

编 委：徐瑚珊

责任编辑：戎欣娟 袁海博 侯欣辰

# HIRFL

## 兰州重离子研究装置

HEAVY ION RESEARCH FACILITY IN LANZHOU

### 2019年度报告

地址：兰州市城关区南昌路509号

邮编：730000

电话：0931-4969207

网址：<http://www.impcas.ac.cn>

联系人：戎欣娟

# HIRFL

## 兰州重离子研究装置

HEAVY ION RESEARCH FACILITY IN LANZHOU

## 2019年度报告

### (中文)

## 一、综述及基本情况

兰州重离子研究装置(HIRFL)经过三个大科学工程的建设及多次改进,已经发展成为我国能量最高、规模最大的重离子加速器,为开展重离子物理基础研究和交叉学科研究提供了先进的实验条件,同时积累了丰富的重离子回旋加速器和同步加速器建造的关键技术和经验。现在的HIRFL由电子回旋共振(ECR)离子源、1.7米扇聚焦回旋加速器(SFC)、大型分离扇回旋加速器(SSC)、SSC直线注入器(SSC-Linac)、冷却储存环(CSR)主环和实验环、放射性束流线、实验终端等主要设施组成。

近代物理所于20世纪60年代初建成了1.5米经典回旋加速器,通过轻核反应实验研究,为我国氢弹研制作出了贡献。70年代初,在国际重离子物理迅猛发展的形势下,将1.5米回旋加速器改建成能加速较轻重离子的加速器,在我国率先开展了低能重离子物理基础研究。

1976年11月,国家计委批准由近代物理所负责设计建造兰州重离子加速器的主加速器系统,主要建设一台大型分离扇回旋加速器及几个实验终端。同时,由中科院匹配经费把原1.5米回旋加速器改建成1.7米扇聚焦回旋加速器作为注入器。兰州重离子加速器的主加速器SSC和注入器SFC于1988年建成,其主要技术指标达到当时国际先进水平,1992年获国家科技进步一等奖。SSC与SFC联合运行,可以把重离子加速到中等能量,用以开展远离稳定线新核素合成、中低能重离子碰撞和热核性质、重离子束应用等研究。并于1991年经国家发改委批准成立了“兰州重离子加速器国家实验室”。

为使我国重离子物理研究继续在部分前沿领域保持国际先进性,同时深入开展重离子治疗肿瘤等交叉学科研究,近代物理研究所经过多年的预研及反复论证,并结合我国国情,提出了在HIRFL上扩建多用途的冷却储存环(CSR)工程。CSR作为国家“九五”重大科学工程,于1997年6月经国务院科技领导小组审议通过,2000年4月经国家发改委批准开工建设,2008年7月通过国家验收,正式投入运行,2012年获国家科技进步二等奖。

兰州重离子加速器的建成,大大提高了我国先进离子加速器物理及技术和核物理及相关学科的国际地位,使兰州重离子加速器国家实验室成为国际上重要的重离子研究中心,增强了我国在重离子物理及其交叉学科国际前沿领域的竞争力。近代物理所依托兰州重离子加速器取得了以首次合成25种新核素特别是两种超重新核素为代表的一批原始创新成果,实现了我国新核素合成零的突破,并开始了超重新元素探索研究的征程;核结构、重离子碰撞和热核性质研究进入国际前沿;从理论和实验两方面对重离子碰撞及热核性质的同位旋相关性研究,获得重要成果;在等时性工作模式下完成了高精度核素质量测量,不仅使得HIRFL-CSR实验环高精度原子核质量测量进入国际先进行列,所获数据在天体核物理研究中也具有重要意义。

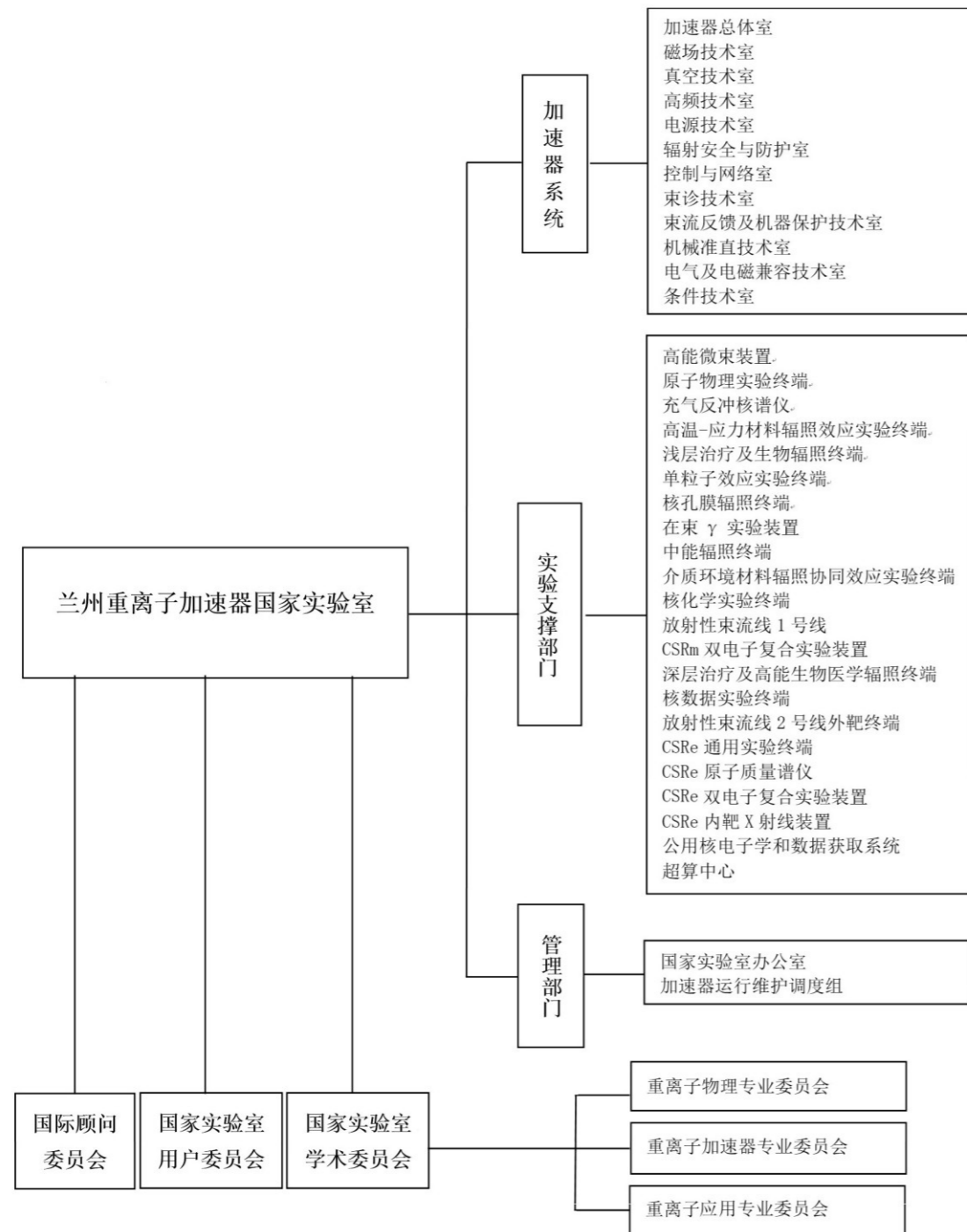
HIRFL是我国核物理及相关交叉领域的大型科研平台,将为以下几个方面的进一步发展发挥更强大的支撑作用:在重离子物理基础研究领域,开展短寿命原子核质量精确测量、弱束缚核结构和反应机制、超重核(元素)性质、核物质性质、高离化态离子碰撞动力学和谱学研究,取得一批在国际上有重大影响的研究成果;在重离子束应用研究领域,开展重离子治疗肿瘤临床试验、重离子治癌机理和诊断及治疗新技术、航天电子器件单粒子效应、离子辐照诱变育种、重离子与特殊环境下材料作用研究,解决与离子辐射相关的关键技术,创造显著的社会经济效益并服务国家重大需求;前瞻部署高能量密度物质性质和空间辐射效应等一批重点研究方向,形成新的学科增长点。



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、徐珊珊
国家实验室学术委员会主任	张肇西	副主任	陈森玉、王克明、叶沿林、周小红

组织框架



承担国家重大项目

项目	学科领域及课题研究内容
基金重点	基于兰州重离子加速器实验装置物理目标的原子核多体系统理论研究 用于高密度物态及惯性约束核聚变诊断的新型高能电子成像关键技术研究 基于单腔多束型加速器的超高强流重离子加速器的前沿研究 丰中子超重核素分离关键技术
重大项目 (课题)	直接测量 AGB 星中关键核反应 $^{19}\text{F}(p,\alpha)^{16}\text{O}$ 在伽莫夫能区的反应截面 天体物理能区关键中子源反应 $^{13}\text{C}(a,n)^{16}\text{O}$ 的直接测量 粒子与新型纳米器件材料相互作用物理机理
重大科研仪器研制项目	低能量强流高电荷态重离子研究装置
杰出青年基金	高功率射频超导质子直线加速器 强流高功率离子加速器束流累积新方法和关键技术
优秀青年基金	激光离子源物理与技术研究
联合基金重点项目	弥散强化的铁基和钒基合金在强辐照条件下脆化机理的研究 宽能域离子束在等离子体中的能量沉积及其激发的自调制不稳定性及尾波场 高能重离子单粒子效应微纳成像技术研究 丰质子区 N=126 附近核素衰变性质研究 基于 HIRFL-CSR 开展中高能轻核诱发核反应研究 离子辐照/LBE 腐蚀协同作用引起铁铬基合金结构演化的机理研究
国家重点研发计划	天体环境中关键核过程研究 高电荷态离子非平衡动力学时空演化研究 多模式引导的多粒子生物适形调强新技术研究与实现 高精度核物理实验研究 新一代强流重离子加速器关键束流物理和核心



## 二、研究进展与成果

2019年,兰州重离子加速器国家实验室的用户依托HIRFL取得一批重要研究成果。

### 国内首台自主知识产权碳离子治疗系统获批注册上市

2019年9月29日,由近代物理所及其控股公司兰州科近泰基新技术有限责任公司研制的碳离子治疗系统(图1)获批第三类医疗器械产品注册,标志着我国有了自主知识产权的碳离子治疗设备,实现了国产重离子治疗设备零的突破,该设备目前安装于甘肃省武威肿瘤医院,入选“中科院2019年度科技成果转移转化亮点工作”。

