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HIRFL2022

兰州重离子研究装置年度报告

ANNUAL REPORT

HIRFL 2022

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ANNUAL REPORT

一、综述及基本情况

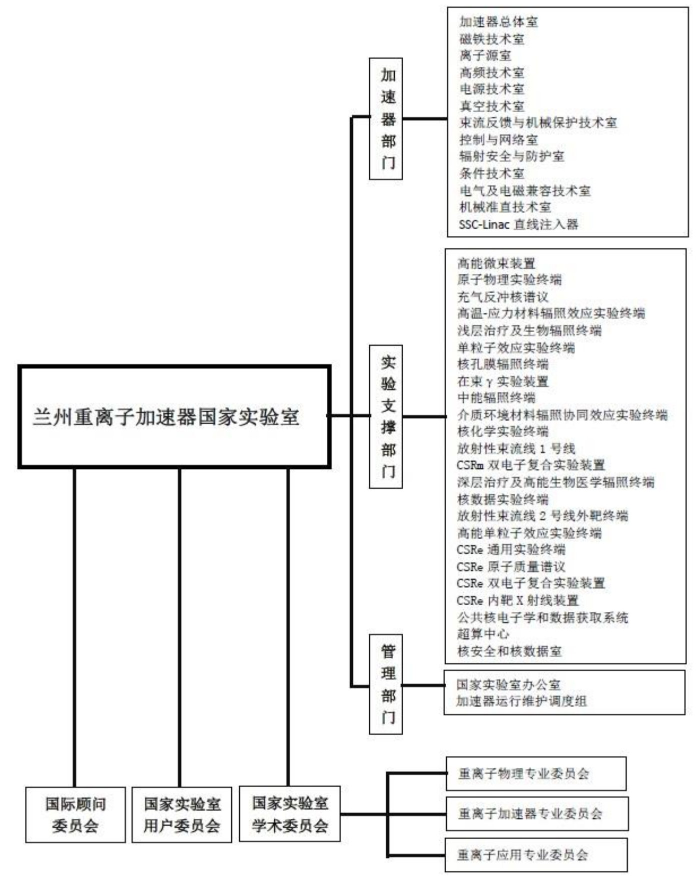
兰州重离子研究装置（HIRFL），是历经三代大科学工程建设而成，我国规模最大、可以把氢到铀的全离子加速到高能的重离子研究装置。装置包括 ECR 离子源、扇聚焦回旋加速器 SFC、SSC 直线注入器、大型分离扇回旋加速器 SSC、冷却储存环 CSR、放射性束流线及若干实验终端，可提供多种类、宽能量范围、高品质的稳定核束和放射性束，主要技术指标达到国际先进水平。依托这一装置，原国家计委于 1991 年 8 月 13 日批准成立兰州重离子加速器国家实验室。

HIRFL 作为我国核物理及相关交叉领域的大型科研平台，在短寿命原子核质量精确测量、超重核（元素）性质、核物质性质、高离化态离子碰撞动力学和谱学研究等领域，取得一批在国际上有重大影响的研究成果；在重离子肿瘤治疗、离子辐照诱变育种等方面，创造了显著的社会经济效益。

设施负责人

国家实验室主任	沈文庆	副主任	肖国青、赵红卫、夏佳文、徐瑚珊
国家实验室学术委员会主任	张肇西	副主任	陈森玉、叶沿林、周小红

组织框架



二、研究进展与成果

2022 年，兰州重离子加速器国家实验室的用户依托 HIRFL 取得一批重要的研究进展与成果。

合成新核素钍-207 和锕-204

依托 HIRFL-SHANS，近代物理所研究人员、中山大学、兰州大学、广西师范大学、中科院理论物理所、同济大学、俄罗斯联合核子研究所的研究者共同通过熔合蒸发反应 $^{36}Ar+^{176}Hf$ 和 $^{40}Ca+^{169}Tm$，成功合成出极端缺中子锕系新核素钍-207 和锕-204，并首次测得钍-207 和锕-204 的 α 衰变能量和半衰期。研究结果已发表在《物理评论 C》（*Physical Review C 105,L051302*）和《物理快报 B》（*Physics Letter B834,*137484）上。

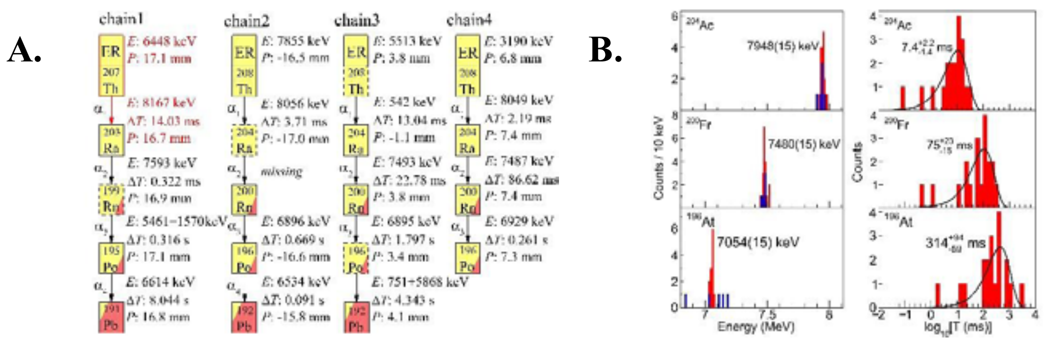


图 1 A.利用 $^{36}Ar+^{176}Hf$ 反应观测到的新核素 ^{207}Th 和已知核 ^{208}Th 的 α 衰变链;B.实验测量的新核素 ^{204}Ac 及其子核的 α 衰变粒子能量和衰变时间的分布。

利用次级束装置研究电子俘获致核激发现象

依托兰州重离子加速器装置（HIRFL），中国科学院近代物理研究所的科研人员及合作者创造性地利用放射性束流线 RIBLL1 产生同核异能态束流，研究了电子俘获致激发同核异能态现象。该实验工作大幅提升了测量精度和可靠性，首次提供了与理论预期相符的测量结果。相关结果于 6 月 17 日发表在《物理评论快报》（*Physical Review Letters* 128,242502）上。

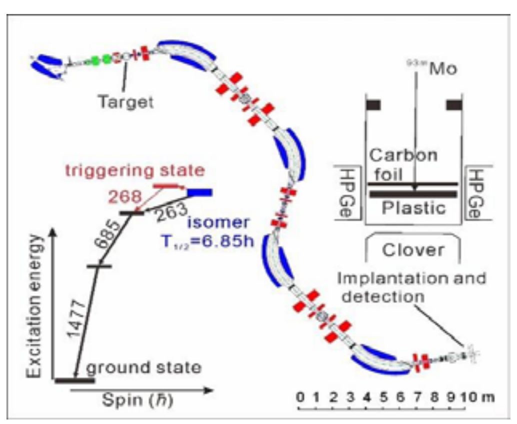


图 2 ^{93m}Mo 粒子在 RIBLL 束流线初级靶位置（左上角）通过熔合蒸发反应产生，经束线进入注入端（右下角）。左下角展示 ^{93m}Mo 在注入端发生同核异能态诱发退激与自发退激的过程，右上角展示探测端设置。

