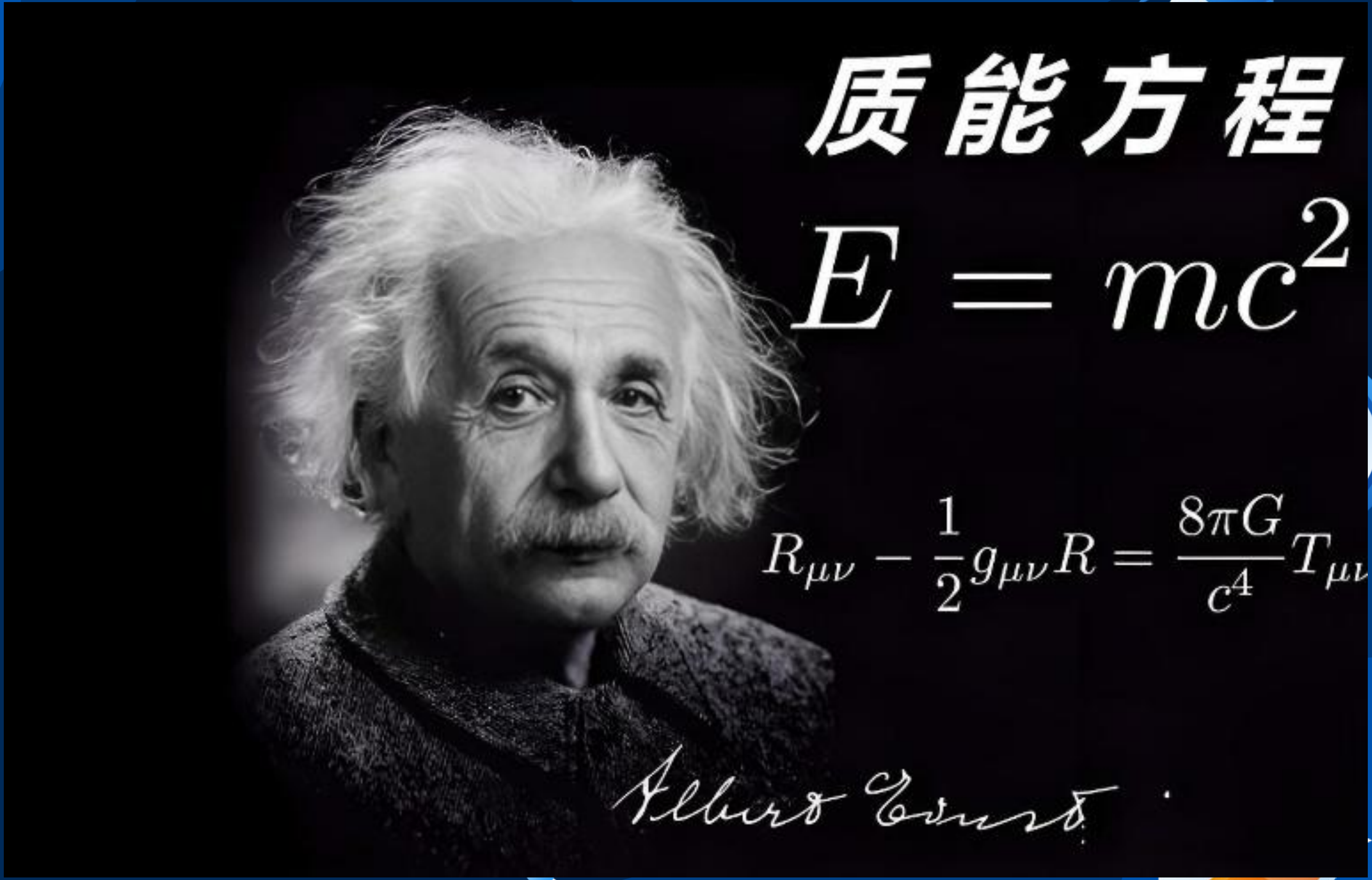
成为创造者

Becoming Creators

那时，我们将不再仅仅是仰望者。我们，将是创造者。

At that time, we will no longer just be observers. We will be the creators.

Thank you!


质能方程
$E = mc^2$
$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}T_{\mu\nu}$
Albert Einstein