国产碳离子治疗系统的获批注册给肿瘤患者带来了新的希望,将有效缓解我国恶性肿瘤先进技术供给不足的问题,对于提升中国肿瘤诊疗手段和水平具有重大意义。

自1993年以来,近代物理所通过先进加速器技术和核探测技术的研发、重离子束治疗相关生物学基础研究以及与相关医疗机构合作进行的临床前期研究积累,培养了一支高水平的重离子治疗技术人才队伍,掌握了相关核心技术。其研发的具有自主知识产权的碳离子治疗系统突破了国外产品的专利壁垒,提高了性价比、降低了运行维护成本,实现了国产重离子治疗设备零的突破,探索出了一条“基础研究→技术研发→产品示范→产业化应用”的全产业链自主创新之路,对实现“健康中国”和战略性新兴产业发展具有重要意义。

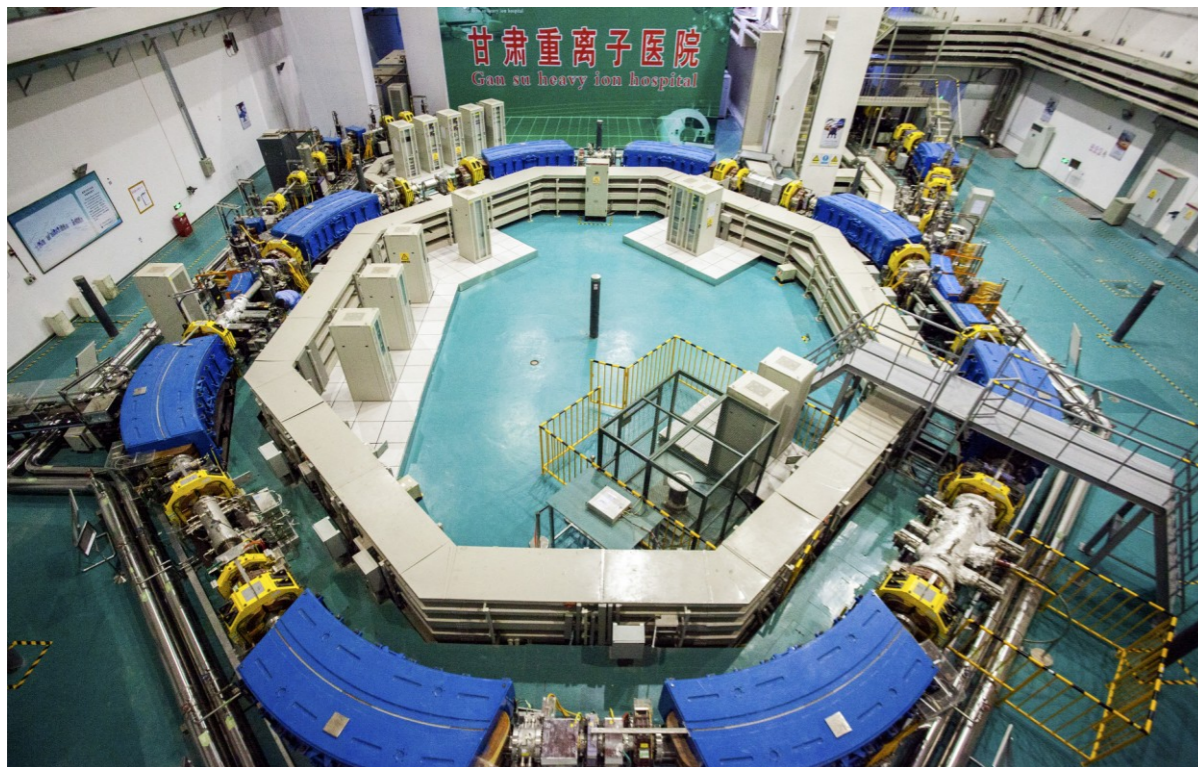


图1. 碳离子治疗系统-同步加速器

### 首次发现新核素 $^{220}\text{Np}$ 并检验到 $\text{Np}$ 同位素 $\text{N} = 126$ 的壳效应

中科院近代物理所、广西师范大学、北京大学、同济大学、中科院理论物理所、俄罗斯联合核子研究所等国内外9家单位的科研人员利用兰州重离子加速器的充气反冲核谱仪SHANS装置开展了相关实验,在 $\text{N} \approx 126$ 的轻锕系核区首次观测到了 $\text{Z} = 93$ 的新核素 $^{220}\text{Np}$ ,这是继发现新核素 $^{219}, ^{223}, ^{224}\text{Np}$ 之后,在该同位素链中发现的又一个新核素。借助于先进的波形采样数字化电子学系统,研究人员首次观测到了新核素 $^{220}\text{Np}$ 的8个 $\alpha$ 衰变事件。实验中测量的 $^{220}\text{Np}$ 衰变链中各核素的 $\alpha$ 衰变能谱和 $\alpha$ 衰变寿命的分布如图2所示。基于新测量的 $\alpha$ 衰变性质以及结合之前发表的 $^{219}\text{Np}$ 和 $^{223}\text{Np}$ 的数据,研究人员在 $\text{Np}$ 同位素的 $\text{N} = 126$ 中子壳附近,首次建立了 $\alpha$ 衰变系统性规律(如图3(a)和(b))。

重核素的 $\alpha$ 衰变系统性规律是反映原子核壳效应的重要实验依据。根据获得的实验结果,研究人员首次给出了 $\text{N} = 126$ 壳效应在 $\text{Z} = 93$   $\text{Np}$ 同位素中仍然存在的实验证据。同时,确定了 $\text{Np}$ 同位素中质子滴线的准确位置(如图3(c)),这一结果是在 $\text{Z} \geq 83$ 的奇 $\text{Z}$ 核区,首次将丰质子核素的质子滴线位置扩展到了 $\text{Z} = 93$ 的同位素中,这也是目前已知质量数最大的质子滴线位置。

该工作得到了国家重点研发计划、中国科学院B类先导科技专项培育项目、国家自然科学基金项目、中国科学院前沿科学重点研究项目、广西自然科学基金项目以及俄罗斯基础研究项目的支持。

相关研究成果以亮点文章“编辑推荐”(Editors' Suggestion)的形式在线发表于国际顶级物理学期刊Physical Review Letters上。

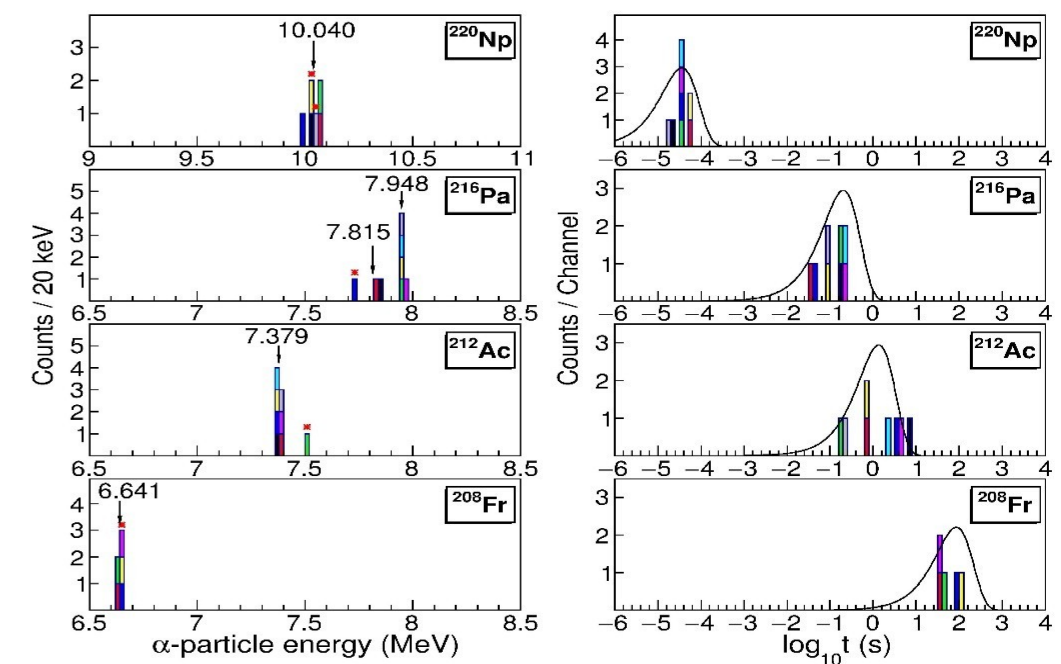


图2. 实验测量的 $^{220}\text{Np}$ 衰变链中各核素的 $\alpha$ 衰变能谱(左)和 $\alpha$ 衰变寿命的分布(右)。



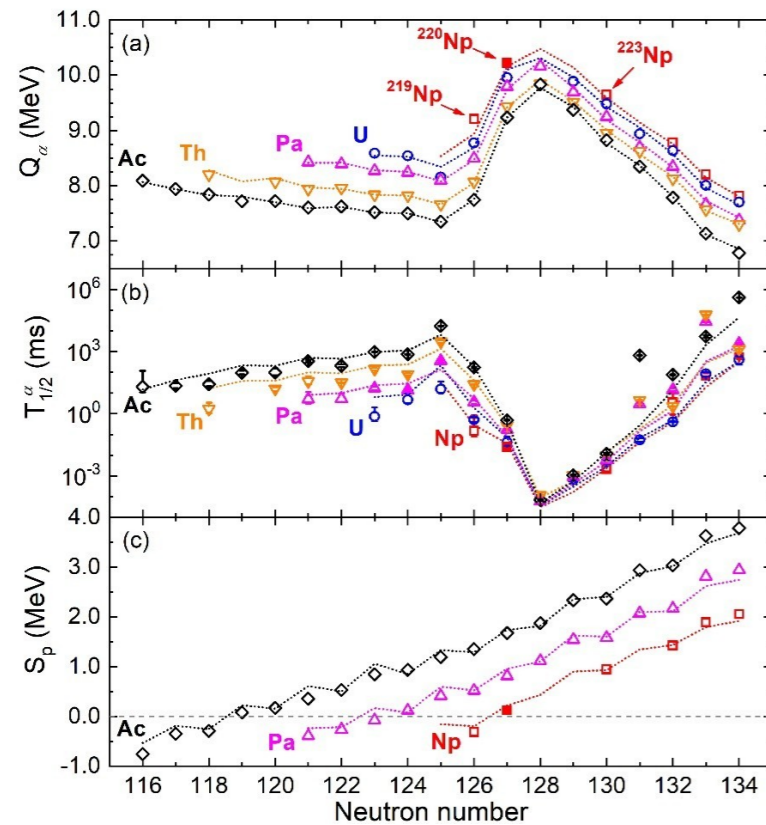


图 3.  $89 \leq Z \leq 93$  缺中子核素的  $\alpha$  衰变 Q 值(a)和半衰期(b)的系统性规律, 以及奇 Z 核 Ac、Pa、Np 同位素的单质子分离能随中子数变化的系统性(c)。