发现最强同位旋混杂现象

依托兰州重离子研究装置（HIRFL），近代物理所及中山大学、上海交通大学等国内外 23 家科研单位的科研人员开展了质子滴线核 ^{26}P 衰变性质的高精度测量, 发现了 β 衰变中最强同位旋混杂现象，直接挑战人们对于原子核相互作用力的理解。研究成果于 12 月 8 日以亮点文章编辑推荐(Editors’ Suggestion)的形式发表在《物理评论快报》（*Physical Review Letters* 129,242502）上。

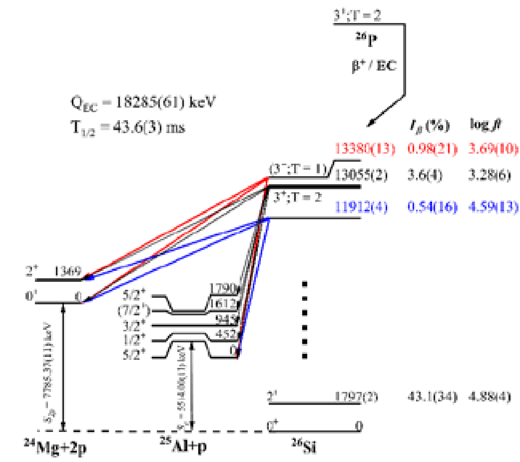


图 3 奇特原子核 ^{26}P 的部分衰变纲图

单离子辐照技术成功用于制备可调离子选择性纳米通道

依托 HIRFL，北京大学和近代物理所研究人员利用高能微束单离子辐照技术制备并研究了具有可调离子选择性的高品质多功能石墨烯异质纳米通道。这项工作为构建类似的具有可调离子选择性的多功能异质纳米通道提供了新思路，开辟了制备二维纳米孔与固态整流纳米通道复合的异质结构以获得可调离子选择性这一新兴的研究领域，有望快速满足实际应用中复杂多变情形的不同需求。成果发表于《自然·通讯》（*Nature Communications* 13(1):4894）。

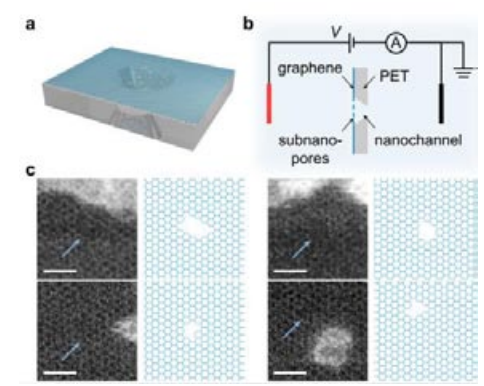


图 4 石墨烯异质纳米通道结构示意与石墨烯亚纳米孔扫描透射电子显微镜图像。

聚变堆先进包层候选钒合金的抗辐照损伤机理

近代物理研究所与北京有色金属研究总院材料所科研人员合作，依托 HIRFL 重离子辐照终端，开展了聚变堆包层候选结构材料钒合金的抗辐照损伤机理研究。

实验采用不同程度冷变形工艺和随后退火处理工艺，对材料中的位错形态和密度进行调控；利用 HIRFL 提供的 6.3 MeV/u 的 ^{56}Fe 离子在材料样品中产生辐照损伤，来模拟聚变堆高能中子辐照条件。

结果表明，高变形量的冷变形预处理可以显著提升材料的强度，同时未造成明显的延性损失。同时，在抗辐照性能方面，对比前人结果，高变形量的冷变形预处理导致钒合金显示更优的抗辐照硬化能力。研究结果发表在核聚变领域顶刊《Nuclear Fusion》上（*Nuclear Fusion* 62,126010）。

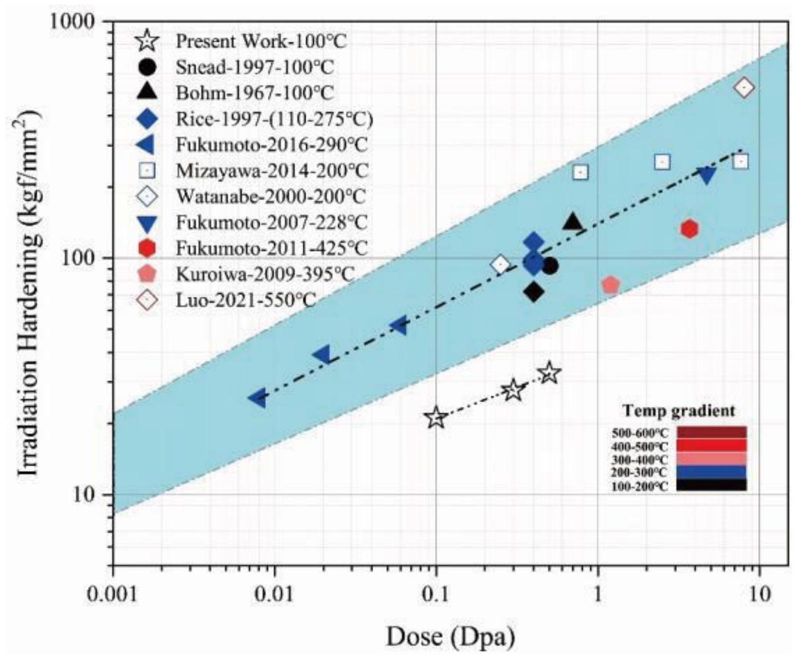


图 5 聚变堆先进包层候选钒合金的抗辐照性能对比，本工作高变形量的冷轧预处理导致钒合金的辐照硬化显著低于前人结果。

聚酰亚胺核孔膜基锂离子电池隔膜的研究

依托兰州重离子研究装置（HIRFL），近代物理所材研究人员利用 12.5 MeV/u ^{181}Ta 辐照有机聚合物聚酰亚胺（PI）薄膜，制备了具有优异力学性能和高热稳定性的 PI 核孔膜。针对锂离子电池中由热失控诱发的起火、爆炸等安全性问题，采用卷对卷工艺将 PI 核孔膜进行有机无机杂化处理（图 6 a），并将具有高热导率的六方氮化硼（hBN）颗粒涂覆在 PI 核孔膜上，制备出了具有高安全性的 PI/hBN 锂离子电池隔膜。

该工作对基于核孔膜的锂离子电池隔膜的研究、开发具有指导意义，也为重离子加速器在国民经济中的应用拓宽了方向，相关工作发表在国际能源类杂志 *ACS Applied Energy Materials* 2022, 5, 8639。