### 质子滴线核衰变研究中的新进展

中国原子能研究院、中国科学院近代物理研究所、北京大学、香港大学、西班牙加泰罗尼亚理工大学等多家单位的科研人员依托兰州重离子加速器在质子滴线核衰变谱学研究方面取得新进展。

研究人员利用自主研发的硅探测器阵列及前端电子学系统, 测量了  $^{27}\text{S}$  的  $\beta$  缓发  $\gamma$  射线谱和迄今为止统计最高的  $\beta$  缓发质子谱, 构建了较为完整的  $^{27}\text{S}$  衰变纲图, 与壳模型理论计算结果进行了对比 (图 4), 并给出了目前精度最高的  $^{27}\text{P}$  质量测量值。基于新的实验结果, 发现计算的  $^{26}\text{Si}(p,\gamma)^{27}\text{P}$  热核反应率远低于 REACLIB 天体数据库推荐值。

在美国举行的第六届国际质子发射会议上, 研究人员以特邀报告形式报告了相关研究成果, 获得国际同行认可。

该研究得到了国家重点研发计划、国家自然科学基金、中国博士后科学基金等项目的支持。文章发表在美国物理学会期刊 Physical Review C。

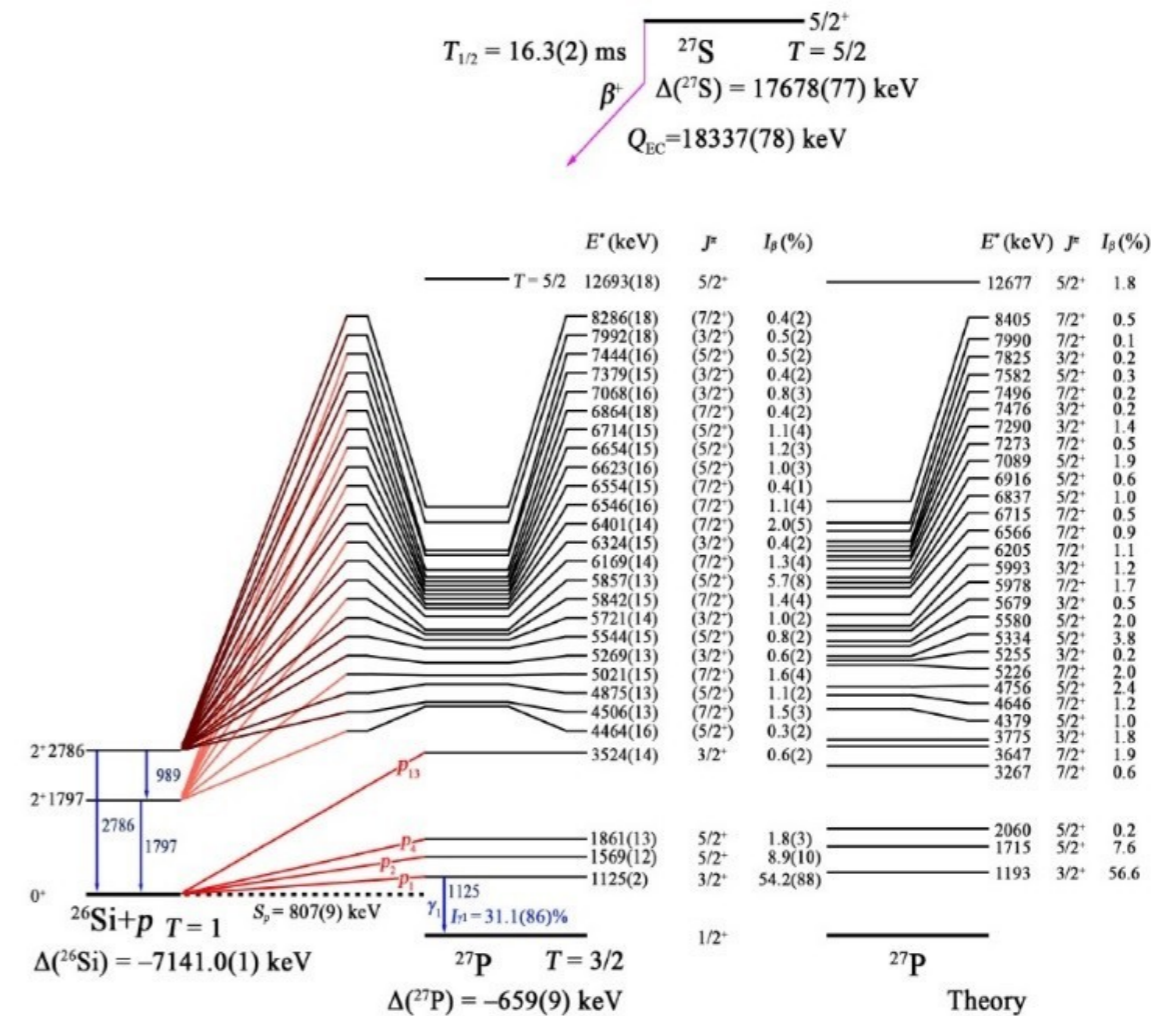


图 4.  $^{27}\text{S}$  衰变纲图, 实验结果与壳模型理论计算结果对比

### 类氟 $^{58}\text{Ni}^{19+}$ 离子的双电子复合精密谱学实验研究获进展

中国科学技术大学联合中科院近代物理所及德国吉森大学等多家单位的科研人员依托兰州重离子加速器冷却储存环 HIRFL-CSRm, 开展了类氟镍离子 ( $^{58}\text{Ni}^{19+}$ ) 的双电子复合实验, 获得最新进展。

实验结果得到 0-160 eV 范围内, 包含  $\Delta N = 0$  所有内壳层跃迁的双电子复合通道。拟合实验结果, 得出横、纵向电子束温度分别为 0.56(0.05) meV 和 23(1) meV。研究人员将实验结果与 Flexible Atomic Code (FAC) 计算的结果仔细对比, 解析出每个共振结构的来源。同时还从双电子复合速率系数得到了可用于等离子体建模的等离子体速率系数, 并与此前的理论计算结果作了对比研究。本次实验结果为天体物理等离子体建模研究提供了数据基准。

该工作得到科技部重点研发计划、国家自然科学基金项目、中科院战略性先导科技专项 B 和中科院重点前沿项目、中科院青年创新促进会的支持。

文章发表在天体物理学专业杂志 *Astronomy & Astrophysics (A&A)* 上 (*A&A* 627, A171 (2019))。

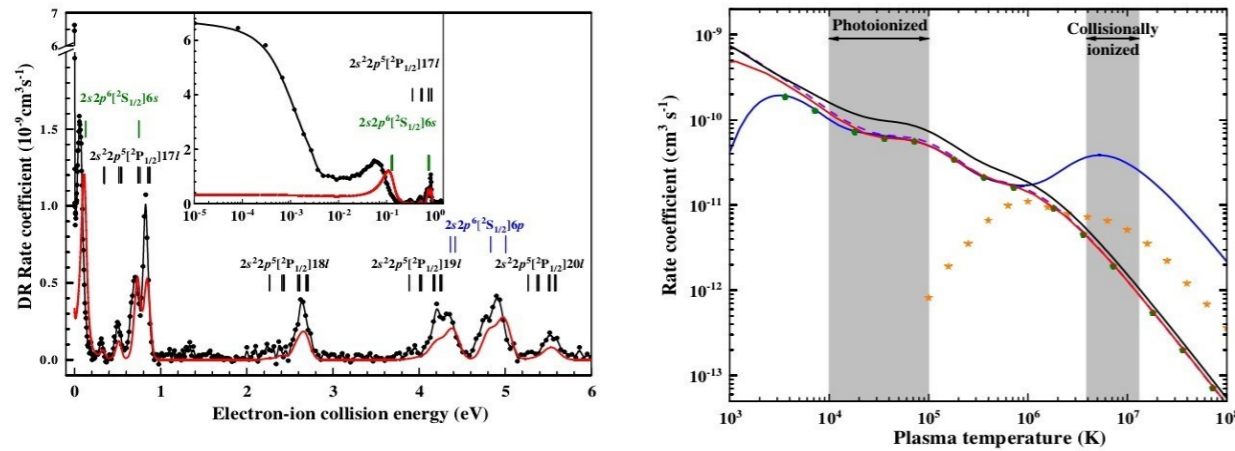


图 5. (左图) 为 0-6 eV 范围内复合速率系数谱, 黑色点线为实验测量结果, 红色实线为 FAC 理论计算结果, 蓝色虚线为辐射复合过程的贡献, 竖线为理论计算各共振态结构。(右图) 为等离子体速率系数, 黑实线为实验结果, 红实线为 FAC 计算结果, 其他数据为此前的理论计算结果。

### 快重离子辐照调制石墨烯电学性能研究

石墨烯作为一种纳米级的新型二维材料, 在电学方面能够实现亚微米级的弹道输运及较高的载流子本征迁移率, 有望成为新一代电子器件的基材。然而目前重离子辐照对石墨烯基器件电学性能影响的研究工作较缺乏, 辐照影响机理仍不清楚。