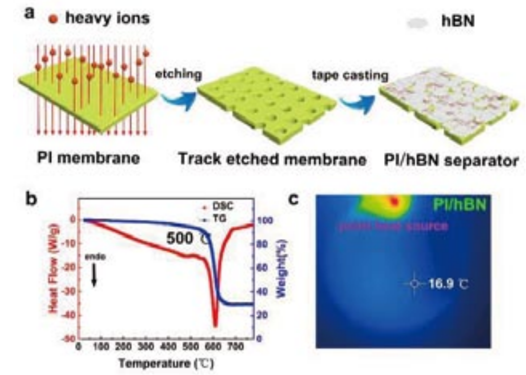


图 6 （a）PI/hBN 电池隔膜的制备过程示意图；（b）PI/hBN 电池隔膜的热分析；（c）PI/hBN 电池隔膜在点热源作用下的热成像图。

一维/二维复合结构反电渗析发电研究

科研人员首先利用 HIRFL 上提供的重离子束流辐照 PET 聚合物薄膜，再结合非对称化学蚀刻技术在 PET 薄膜中制备出锥形纳米孔道。随后将 PET 锥形纳米通道与二维层状氧化石墨烯（GO）膜相结合制备出一维/二维复合结构，并系统研究了复合结构的反电渗析发电特性（图 7）。

研究表明，一维/二维复合结构不仅在增加结构不对称性的基础上实现了阳离子选择性增强传输和离子整流效应的提升，且所获得的一维/二维复合结构发电功率最高可达 118.2 pW，发电效率达 40.3%。研究成果发表在 *ACS Applied Materials & Interfaces* 2022, 14, 29197。

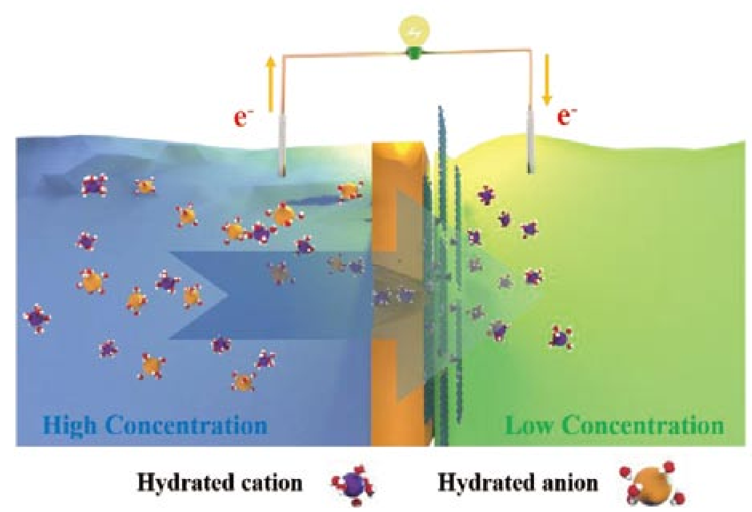


图 7 GOM/PET 结构用于反电渗析的示意图。

石墨烯器件快重离子辐照损伤及退火效应研究

近代物理所研究人员依托 HIRFL 开展了对石墨烯场效应晶体管的快重离子辐照效应及热退火效应研究。

研究结果表明在高辐照注量条件下，器件性能发生明显退化。不同温度 N_2 气氛下热退火后器件性能会有一定程度提升，然而热退火对辐照石墨烯器件主要是除气作用，随着辐照强度的增加，热退火的影响逐渐减小（如图 8）。高温 1100℃的退火下，快重离子辐照在石墨烯和 SiO_2/Si 层造成的永久性辐射损伤仍不能恢复。成果发表在一区期刊 *Applied Surface Science* 588 (2022) 153005。

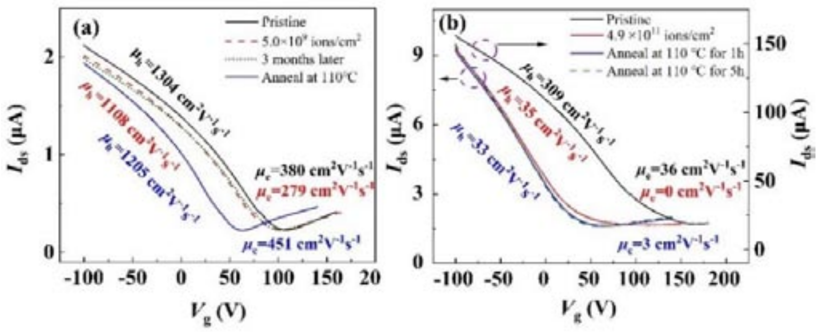


图 8 在不同辐照注量与退火条件下器件的转移特性对比。

研究揭示 MAX 相材料中 He 行为与离子辐照损伤的相互作用

近代物理所科研人员依托 HIRFL 开展了在 MAX 相材料中氦离子与铁（Fe）离子顺序和逆序辐照实验。

在逆序（Fe+He）辐照实验中，两者在材料中产生的辐照效应相对比较独立，两者相互影响弱。而在顺序（He+Fe）辐照实验中，预注入的氦离子对后续铁离子辐照引起的相变有明显的抑制作用。氦离子注入和铁离子辐照实际上互相抑制了对方对材料的辐照损伤，这种效应在材料抗辐照损伤方面将发挥积极作用。同时，该研究也为深入认识 Ti_3AlC_2 材料抗辐照损伤机理提供了新的见解。相关成果发表在 *Journal of the European Ceramic Society* 42 (2022) 7421。

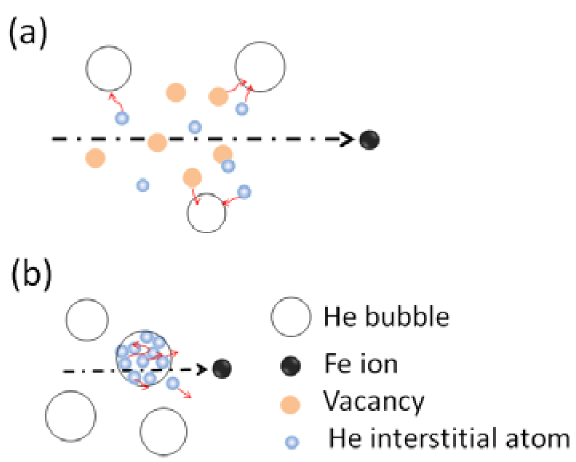


图 9 铁离子辐照驱动氦气泡演化机制示意图，（a） 氦气泡的生长过程；（b） 氦气泡的再溶解过程。

重离子束辐照诱变水稻新品种选育及示范推广

依托兰州重离子研究装置（HIRFL），2022 年 8 月，由近代物理所与东北地理与农业生态研究所联合组成的水稻高能重离子束辐射诱变育种团队合作培育的 3 个水稻新品种"东稻 211"、"东稻 812"和"东稻 862"通过品种审定，分别比对照增产 6.9%、5.3%和 7.4%。同时利用这一方法得到的首个新品种"东稻 122"（2020 年审定）2022 年在吉林省和黑龙江省推广种植已达到 52 万亩，创造了可观的社会和经济效益。

"东稻 122"、"东稻 275"（2021 年审定）、"东稻 211"等 5 个品种的成功审定，预示着重离子辐照诱变育种技术和方法获得了巨大成功，这也将为国家种质安全和院"黑土粮仓科技会战"的胜利做出重要贡献。

图 10 3 个水稻新品种的审定证书

重离子治癌及医用重离子加速器装置产业化

2022 年，医用重离子加速器装置累计推广 7 台，合同额共计约 42 亿元，入选国家"奋进新时代"主题成就展。

武威装置 2 号治疗室已完成 630 余例病人的治疗，疗效显著，包括国内率先开展的重离子乳腺癌治疗和世界首例重离子膀胱癌治疗，装置 1 号治疗室正在进行临床试验，预计明年正式投入临床使用。兰州装置即将完成临床试验治疗。莆田装置完成安装调试，开始检测。杭州、武汉装置开始安装。长春、南京装置进入设计阶段。

2022 年科技论文发表、获奖、专利的统计数据

SCI 收录论文数	论文引用数	国外发表论文数	用户相关论文数	获省部级以上奖数	发明专利授权	实用新型专利授权	软件著作权
226	193	199	226	3	84	25	32

三、设施建设、运行与改造

2022 年 HIRFL 计划运行 7000（常规供束）+2000（并行供束）小时，实际运行 7944（常规供束）+514（并行供束）小时；计划实验供束时间 4688（常规供束）+1000（并行供束）小时，实际实验供束 5643（常规供束）+452（并行供束）小时；计划机器研究时间 410（常规供束）+200（并行供束）小时，实际机器研究时间 910.5（常规供束）小时；故障时间占总运行时间的 2.2%（常规供束）+1.8%（并行供束）；换束 19 次，其中 Linac 换束 2 次，共完成 203 项常规用户实验及 2 项并行用户实验。

专用研究设施/ 公共实验设施

设施名称	设施运行总机时	换束机时	提供束流机时	机器研究机时	用户实验机时	停机检修机时	故障机时	实验束线数	实验站（终端）数	用户完成实验课题数	用户实验涉及领域及比例
兰州重离子研究装置	7944	1209	6553.5	910.5	5643	816	176.5		22	203	核物理与原子物理 47.9%、材料科学 29%、生命科学 5.8%、空间科学 17.3%

用户课题数

设施	用户课题总数	院内	院外		其中		
			国内	国外	大学	研究所	企业
HIRFL	203	112	91	0	29	157	17

四、科技队伍与人才培养

设施人员总数	按岗位分			按职称分			学生			在站博士后	引进人才*
	运行维护人员	实验研究人员	其他	高级职称人数	中级职称人数	其他	毕业博士	毕业硕士	在读研究生		
558	314	221	23	275	120	163	56	37	93	23	3

*指通过“百人计划”、“千人计划”等引进的人才。

五、合作与交流

2022 年，面对新冠疫情持续蔓延，在国内“外防输入、内防反弹”政策下，我所科研人员采取视频会谈、远程办公以及线上国际会议等形式积极开展中外学术交流，保证我所科研工作的顺利开展。

2022 年我所与美国、俄罗斯、塞尔维亚等 3 个国家的 7 所大学或科研机构签订或续签了合作协议，共获得中国科学院国际人才计划资助 8 项，科技部外国专家项目 7 项，甘肃省高端外国专家项目 2 项，中国科学院特别交流计划 2 项，10 人获得国家公派留学资助。截止 2022 年 12 月份，我所共招收 29 名外籍人员，其中 11 名外籍员工、10 名外籍博士后、1 名 Fellowship 与 7 名外籍留学生。由于我所王惠仁研究员在科研方面的突出贡献，他获得“2022 年度甘肃省外国专家敦煌奖”。

2 月 28 日，中科院近代物理所科普品牌“猫小野科普星球”开展了今年第一期“星球校园”活动。近代物理所科研人员在兰州市华侨实验小学开展了主题为“细胞与我们的加速器”的科普报告，并安排了用显微镜观察人体细胞、肿瘤细胞以及植物表皮细胞的互动实验。

5 月 21 日下午，近代物理所线上举办以“爱科学，向未来——追‘核’者的科学魔方世界”为主题的第十八届公众科学日活动。今年线上直播时长首次突破 5 小时，B 站直播观看量达到 1.5 万人次，弹幕量 1.3 万余条，公众参与度创新高。

六、大事记

1 月 30 日 侯建国慰问全院科研人员、干部职工、离退休老同志和青年学生致以新春祝福，并通过视频连线听取中科院近代物理研究所国家重大科技基础设施建设运行及航天元器件单粒子效应科学实验任务的情况介绍。

5 月 28 日 兰州重离子加速器国家实验室 2022-2023 年度束流评审会召开，会议以“线上+线下”的方式进行。

图 11 评审会现场

5 月 30 日 兰州市科学技术协会召开了“创新争先、自立自强---2022 年‘全国科技工作者日’弘扬科学精神和科学家精神座谈会”。近代物理所赵环昱研究员获评 2022 年度兰州市“优秀科技工作者”。

6 月 16 日 谢漪副研究员等完成的“多酚类化合物对放射性损伤的保护作用及功能基因筛选”项目获得甘肃省科技进步奖三等奖。

8 月 28 日 中共中央政治局常委、全国人大常委会委员长栗战书考察了兰州新区重离子应用技术及装备制造产业基地。

图 12 中共中央政治局常委、全国人大常委会委员长栗战书在兰州新区重离子应用技术及装备制造产业基地现场考察。

9 月 27 日 中科院重大科技基础设施维修改造项目“超导 ECR 离子源改造”等三项项目完成验收。

图 13 维修改造项目验收会现场

10 月 25 日 兰州重离子加速器研究装置及 320kV 低能重离子综合研究平台等 38 台套大型科研平台及仪器在 2022 年中央级高校和科研院所等单位重大科研基础设施和大型科研仪器开放共享评价考核中再次被评为优秀。

11 月 18 日 杨建成研究员荣获 2021-2022 年度中国物理学会的胡刚复物理奖（实验技术）。

12 月 7 日 中国科学院与日本理化学研究所（RIKEN）共同举办了合作四十周年纪念仪式。纪念会上颁发了相关奖项，近代物理所周小红研究员荣获中国科学院与日本理化学研究所合作贡献奖。

图 14 中国科学院与日本理化学研究所合作贡献奖

Ⅰ. Overview

The Heavy Ion Research Facility in Lanzhou (HIRFL), operated by the Institute of Modern Physics, Chinese Academy Sciences (IMP), is the largest heavy ion research facility in China. In August 1991, the former State Planning Committee of China approved to set up the National Laboratory of Heavy Ion Accelerator of Lanzhou based on this facility and opened to the domestic and international users.