中科院近代物理研究所研究人员依托兰州重离子加速器开展了快重离子辐照石墨烯晶体管引起电学性能改变的研究, 取得了重要进展。

研究人员设计并制备了 360 个具有不同长宽尺寸的石墨烯带的背栅型场效应晶体管 (GFET)。基于兰州重离子加速器, 通过改变入射离子的能量和电子能损, 采用不同注量 ( $5 \times 10^8 \text{ ions/cm}^2 - 5.4 \times 10^{10} \text{ ions/cm}^2$ ) 的 Ta 束辐照 GFET。对比不同辐照注量条件下石墨烯的电学性质变化, 发现快重离子辐照对石墨烯带的电学性能有调制作用。在低注量 ( $\sim 10^9 \text{ ions/cm}^2$ ) 下, 快重离子辐照会提升 GFET 的性能, 在较高注量 ( $\sim 10^{11} \text{ ions/cm}^2$ ) 下, GFET 性能明显退化。当石墨烯带长宽比小于 5 时, 离子注量  $10^9 \text{ ions/cm}^2 - 4 \times 10^{10} \text{ ions/cm}^2$  范围辐照后, GFET 的电阻值减小 (如图 6 (a)), 载流子迁移率增大 (如图 6 (b))。

研究获得了重离子辐照 GFET 电学性能优化的条件, 在该条件下石墨烯载流子迁移率可提升约 12 倍。研究结果为石墨烯电学性能优化提供了新方法。

研究成果发表在工程技术类一区杂志: *Carbon*, 154 (2019) 244-253 (Impact factor 7.082)。

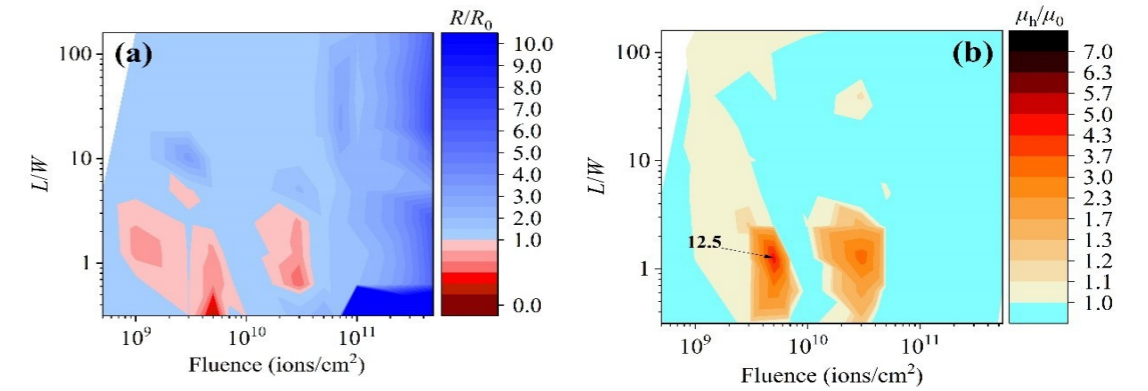


图 6. (a) 不同长宽比石墨烯带电阻比值随辐照注量的变化情况。(b) 不同长宽比石墨烯带空穴迁移率随辐照注量的变化情况。

### 纳米孔的离子选择性增强传输研究取得新进展

核孔膜具有孔径分布均匀、孔尺寸和孔密度方便可调等特点, 目前已应用于水处理、药物筛分、除尘防霾等领域并发挥重要作用。但是核孔膜在溶液中离子的选择性分离和过滤方面仍有不足, 尤其是核孔膜的离子选择性和通量的“跷跷板”效应更是难以权衡。

中科院近代物理研究所科研人员将氧化石墨烯膜制备技术与核孔膜技术相结合, 制备出氧化石墨烯膜/聚合物复合纳米孔结构, 用以开展复合结构中的离子传输特性研究。

科研人员利用兰州重离子加速器提供的高能重离子对 PET 聚合物进行辐照, 再结合非对称化学蚀刻得到 PET 锥形纳米孔, 然后利用旋涂法在 PET 纳米孔上制得氧化石墨烯薄膜 (GOM), 形成 GOM/PET 复合结构。氧化石墨烯膜与核孔膜相结合, 在提高阳离子通量的同时, 抑制了阴离子的传输, 使得体系的离子整流系数从 4.6 增加到 238.0, 实现了溶液中阳离子的选择性增强传输。另外, 该结果在促进微纳流控制器件研制和氧化石墨烯纳滤膜研究方面也具有重要意义。

该工作得到国家自然科学基金项目支持, 成果发表在国际化学领域期刊 *ACS Applied Materials & Interfaces* 上。

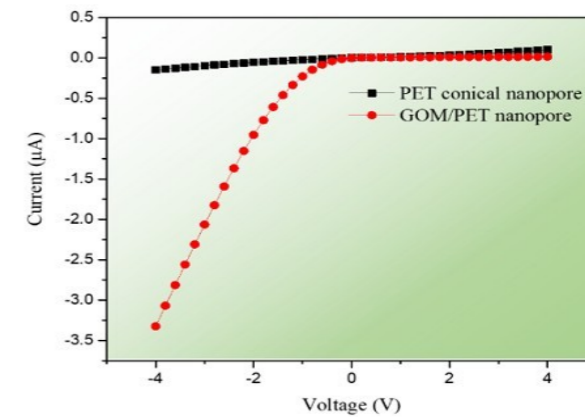


图 7. PET 锥形纳米孔和 GOM/PET 复合结构中离子传输特性



### 纤维素酶水解碱处理秸秆可视化研究方面取得新进展

木质纤维素是地球上储量最丰富的生物质资源之一，纤维素酶降解技术是生物转化高效利用木质纤维素的关键。纤维素酶水解木质纤维素过程中木质素的作用方式（阻止纤维素酶吸附？还是存在非降解性吸附？）一直存在争议，纤维素酶对植物细胞壁具体降解方式的研究也未见报道。因此，木质纤维素的有效前处理和纤维素酶水解植物细胞壁过程的可视化研究，将大大提升木质纤维素生物炼制效率。

科研人员在纤维素酶水解碱处理秸秆的过程研究中取得新进展。研究人员发现，当采用稀碱、稀酸和过氧化氢对甜高粱秸秆进行化学前处理均提高了秸秆生物质的酶水解效率，其中稀碱前处理的酶水解效率达到了 86.44%。采用显微镜实时成像和荧光共聚焦技术（CLSM）进行了酶水解过程的可视化研究，观察到了纤维素酶水解细胞壁的具体方式，即纤维素酶先溶解植物细胞壁中部，然后从中间向两端移动，最后降解细胞壁角隅，纤维素酶对细胞壁的总水解效率与细胞壁中木质素含量成反比。CLSM 结果表明植物秸秆中维管束组织被高度木质化，在纤维素酶水解木质纤维素过程中，纤维素酶与木质素发生了非功能性吸附，减少了与纤维素的功能性吸附。稀碱前处理甜高粱秸秆可以有效的去木质化，减少木质素与纤维素酶的非功能性吸附，提高了植物秸秆的酶水解效率。

此项工作从秸秆纤维素结构变化和酶水解过程可视化两个层面研究了植物细胞壁的前处理效应和纤维素酶水解方式，该结果将有助于从植物组织水平上设计植物细胞和组织类型，以降低其天然抗降解屏障，从而提高天然木质纤维素类材料的转化利用率。

相关研究结果发表在生物质能源期刊 *Biotechnology for Biofuels*. 该研究得到中国科学院重点项目的资助。

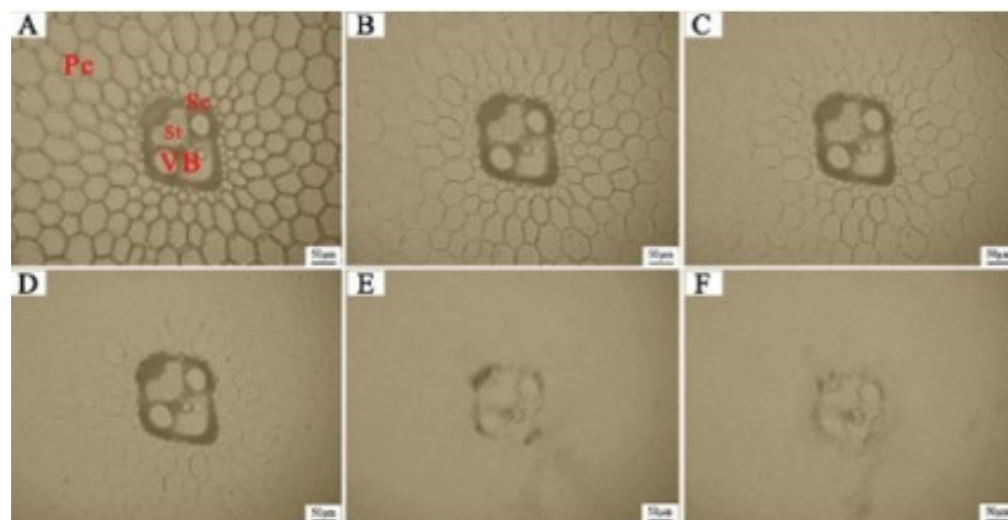


图 8. 碱处理甜高粱秸秆酶水解过程的显微镜实时成像

### 科技论文发表、获奖、专利

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
161		154	161	3	21	11	9

### 三、设施建设、运行与改造

2019 年兰州重离子加速器运行 7392 小时，实验供束时间 5312 小时，机器研究 438.5 小时，实际为各类实验提供 25 种重离子束流，完成 182 项用户实验。

#### 专用研究设施

设施名称	设施运行 总机时	调束注入 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	其他
兰州重离子 研究装置	7392	1416.5	5750.5	438.5	5312	1368	208.5	16.5

#### 公共实验设施

设施 名称	实验终 端数	用户单 位数	用户计划 实验课题数	用户完成 实验课题数	用户实验 参加人数	用户实验涉及领 域及比例	故障 机时
兰州重 离子研 究装置	20	69	150	182	601	原子物理与核物 理 50.29%，生命 科学 3.6%，材料 科学 38.87%，空 间科学 7.23%	208.5

#### 用户单位数

设施	用户 总数	院内	院外		其中				
			国内	国外	大学	研究所	政府 机构	企业	其他
兰州重离子研究装置	75	13	59	3	29	40		6	

### 四、科技队伍与人才培养

实施“黄河之子”人才计划，设立“近物所青年科技人才奖”和“所长基金”，吸引、培养和稳定优秀年轻人才；在重大项目中大胆启用年轻人才，使他们尽快成长起来；推进协同创新战略，与国内大学联合培养创新型人才；充分利用国际合作的良好契机，与国外著名的研究机构、大学联合培养实用型的科技人才。