As a multi-purpose research facility, the main device of HIRFL is its accelerator complex, which consist of the Electron Cyclotron Resonances (ECR) ion sources, the Sector Focused Cyclotron (SFC), the Sector-Separated Cyclotron (SSC), the Cooler Storage Ring (CSR), the radioactive ion beam separators (RIBLL1/2). With this complex, HIRFL can deliver all kinds of ion beams, from hydrogen to uranium, either stable or unstable, with energies from few MeV/u up to several hundreds MeV/u.

HIRFL can support experimental research works on nuclear physics, nuclear astrophysics, atomic physics and many interdiscipline or applications with heavy ion beams, and as a very important tool for the whole Chinese nuclear physics society, a lot of important achievements were obtained in the past. Such as the synthesis of more than 30 new nuclides for the first time in the world, includes 2 super-heavy isotopes, the precise mass values of 35 short-lived isotopes measured firstly with the isochronous mass spectrometry method, the independently developed heavy ion cancer therapy equipment, the new species and strains of some crops fostered by heavy ion irradiation induced mutation, and so on.

Ⅱ. Research progress and results

In year 2022, there are also many important results from the research works on HIRFL, and here shows some as an example.

Discovery of two new isotopes ^{207}Th and ^{204}Ac

Two new neutron-deficient isotopes thorium-207 and actinium-204 were discovered for the first time in the experiments performed by a joint group from the Institute of Modern Physics, CAS, Sun Yat-Sen University, Lanzhou University, Guangxi Normal university, the Institute of Theoretical Physics, CAS, Tongji University and JINR.

These new isotopes were separated in flight by the gas-filled recoil separator SHANS (Spectrometer for Heavy Atoms and Nuclear Structure), and identified on the basis of the correlated α-decay chains. The α decay of thorium-207, measured with an α-particle energy of 8167(21) keV and a half-life of 9.7(+46.6/-4.4) ms, was assigned to originate from ground state. The α-particle energy and half-life of actinium-204 were determined to be 7948(15) keV and 7.4(+2.2/-1.4) ms, respectively. All the new data are consistent with the theoretical prediction.

These works discovered a regular and distinct odd-even staggering (OES) in the systematics of α-decay energies and decay half-lives for nuclei with Z>82 and N<126. It reveals a novel mechanism of odd-even staggering induced by pairing scattering and presents a challenge to nuclear-mass models.

These studies have been published in *Physical Review C* 105,L051302 and *Physics Letters B* 834,137484..

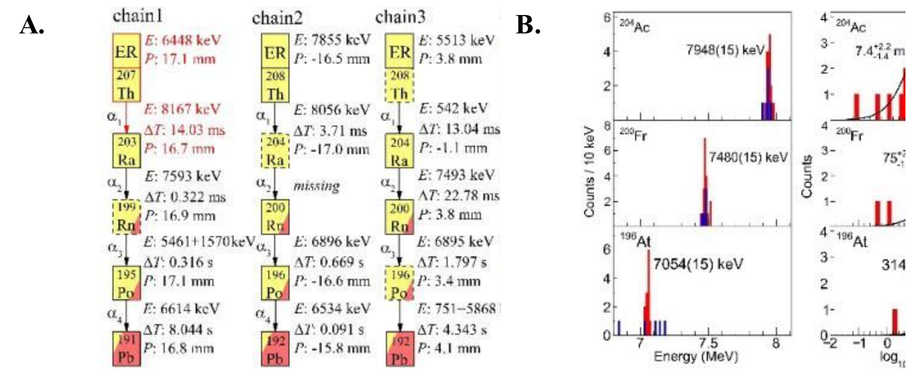


FIG. 1. A. The observed α-decay chains assigned to ^{207}Th and ^{208}Th. The annotations are the measured energy (E), decay time (ΔT), and vertical position (P) for each event within the chains. Escaped α decays are marked by rectangles with dashed frames. B. Stacked histograms of α-particle energy (left panel) and decay time distributions (right panel) for ^{204}Ac and descendant nuclei. The average α-particle energies were deduced without considering the escaped α particles shown in blue color.

Physicists Reinvestigate Nuclear Excitation by Electron Capture via Isomer Beam

A "dark" environment has been created at the Radioactive Ion Beam Line in Lanzhou (RIBLL) of HIRFL to look for a faint flash of light from the isomer depletion, which is a prerequisite for developing nuclear energy stored in long-lived isomeric states in the process of Nuclear Excitation by Electron Capture (NEEC).

Several million of electron volts can be stored in one atomic nucleus. Therefore, long-lived isomers with high excitation energies are considered to be ideal energy storage materials, with high energy density, long storage period and excellent stability.

Nevertheless, there exists a critical challenge to artificially control the energy release process. As a consensus, the rapid release of the isomeric energy is expected to be achieved by isomer depletion, that is, by exciting the isomer to an adjacent excited state which then decays to the ground state promptly. Scientists have proposed several methods, among which NEEC attracts particular attention.

However, in this independent experiment, the evidence of isomer depletion is not observed, and with the NEEC probability measured to be less than 2×10^{-5}, shedding doubt on the first reported experimental observation of NEEC.

The results have been published in *Physical Review Letters* 128, 242502.

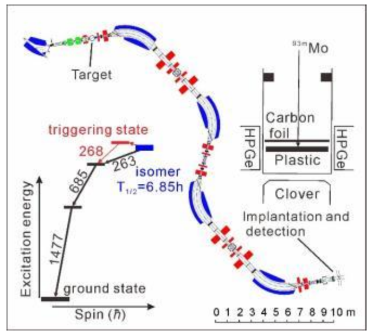


FIG. 2. Experimental setup in the present Letter. The secondary beam line RIBLL is shown with the corresponding distance scale. ^{93m}Mo residues were produced at the primary target position and transported to the end of RIBLL to study the isomer depletion. In the lower left area, the isomer depletion of ^{93}Mo is sketched together with the spontaneous decay of the long-lived isomer. The setup for implantation and detection is shown in the upper right area.

The Strongest Isospin Mixing in β-Decay

β-decay of proton-rich nuclei plays an important role in exploring isospin mixing. Recently, researchers at the Institute of Modern Physics,Chinese Academy of Sciences, and their collaborators conducted the β decay experiment of the exotic nucleus ^{26}P with T = 2 at HIRFL-RIBLL1. The isobaric analog state (IAS) at 13055 keV and two new high-lying states at 13380 and 11912 keV in ^{26}Si are unambiguously identified through β-delayed two-proton emission (β2p). Angular correlations of two protons emitted from ^{26}Si excited states populated by ^{26}P β decay are measured, suggesting that the two protons are emitted mainly sequentially. A strongly isospin-mixed doublet, the IAS and 13380-keV state in ^{26}Si, was observed based on their abnormally log *ft* values. The large isospin mixing matrix element 130(21) keV between them is determined, representing the strongest mixing ever observed in β decay experiments. The abnormally strong isospin mixing in the work, which may have to do with the weakly bound (or continuum) effect or nuclear deformation, presents a direct challenge to our understanding of nuclear force. As Editors' Suggestion, this result has been published in *Physical Review Letters* 129, 242502.

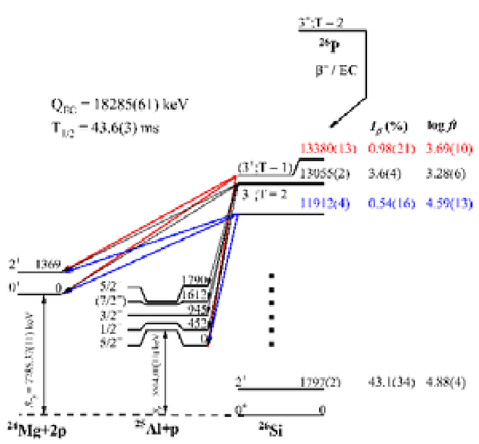


FIG. 3. Partial decay scheme of ^{26}P deduced from the present Letter. The black, blue, and red arrows represent transitions from the initial states of IAS, 11 912 keV, and 13 380 keV, respectively.

Multifunctional graphene heterogeneous nanochannel with voltage-tunable ion selectivity

Ion-selective nanoporous two-dimensional (2D) materials have shown extraordinary potential in energy conversion, ion separation, and nanofluidic devices; however, different applications require diverse nanochannel devices with different ion selectivity, which is limited by sample preparation and experimental techniques. Herein, we develop a heterogeneous graphene based polyethylene terephthalate nanochannel (GPETNC) with controllable ion sieving to overcome those difficulties. Simply by adjusting the applied voltage, ion selectivity among K+ , Na+ , Li+ , Ca2+, and Mg2+ of the GPETNC can be immediately tuned. At negative voltages, the GPETNC serves as a mono/divalent ion selective device by impeding most divalent cations to transport through; at positive voltages, it mimics a biological K+ nanochannel, which conducts K+ much more rapidly than the other ions with K+ /ions selectivity up to about 4.6. Besides, the GPETNC also exhibits the promise as a cation responsive nanofluidic diode with the ability to rectify ion currents. Theoretical calculations indicate that the voltage-dependent ion enrichment/depletion inside the GPETNC affects the effective surface charge density of the utilized graphene sub-nanopores and thus leads to the electrically controllable ion sieving. This work provides ways to develop heterogeneous nanochannels with tunable ion selectivity toward broad applications. This result has been published in *Nature Communications* 13(1):4894.

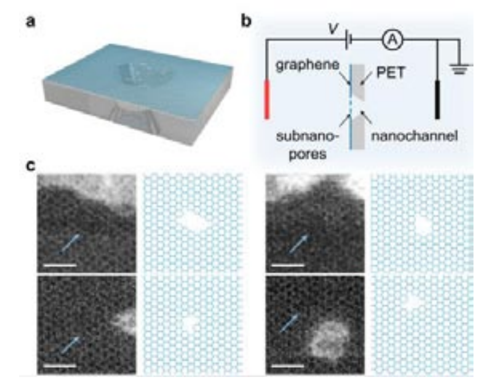


FIG. 4. Structure of graphene-based polyethylene terephthalate nanochannel (GPETNC) and experimental setup.

Mechanisms underlying the irradiation resistance of the vanadium alloys candidate to the advanced blankets of fusion reactors

A novel collaborative research on the irradiation resistance of vanadium alloys candidate for the advanced blankets of fusion reactors was carried out on HIRFL by the Energy Materials Group (GEM) of IMP and the Institute of Materials of GINFM.

The beam of ^{56}Fe ions with 6.3 MeV/u was used to simulate the intensive irradiation of fusion neutrons. A quasi-uniform distribution of irradiation damage was introduced in the alloy samples, facilitating the accurate evaluation of irradiation response of materials.

The results show that, with increasing deformation amount by the pre-irradiation cold-work treatment, the irradiation hardening decreased. The high-density of dislocations introduced by the cold-work deformation is responsible for the improved hardening resistance, benefiting from the enhanced absorption ability of point defects. The sink strength was utilized to quantify the effects of dislocations. It is found that the irradiation hardening obviously decreased with increasing sink strength. Meanwhile, micro-cavities with a high number density were also observed in the irradiated alloy samples, and are proven to be efficient defects sinks. Compared with previous work, the present vanadium alloys with a heavy cold-deformation treatment exhibit a superior irradiation resistance.

It is therefore indicated that the pre-irradiation modification of microstructures can effectively improve the irradiation hardening resistance of the vanadium alloys, promoting their application in future fusion reactors as advanced blanket components.

This result has been published in *Nuclear Fusion* 62, 126010.

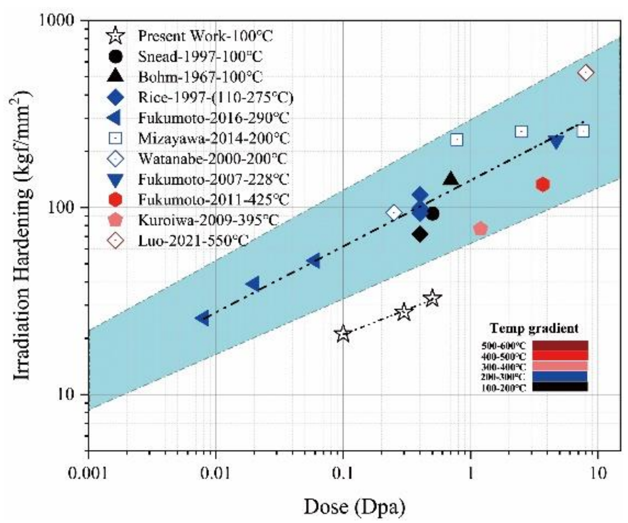


FIG. 5. Log–log plots of dose dependence of irradiation hardening of the vanadium alloy with 40% cold work followed by thermal annealing (represented with star symbols), in comparison with V–(4–5)Cr–(4–5)Ti specimens irradiated at varying temperatures with neutrons (represented with solid symbols) or ions (represented with open symbols). The dotted lines are the corresponding linear fitting results.

Hexagonal Boron Nitride-Coated Polyimide Ion Track Etched Separator with Enhanced Thermal Conductivity and High-Temperature Stability for Lithium-Ion Batteries

The separator plays a vital role in preventing thermal runaway in lithium-ion batteries (LIBs). Herein, a PI/hBN (polyimide/hexagonal boron nitride) separator with excellent thermal stability and enhanced thermal conductivity is successfully prepared by ion track etching and doctor blade coating to achieve highly safe LIBs. The PI/hBN separator displays good electrolyte wettability, high mechanical strength, excellent thermal stability, and enhanced in-plane thermal conductivity, as well as good ectrochemical performance when applied in LIBs.