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		
446	250	174	11	235	141	70	47	26	416	31	2

## 五、合作与交流

2019年,全所职工出国(境)参加国际会议、访问以及合作研究406人次,接待来访和合作外籍专家332人次。在我所进行长、短期科技合作和学术交流工作的外国专家达163人次。分别与欧洲CERN、俄罗斯JINR、FLN、日本CNS、白俄罗斯NAS签订了合作备忘录。

5月18日至19日,兰州重离子加速器开展了第十五个公众科学日。作为迎接新中国成立70周年和建院70周年的系列活动,活动共安排有参观兰州重离子加速器等7大板块,充分展示了近代物理所在“面向世界科技前沿、面向国家重大需求、面向国民经济主战场”方面做出的重大科技创新成果,展现了科技造福人类的美好愿景,塑造了近代物理所良好的社会形象。活动还邀请了研究所精准扶贫帮扶联系点临夏和政县陈家集镇王泉村小学及幼儿园师生共计18人来到现场参加活动,活动两日共接待社会公众5000余人。

同期,以“科技强国 科普惠民”为主题的2019年全国科技活动周暨北京科技周在北京军事博物馆启动。近代物理所碳离子治癌系统和加速器驱动的嬗变研究装置模型参展。



图9. 兰州重离子加速器国家实验室第十五届公众开放日。

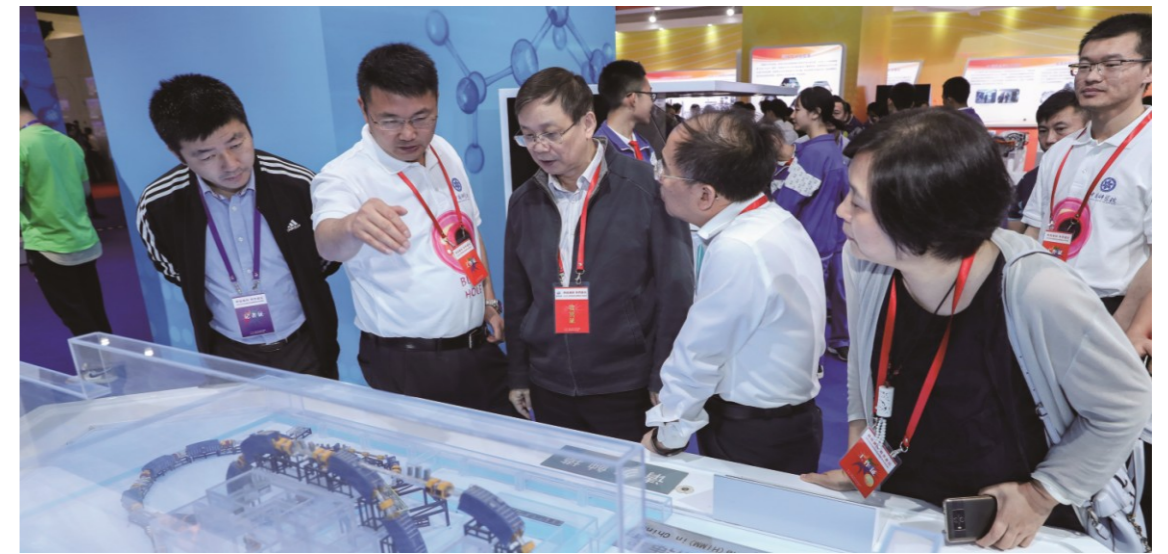


图10. 中科院党组副书记、副院长侯建国在全国科技周暨北京科技周主场听取胡正国副所长关于碳离子治疗系统的汇报

## 六、大事记

1月24日,新投入运行的SECRAL-II超导离子源为兰州重离子加速器不间断连续稳定供束超过1000小时,创造了同类高电荷态离子源单次不间断连续运行的世界纪录。

1月26日,兰州重离子加速器(HIRFL)国家实验室2019年末流评审会在兰州召开。

5月18日至19日,兰州重离子加速器国家实验室举办“科技强国 科普惠民”第十五届公众科学日活动。

5月31日,兰州重离子加速器国家实验室离子束辐照材料学术研讨会在兰州召开。

7月12日,浙江省副省长成岳冲调研兰州重离子加速器。



图11. 成岳冲副省长参观兰州重离子加速器



8月22日,国务院副总理刘鹤在中科院兰州分院召开科技创新座谈会,深入了解重离子治癌及医用同位素相关事宜。



图12. 刘鹤副总理听取徐珊珊所长关于重离子治癌、医用同位素等工作的汇报

9月11日,甘肃省政协主席欧阳坚一行赴兰州重离子医院、中国科学院近代物理研究所现场督办十二届二次会议《关于继续加大力度争取国家支持我省国产重离子治疗装置产业化的提案》,并在近代物理所召开了协商座谈会。



图13. 省政协十二届二次会议重点提案督办协商座谈会

9月29日,碳离子治疗系统获批上市,该产品安装于甘肃省武威肿瘤医院,是国内首台由国家药品监督管理局批准注册的国产碳离子治疗系统。



图14. 2019年10月10日,碳离子治疗系统注册上市新闻发布会在京召开

11月1日,国务院副总理刘鹤参加中国科学院建院70周年成果展,听取肖国青研究员对碳离子治疗系统的汇报。

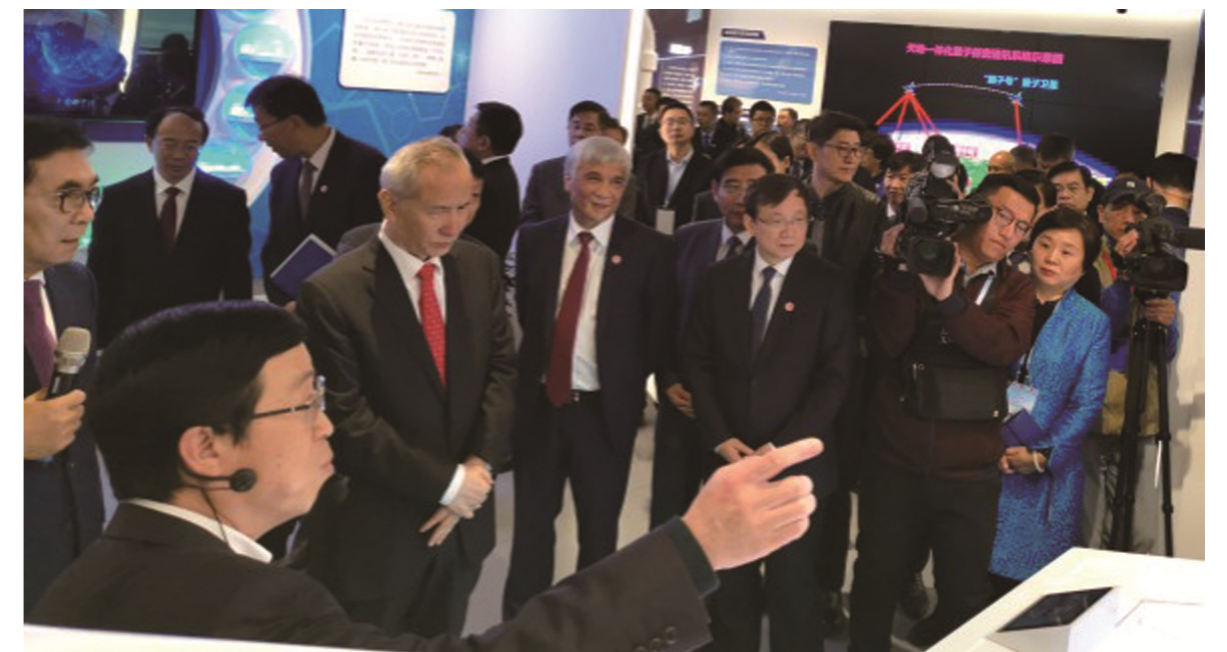


图15. 刘鹤副总理参观中国科学院建院70周年创新成果展——碳离子治疗系统





图 16. 11 月 22 日, 中国科学院近代物理研究所赵红卫研究员当选中国科学院院士。

12 月 17 日, 中科院近代物理研究所自行设计研制的国内首台连续波高电荷态强流重离子直线加速器 (SSC-Linac) 与分离扇回旋加速器 (SSC) 联合调试, 首次成功引出了  $5.98 \text{ MeV/u}$  的  $^{40}\text{Ar}^{7+}$  离子束流, 标志着兰州重离子加速器 (HIRFL) 进入多注入器供束新时代。

# HIRFL

兰州重离子研究装置  
HEAVY ION RESEARCH FACILITY IN LANZHOU

## 2019年度报告 (英文)

## I. Overview

Heavy Ion Research Facility in Lanzhou (Lanzhou Heavy Ion Accelerator, HIRFL), operated by the Institute of Modern Physics, Chinese Academy Sciences (IMP), is the largest heavy ion research facility in China and one of a few large-scale full-ion accelerating systems in the world, which can accelerate ions from hydrogen to uranium to high energy for domestic and growing international user-communities. HIRFL comprises a number of conventional and superconducting magnet Electron Cyclotron Resonances (ECR) ion sources, the Sector Focused Cyclotron (SFC), the Sector-Separated Cyclotron (SSC), the experimental Cooler Storage Ring (CSR) which is a multi-purpose research system consisting of a Main Ring (CSRm), an Experimental Ring (CSR<sub>e</sub>) and a radioactive beam line (RIBLL2) connecting the two rings, a fragment separator – the radioactive Ion Beam Line (RIBLL1) and some experimental devices, etc.. It has worked on nuclear physics, atomic physics, heavy ion applications and interdisciplinary researches. Based on HIRFL, IMP dedicates to fundamental researches in nuclear physics, nuclear astrophysics and atomic physics, including high precision mass measurement of short-lived nuclides, nuclear structure and reaction, properties of nuclear matter, synthesis of new heavy isotopes, chemistry of super-heavy elements, nuclear reaction in stellar environment, spectroscopies and interactions of highly-charged ions.

The SFC is the 1.5m classic cyclotron built in 1962 and later upgraded into a 1.7m Sector Focus cyclotron. Running alone, it can provide beams for low energy heavy ion physics studies.

In December 1988, Lanzhou Heavy Ion Accelerating System (SFC+SSC), designed and constructed by IMP, was completed and put into operation. In August 1991, the National Laboratory of Heavy Ion Accelerator of Lanzhou was approved by the State Planning Committee and opened to the public.