Specifically, PI track-etched membranes have been used to prepare separators with rigid structures and functional groups in polymer chains, thereby enabling the separators to be stable at temperatures as high as 500 °C. Moreover, hBN-coated nanoplates enhance the in-plane thermal conductivity of the separator to reduce the local heat accumulation in the battery while also promoting interfacial compatibility to facilitate the conduction of lithium ions. Lithium iron phosphate/lithium cells with the PI/hBN separator deliver better rate capability and superior capacity retention.

This work has been published on *ACS Applied Energy Materials* 2022, (7), 8639.

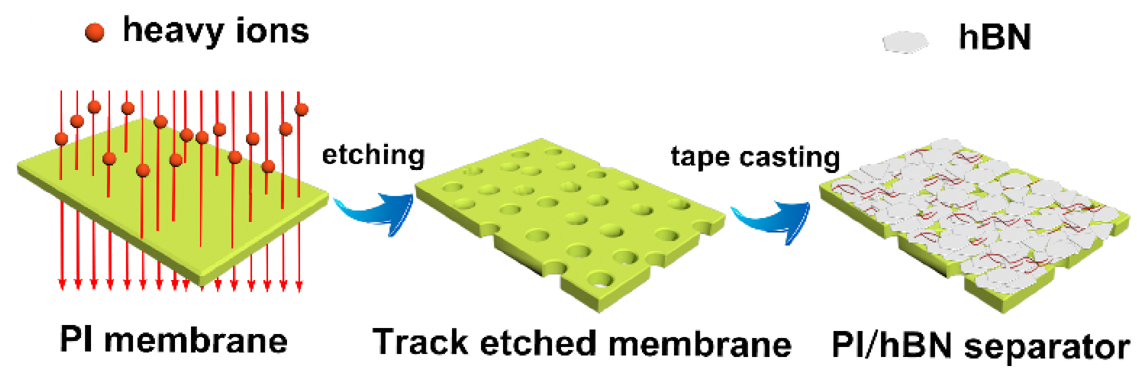


FIG. 6. Schematic illustration showing the preparation process of the PI/hBN separator for LIBs

The study on osmotic power generation of the 1D/2D hybrid nanochannel system

The nanochannels with special structure play important roles in the following areas, such as ion separation, molecular detecting and so on. Besides, they also can be used as the key part for osmotic power generation assisting of their high ion selectivity and excellent ion rectification.

In order to prepare the osmotic power generating structure, the PET film was irradiated by the heavy ions supplied by Heavy Ion Research Facility in Lanzhou (HIRFL) and underwent asymmetric chemical etching to obtain conical nanochannel. After that, the graphene oxide membrane was spin-coated on the PET conical nanochannel to form 1D/2D hybrid structure and the corresponding osmotic power generation properties was also studied .

It was proved that the selectively enhanced cation transport and improved ionic rectification effect was realized due to the increasement of asymmetry of the structure. Meanwhile, the osmotic current and the osmotic voltage were also increased. The influence of differential concentration, pH value, solution and the structure on the osmotic power generation properties was studied. The power of 118.2 pW and the efficiency of 40.3% were realized in current study.

This work was published on *ACS Applied Materials & Interfaces* 2022, 14, 29197.

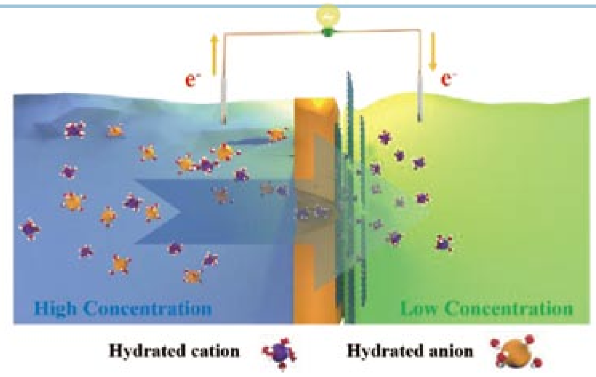


FIG. 7. The schematic picture of osmotic power generation on 1D/2D hybrid nanochannel system.

Unrecovered ion-irradiated damage after thermal annealing in graphene field effect transistors

Graphene has excellent electrical, thermal and optical properties, which make it a highly promising material for future nanoscale electronics applicative in the aerospace field. However, the electronic properties of graphene are strongly influenced by the radiation-harsh environment. In this work, we concentrate on the performance degradation of graphene field effect transistors (GFETs) under swift heavy ions (SHIs) irradiation. The irradiated samples were annealed in in N_2 atmosphere at different temperature to investigated the stability of the irradiated samples. In order to further explore the reason for deteriorated electrical properties of GFETs, the evolution of defects in graphene, SiO_2, Au layers and the interface of SiO_2/Si were investigated by using Raman Spectrometer, AFM and HRTEM. Our result shows that the defects in graphene layer acted as scattering centers, which induced the decrease of carrier mobility. The damages in SiO_2/Si interface resulted in the degeneration of modulation capability of the gate capacitance. Moreover, SHIs irradiation induced permanent radiation damage in graphene and SiO_2/Si layer could not be recovered by thermal annealing even at temperatures as high as 1100 °C. The main role of thermal annealing in irradiated GFET was degassing effect, and the influence of thermal annealing decreased with the increasing irradiation fluences. Our work gives a good understanding of irradiation damage mechanism in GFETs, which is also crucial importance to other 2D materials-based devices work under the harsh irradiation environment.

This work has been published on *Applied Surface Science* 588 (2022) 153005.

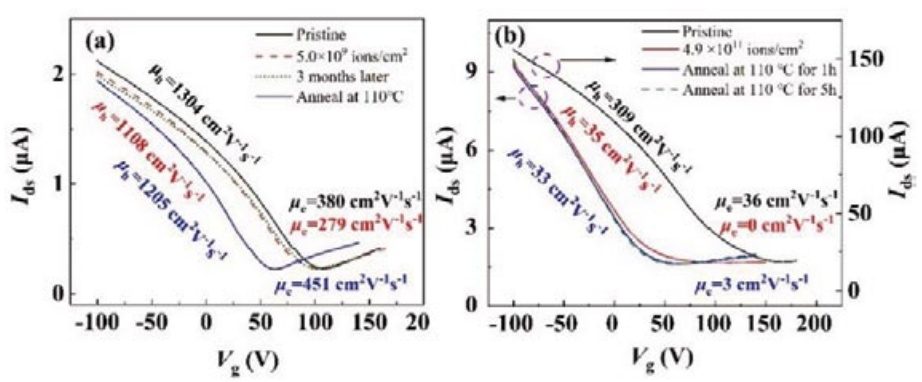


FIG. 8. Transfer curves of the pristine GFET and GFET irradiated with fluence of (a) 5.0×10^9 ions/cm^2, (b) 4.9×10^{11} ions/cm^2.