In July 1997, a middle energy radioactive ion beam line (RIBLL) with innovative structure was constructed at HIRFL, which has paved the way for the research on radioactive ion beam physics in China. With the superconducting ECR ion source built in 2005 having the best performance in the world at that time, the operation of HIRFL has reached an internationally advanced level. In June 2005, the successful acceleration of the uranium ions was carried out.

The Heavy Ion Research Facility in Lanzhou-Cooler Storage Ring (HIRFL-CSR) was commissioned in 2008. The HIRFL-CSR is a multi-functional facility, not only accumulating and cooling but also accelerating heavy ions from Carbon to Uranium up to 1 GeV/u to hundreds of MeV/u. Internal target experiments with highly charged ions, external target experiments with both extracted stable and radioactive beams and high precision mass measurement experiment have been carried out. It can provide experiment complex for research in heavy ion physics and its interdisciplinary subjects in China.

IMP has achieved many innovations at HIRFL over the past year: 30 plus new nuclides have been synthesized for the first time in the world, among which two are super-heavy nuclides; the mass of 35 radioactive nuclides have firstly been measured in the isochronous



mode and the relative measurement precision of more than fifty nuclides has increased; the independently researched and developed heavy ion medical machine (HIMM) has realized the zero breakthrough of domestic heavy ion therapy equipment; new species and strains of several crops have been fostered by utilizing heavy ion irradiation induced mutation; and that the popular plantation of optimized sweet sorghum in western china has developed into industrial chain, contributing to the regional economic development.

## II. Research progress and results

Significant results and achievements at HIRFL – 2019

### China's First Self-developed Carbon-ion Treatment System Gets Approval for Registration and Market Access

On Sept. 29, 2019, China's carbon-ion treatment system, which is self-developed by the Institute of Modern Physics, Chinese Academy of Sciences (IMP) and its holding company -Lanzhou Kejin Taiji Corporation, LTD., obtained the approval of the National Drug Regulator for the Class-III Medical Device Product registration. It is the first time that the National Medical Products Administration has approved a domestically produced carbon-ion treatment system.

Since 1993, through the research and development of advanced accelerator technology and nuclear detection technology, basic biological researches related to heavy ion beam therapy and the accumulation of pre-clinical research conducted in cooperation with relevant medical institutions, IMP has cultivated a high-level team of the heavy ion therapy technical team and mastered relevant core technologies. It is installed in Wuwei Cancer Hospital in Gansu province.

This system realizes a zero breakthrough of domestic heavy ion therapy facility. Meanwhile, it improves the cost-effectiveness and reduced the operation and maintenance expenses.

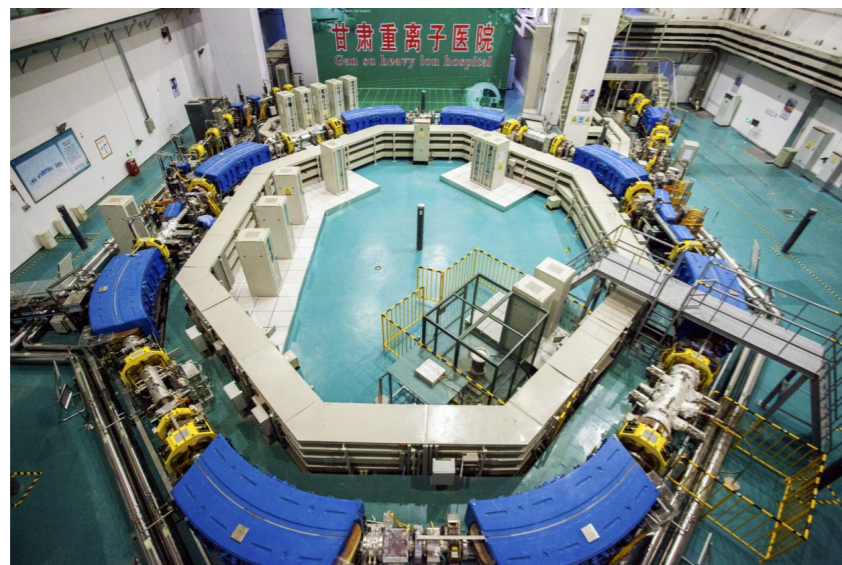


Fig. 1 Carbon-ion therapy system – Synchrotron

### New isotope $^{220}\text{Np}$ : probing the robustness of the $N = 126$ shell closure in neptunium

The examination for the persistence of shell effects for nuclei far from stability is an intriguing topic in contemporary nuclear physics. While the onset of deformations together with the weakening of magic shell effect in most proton-rich isotones with neutron number  $N=126$  was expected, the extension of nuclei in this region of the nuclear chart is undoubtedly interesting for checking the nuclear shell model.

In this work, a research team led by Prof. GAN Zaiguo from the Institute of Modern Physics, Chinese Academy of Sciences reported the discovery of a new nucleus  $^{220}\text{Np}$  with proton number  $Z=93$  and neutron number  $N=127$ . The experiment was carried out on the gas-filled recoil separator SHANS at HIRFL in Lanzhou. Eight correlated alpha-decay chains from  $^{220}\text{Np}$  were identified significantly. Their decay-energy spectra and decay-time distributions for each chain member are shown in Fig. 2. The measured alpha-decay properties (see Fig. 3) of the new neptunium isotope as well as the recently reported  $^{219}, ^{223}\text{Np}$ , around the  $N=126$  closed shell and 11 protons above the well-known doubly magic center  $^{208}\text{Pb}$  ( $Z=82, N=126$ ), allowed us for the first time to test the stability of the  $N=126$  shell effect in Np isotopes. In addition, the new results indicated that, in the region of nuclei with  $Z \geq 83$ , the proton drip line has been reached for all odd- $Z$  isotopes up to Np. Prior to this work, the last identification of the proton drip line in this mass region was for  $Z=91$  protactinium in 1995, more than twenty years ago.

This work has been done in collaboration with research institutes and universities from China and Russia, totally 9 research organizations, which was supported by the National Key R&D Program of China, the Key Research Program of the Chinese Academy of Sciences, the National Natural Science Foundation of China, the Chinese Academy of Sciences, the Natural Science Foundation of Guangxi, and the Russian Foundation for Basic Research.

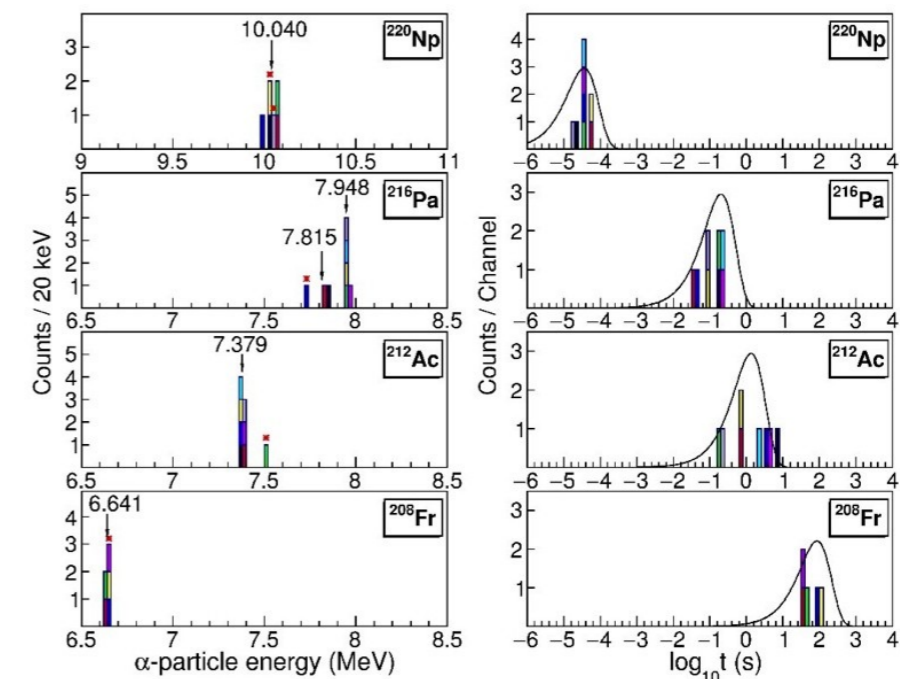


Fig. 2 Left: Energy spectra of the correlated decay events from  $^{220}\text{Np}$ . Right: Decay-time distributions for each chain member.



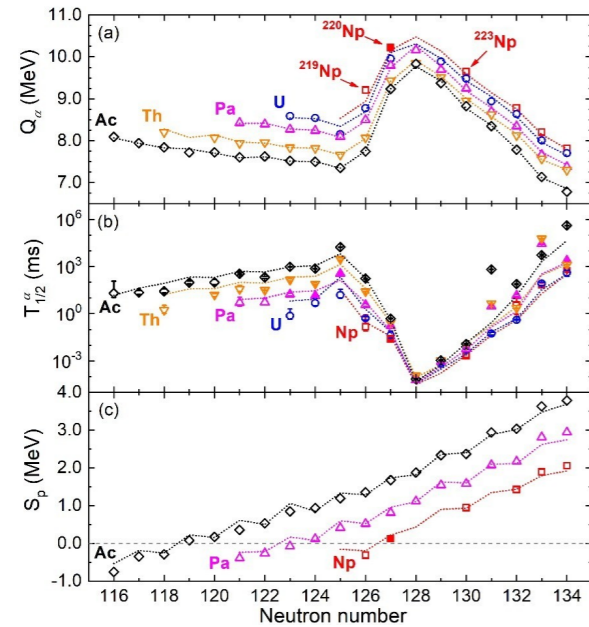


Fig. 3 Systematics of (a)  $\alpha$ -decay  $Q_\alpha$  values, (b) partial  $\alpha$ -decay half-lives  $T_{1/2}^\alpha$  of g.s. to g.s. transitions for neutron-deficient  $89 \leq Z \leq 93$  isotopes, and (c) proton separation energies  $S_p$  for odd- $Z$  Ac, Pa, and Np isotopes as a function of neutron number.

### Progress on $\beta$ -decay protons spectroscopy research

$\beta$ -decay spectroscopy provides valuable nuclear physics input for accurate modeling of nova and x-ray burst observables and a stringent test for shell-model theories far from the stability line. The decay scheme of  $^{27}\text{S}$  is complicated and far from being understood due to a lack of experimental data prior to this work.

Researchers from the China Institute of Atomic Energy, the Institute of Modern Physics of Chinese Academy Sciences, Peking University, Hong University, Shanghai Jiao Tong University, Guangxi Normal University, etc. made the latest progress in  $\beta$ -delayed proton spectroscopy research.

The researchers measured the  $\beta$ -delayed  $\gamma$ -ray spectrum of  $^{27}\text{S}$  and  $\beta$ -delayed proton spectrum with the highest statistical so far by using self-designed and developed detection system composed of several DSSDs and Quadrant silicon detectors, constructed the relatively complete decay scheme of  $^{27}\text{S}$ , and gave the  $^{27}\text{P}$  quality measurement value with the highest accuracy compared with the result of theoretical shell-model calculations. Based on the new experimental results, it was found that the calculated thermonuclear  $^{26}\text{Si}(p, \gamma)^{27}\text{P}$  reaction rates was far lower than that recommended in REACLIB astronomical databases.

The work is supported by the National Key R&D Program of China, the National Natural Science Foundation of China, the Youth Innovation Promotion Association of Chinese Academy of Sciences, the China Postdoctoral Science Foundation and the Office of China Postdoctoral Council under the International Postdoctoral Exchange Fellowship Program (Talent-Dispatch Program).

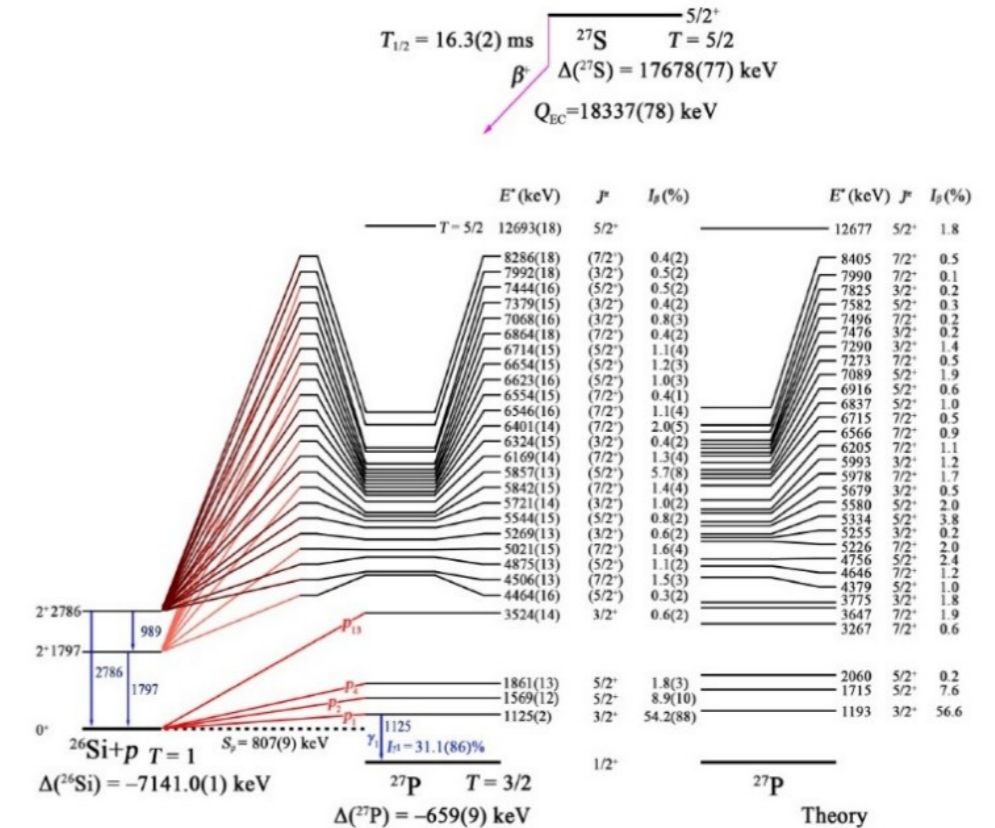


Fig. 4 Left: Decay scheme of  $^{27}\text{S}$ . All the energies, mass excesses, and intensities labeled in the scheme are deduced from the present work except for the mass excess of  $^{26}\text{Si}$ . The proton emissions to different  $^{26}\text{Si}$  states are indicated by using different shades of red (gray). Right:  $^{27}\text{P}$  levels populated in  $^{27}\text{S}$   $\beta$  decay obtained from a USD shell-model calculation

### Progress on the high precision dielectronic recombination spectroscopy experiment with F-like $^{58}\text{Ni}^{19+}$

Electron-ion recombination is one of the most important collision processes in the plasma. Accurate recombination rate coefficients are the basic input parameters for the plasma model in astrophysics and fusion science. Radiation associated with dielectronic recombination (DR) is usually used to probe the plasma properties, such as electron density and electron temperature. In addition, atomic energy levels can be obtained by analyzing the resonant features. Further studies, such as QED test, isotope shift measurement and hyperfine induced (HFI) transitions, can be approached with high precision DR spectroscopy. Storage rings equipped with electron coolers serve as ideal platforms for electron-ion collision experiments, in particular for the recombination at low collision energies.

Researchers from University of Science and Technology of China (USTC), Institute of Modern Physics of Chinese Academy of Sciences, Giessen University (Germany), Fudan University and Northwest Normal University have performed DR experiments with F-like  $^{58}\text{Ni}^{19+}$  at the cooler storage ring (HIRFL-CSRm). DR spectrum in the energy range 0-160 eV, including all the DR channels associated with  $\Delta N = 0$  core excitations, is obtained. The parallel and perpendicular electron temperatures are  $k_B T_{\parallel} = 0.56(0.05)$  meV and  $k_B T_{\perp} = 23(1)$  meV, respectively, according to the fitting of the low energy spectrum. The experimental

results are compared with the theoretical calculation with Flexible Atomic Code (FAC) in detail. The origins of all the resonance features are analyzed. Moreover, we have deduced the plasma recombination rate coefficients and compared with the present as well as the previous theoretically calculated data. The experimental results constitute a set of benchmark data for use in plasma modeling.

The work is partly supported by the National Key R&D Program of China, the National Natural Science Foundation of China, the Strategic Priority Research Program of Chinese Academy of Sciences, the Key Research Program of Frontier Sciences and the Youth Innovation Promotion Association of Chinese Academy of Sciences.

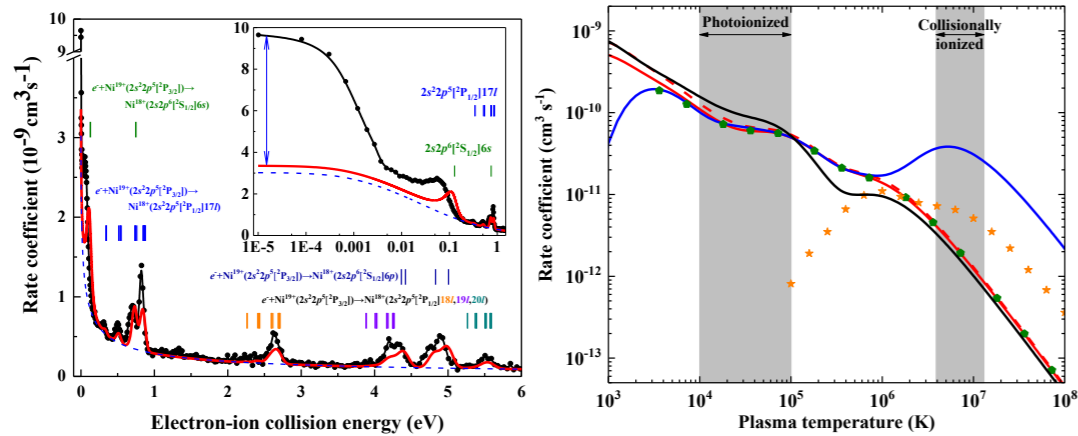


Fig. 5 (left panel) Recombination spectrum of 0-6 eV. Black dotted line is the experimental result; red solid line is the calculation with FAC; blue solid line is the contribution of radiative recombination (RR); vertical bars are the calculated resonance positions. (right panel) Plasma recombination rate coefficients as a function of electron temperature. Black solid line is the experimentally derived data; the red lines (solid: present; dash: Gu 2003) are the calculated ones with FAC. The others are the previous calculations.

### Selectively enhanced ion transport in graphene oxide membrane/PET conical nanopore system

Graphene oxide (GO) in the form of partially oxidized graphene has attracted great attention as a new functional material because of its atomically thin thickness, two-dimensional structure, high strength and chemical stability. In this paper, the ultrathin GO membrane (GOM) is spin-coated on PET conical nanopore which can not only support the GOM but also possess ion rectification effect. It is confirmed that the existence of GOM enhances the cation transport but depresses the anion, which gives rise to enhanced ion rectification effect. COMSOL simulation proves that the GOM can collect cations from reservoir and act as cation source for selective ion transportation in PET conical nanopore. The GOM/PET conical nanopore can display good selective ion transport features in a wider pH range than pure PET conical nanopore because of the chemical stability of graphene oxide. Finally, we believe that the combination of GOM and conical nanopore is a facile design that not only can magnify the ion rectification effect of conical nanopore but also can selectively increase the ionic current, which makes the GOM/PET conical nanopore hold great potential in nanofluidic sensor design and high-efficiency separation membrane production.