兰州重离子研究装置2022年度报告（英文）HIRFL

New insight into the irradiation resistant of Ti_3AlC_2

Ti_3AlC_2 material, possessing good properties of both ceramics and metals, has attracted much attention for its excellent resistance to irradiation and high tolerance for He. With the ion beams provided by HIRFL, Ti_3AlC_2 samples were irradiated by energetic He ions and Fe ions in sequential to simulated the accumulation of He and particle irradiation damage in Ti_3AlC_2 material in the reactor.

It was found that the pre-implanted He significantly suppresses the phase transitions caused by the following Fe ions irradiation. The following Fe ions irradiation was also found to promote the evolution of the pre-formed He bubble, which can cause not only the growth but also the re-solution of He bubbles. This will improve the resistance of Ti_3AlC_2 to He bubbles induced damage.

The study indicates that both the He ions implantation and Fe ions irradiation actually inhibit each other's irradiation damage to the material. This may play a positive role in reducing irradiation damage to the Ti_3AlC_2 material, and also provides new insights into irradiation resistance of this material.

This work was published in *Journal of the European Ceramic Society* 42 (2022) 7421–7429.

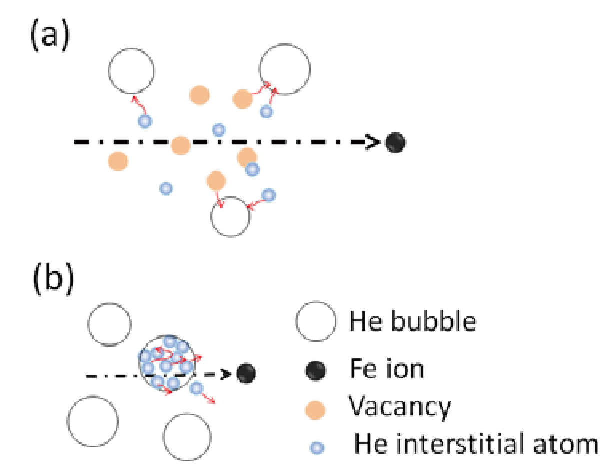


FIG. 9. Schematic illustration of the evolution mechanism of He bubbles driven by the following Fe ion irradiation. (a) The growth process of He bubbles; (b) The re-solution process of He bubbles.

Creation of new rice germplasm by heavy ion beam irradiation

With heavy ion beam irradiation at HIRFL, three new rice varieties, DONGDAO 211, DONGDAO 812 and DONGDAO 862, were cultivated by the Northeast Institute of Geography and Agroecology, CAS and the Institute of Modern Physics, CAS in 2022, which makes this year be the most rice varieties approved. DONGDAO 122 released in 2020, the first new japonica rice variety obtained by using high-energy heavy ion beam breeding technique in China, was promoted planting for 520,000 mu in Jilin and Heilongjiang Provinces in 2022, creating remarkable social and economic benefits. This achievement has opened up a simple and efficient new way of japonica rice breeding, promoted the scientific and technological progress of japonica rice breeding technology in China, and made positive contributions to the "Science and Technology (Sci-Tech) Battle of Black Soil Granary" from Chinese Academy of Sciences. The impact of these new japonica rice varieties obtained by high-energy heavy ion beams breeding technique have been widely reported by Netease, Sohu, Science and Technology Daily, Jilin Daily and other media.

Significant progress on Carbon-ion therapy research and industrialization

Up to 2022, the Heavy Ion Medical Machine (HIMM) has been totally promoted 7 sets with a contract amount of 4.2 billion yuan. Encouragingly, it has been displayed on the exhibition - “Forging Ahead in the New Era” - at the Beijing Exhibition Hall in Beijing.

In 2022, more than 630 cancer patients have been treated by the machine in Wuwei, Gansu Province. Significant effects were achieved, include one breast cancer case and one bladder cancer case, both are treated with heavy ions firstly in China and in the world. Moreover, the newly built treatment room No.1 at HIMM in Wuwei would be officially put into clinical usage after finishing the trial in 2023. For other HIMM machines, in Lanzhou, Gansu Province, the clinical trials are undergoing, in Putian, Fujian Province, the machine has been in process of examining, and for those in Hangzhou, Jiangsu Province, and Wuhan, Hubei Province, the machine installations are on-going. For the newly started ones in Changchun, Jilin Province and Nanjing, Jiangsu Province, they are both at the design stage.

Ⅲ. Cooperation and exchange

In 2022, in spite of the seriously influence of COVID-19, the Institute of Modern Physics, CAS, insisted in the collaborations with our domestic and international partnership via video talks, telecommuting and online international conferences and in more dynamic interaction tunnels to extend mutual collaboration.

In 2022, IMP has signed or renewed the agreements with 7 universities or institutions from USA, Russia and Serbia. Get more funds for exchange programs, include 8 CAS President’s International Fellowship Initiative (PIFI) supported by the Chinese Academy of Sciences, 7 Foreign Researcher Grants financed by the MOST of China, 2 Foreign Senior Scientist Scholarships supported by Gansu Province, 2 CAS’ Special Exchange Program, and 10 cases supported by the China Scholarship Council (CSC).

Up to December 2022, 29 foreign nationals, i.e. 11 employees, 10 postdocs, 1 fellowship and 7 overseas students, were working or studying at IMP. Especially, prof. ONG HOOI JIN is honored with “Dunhuang Award” in Gansu Province due to his great contribution in scientific field and talent nurturing.

Ⅳ. Chronicle of events

On May 21st, 2022, the 18th Public Science Day was organized by the Heavy Ion Research Facility in Lanzhou (HIRFL).

On May 28th, 2022, the review of the 2022 HIRFL beam time application was held in Lanzhou in an "online + offline" model.

On May 30th, 2022, Lanzhou Science and Technology Association held a symposium with the theme of "Striving for Excellence in Innovation, Self-reliance and Self-improvement -- 2022" on the National Science and Technology Workers' Day to promote the spirit of science and scientists. Prof. Zhao Huanyu, a researcher from IMP, was awarded the "Excellent Scientific and Technological Worker" of Lanzhou in 2022.

On Jun. 16th, 2022, the project of “Protective effect of polyphenols on radiation damage and functional gene screening” won the third prize of Gansu Provincial Science and Technology Progress Award.

On Nov. 18th, Prof. Yang Jancheng won HU GANGFU EXPERIMENTAL PHYSICS AWARD-the highest award of Chinese Physics Society.

On Dec. 7th, 2022, Prof. Zhou Xiaohong from the Institute of Modern Physics, Chinese Academy of Sciences, was presented a Certificate of Commendation on the occasion of the fortieth anniversary of researcher exchange and cooperation between RIKEN and the Chinese Academy of Sciences.