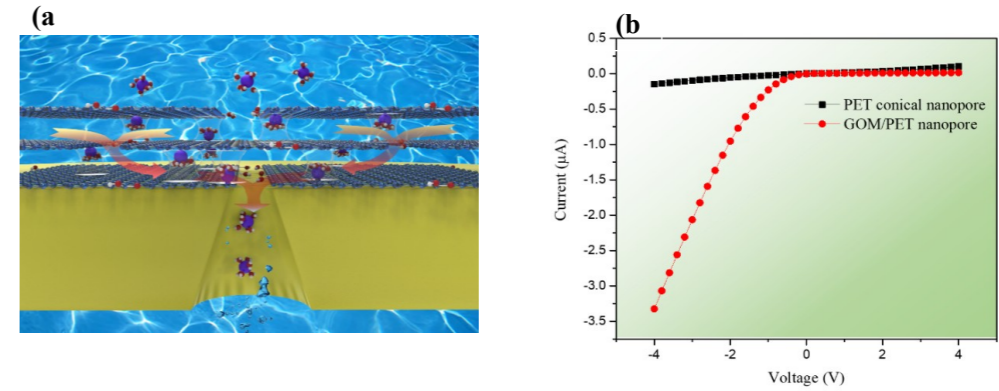


Fig. 6 (a) The schematic picture of ion transport through GOM/PET conical nanopore (b) The ionic transport properties of PET conical nanopore and GOM/PET nanopore

### Graphene electrical properties modulated by swift heavy ion irradiation

The electrical properties of graphene have attracted much attention since its first successful isolation from the bulk graphite by mechanical exfoliation method. Excellent electrical, thermal and optical properties make graphene a very suitable alternative for the silicon. However, the electronic properties of graphene are expected to be strongly influenced by the presence of defects. Several researchers have shown that electron-beam and energetic ion irradiation induce shift in charge-neutral point (CNP) and degrade the performance of the graphene field effect transistors (GFETs). The mechanism behind this process is controversial and unclear so far.

SHIs (1.79 GeV Ta) provided by the accelerator HIRFL at IMP were used to irradiate GFETs. It was found that at lower fluence ( $10^9$ - $10^{10}$  ions/cm<sup>2</sup>), the SHIs irradiation can effectively optimize the performance of GFETs, while at higher fluence ( $\sim 10^{11}$  ions/cm<sup>2</sup>), the electrical properties of the devices were significantly deteriorated after the irradiation process. As shown in Fig.4 (a) and (b), the improvement of electrical properties of GFET more easily occurs when  $L/W$  is lower than 5 and the irradiation fluence is in the range of  $1 \times 10^9$  ions/cm<sup>2</sup> -  $4 \times 10^{10}$  ions/cm<sup>2</sup>. It was found that the competition among various factors such as the doping, local annealing and defect creation dominates the GFET performance. This work explores the best conditions for improving the electrical properties of GFETs and provides a significant reference data for the utilization of graphene based irradiated devices in aerospace electronics.

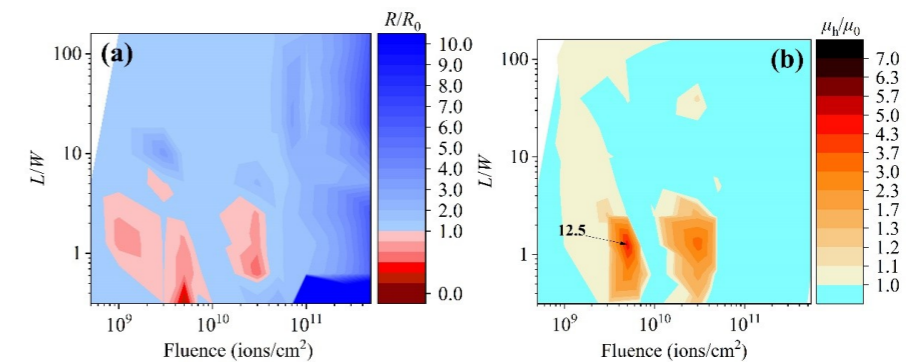


Fig. 7 (a) relative resistance as a function of graphene shape ( $L/W$ ) and ion fluene. (b) evolution of relative mobility for the holes ( $\mu_h/\mu_0$ ) with  $L/W$  and ion fluence.

### III. Construction, operation and upgrading

In 2019, HIRFL has been operated for about 7392 hours, including 438.5 hours for the accelerator study and 5312 hours for 182 experiments on the targets. The operation efficiency is about 71.43%. In this year, 2671.5 beam hours were used for the nuclear and atomic physical experiments, 2065 beam hours for the material sciences, 191.5 beam hours for life sciences (biological sciences), and 384 beam hours for space sciences.

HIRFL has provided 25 kinds of heavy ion beams for various experiments, especially, 17 kinds of which were provided for the experiments firstly by HIRFL (detailed in Table 1) in this year. A summary of the HIRFL operation is shown in Table 2.

Table 1. the Typical Ion Beams Provided by HIRFL in 2019

No.	SFC			SSC		CSR		
	ion	energy (MeV/u)	current (μA)	energy (MeV/u)	current (μA)	energy (MeV/u)	current at CSRm (μA)	current at CSRc (μA)
1	<sup>86</sup> Kr <sup>25+/30+</sup>	5	4			418-472.3	600-1200	次级束
2	<sup>86</sup> Kr <sup>24+</sup>	5	3.5			5	200	
3	<sup>78</sup> Kr <sup>19+</sup>	4	3			4	150	
4	<sup>4</sup> He <sup>2+</sup>	10.5	6					
5	<sup>13</sup> C <sup>4+/6+</sup>	4.95	4	55	0.3			
6	<sup>12</sup> C <sup>4+/6+</sup>	7	3	80.55	0.15			
7	<sup>40</sup> Ar <sup>11+</sup>	4.96	3.5					
8	<sup>18</sup> O <sup>6+</sup>	6.3	3					
9	<sup>40</sup> Ar <sup>12+</sup>	6.17	3					
10	<sup>36</sup> Ar <sup>10+</sup>	4.03	3					
11	<sup>40</sup> Ca <sup>14+</sup>	6.17	2.4			6.17	100	
12	<sup>40</sup> Ca <sup>15+</sup>	6.17	2.8			6.17	100	
13	<sup>181</sup> Ta <sup>32+</sup>	1.287	0.28	13.5	0.023			
14	<sup>18</sup> O <sup>6+/8+</sup>	5.361	10	60	0.6			
15	<sup>86</sup> Kr <sup>17+/26+</sup>	2.345	2	25	0.05			
16	<sup>209</sup> Bi <sup>36+</sup>	2	3			140	80	
17	<sup>209</sup> Bi <sup>27+</sup>	1	1.5			1	3	
18	<sup>12</sup> C <sup>4+</sup>	7	3					
19	<sup>56</sup> Fe <sup>17+</sup>	6.3	1					
20	<sup>12</sup> C <sup>4+</sup>	4.906	2					
21	<sup>12</sup> C <sup>3+</sup>	4.2	3					
22	<sup>20</sup> Ne <sup>7+</sup>	6.17	3.5					
23	<sup>86</sup> Kr <sup>25+</sup>	5	5.2			80	500	500
24	<sup>40</sup> Ar <sup>7+</sup>	0.58	9	5.98	0.3			
25	<sup>86</sup> Kr <sup>25+</sup>	5.5	1.5					

\*\* : the ions marked in red color were provided firstly by HIRFL in 2019.

Table 2: Distribution of HIRFL Operation Time in 2019

Operation time distribution	Time (h)	Percentage (%)
<b>Total operation time</b>	7392	100
<b>Failure time</b>	208.5	2.8
<b>Preparation of beam</b>	586.5	7.9
<b>Beam testing</b>	830	11.21
<b>Other time</b>	16.5	0.2
<b>Target beam time</b>	5750.5	77.8
Nuclear physics	2671.5	46.5
Material sciences	2065	35.9
Biophysics	191.5	3.3
Space sciences	384	6.7
Machine study	438.5	7.6

### IV. Scientific & technical personnel and talent training

The total number of staff for HIRFL is up to 446, composed of 250 operating and maintaining staff, 174 researchers and other 11 employees. 235 out of the 446 have senior and 141 have intermediate title. In addition, regarding to the postgraduate education at IMP in 2019, up to 73 students have graduated from IMP with a doctoral degree or a master degree whereas 416 students have been doing their postgraduate work.

In order to train, attract and keep talented personnel, the Institute of Modern Physics, Chinese Academy of Sciences (IMP) has taken a series of effective measures. The “Huang He Zhi Zi” project for talents is implemented, “IMP Award for Young Talent in Science and Technology” and “Foundation of Director” are initiated; second, young talents are assigned important tasks in major projects to make them experienced; third, the good opportunities of international cooperation are fully enjoyed to jointly foster practical and creative talents of science and technology with celebrated institutions and prestigious universities around the world.

### V. Cooperation and exchange

This year, totally 406 researchers and staff at IMP have gone abroad to attend international conferences, visit the long-term collaborative and international research organizations and participate in or conduct the international cooperative researches and



experiments. Meanwhile, researchers from all over the world are warmly welcomed to IMP for studying, doing experiments or for making the research presentations or lectures. Significantly, in this year, IMP has established the long-term international collaboration relationships with CERN in Switzerland, JINR & FLN in Russia, CNS and NAS by signing the Memorandum of Understanding. Furthermore, the 18<sup>th</sup> International Conference on Ion Sources was successfully held by IMP, in Lanzhou, China; this is a biennial international event in the ICIS series after recent three conferences hosted in Geneva, New York City, and Chiba, respectively. After 6 years, this conference turns to Asia again. It was the second time that this event had been hosted in China after the ICIS1993 in Beijing hosted by PKU. (Group Pic. see Fig. 8)



Fig. 8 the 18<sup>th</sup> International Conference on Ion Sources (ICIS2019)

From May 18<sup>th</sup> to 19<sup>th</sup>, 2019, the 15<sup>th</sup> Public Science Day organized by the Heavy Ion Research Facility in Lanzhou (HIRFL). In this event HIRFL received more than 5000 visitors.



Fig. 9 the 15<sup>th</sup> Public Science Day organized by HIRFL

On May 18<sup>th</sup>, 2019, the self-developed Carbon-ion Treatment System and the Accelerator Driven System by IMP were exhibited during the 2019 National Science and Technology Week at the China People's Revolution Military Museum, Beijing, China.

In September 2019, HIRFL was exhibited in the achievements exhibition for celebrating the 70<sup>th</sup> anniversary of the founding of the People's Republic of China at Beijing Exhibition Center, Beijing, China.

In November 2019, Innovation achievements exhibition for celebration the 70<sup>th</sup> anniversary of the founding of the Chinese Academy of Sciences (CAS) was held in the National Science Library, Chinese Academy of Sciences. HIRFL, Synthesis of new isotopes, High-accuracy Mass Measurements of short-lived exotic nuclides, the Carbon-ion Treatment System, advanced nuclear energy system, etc. were selected for the exhibition.

## VI. Chronicle of events

On Jan. 24<sup>th</sup>, 2019, the latest operational superconducting magnet ion source – SECRAI-II made a new world record of the same highly charged ion sources with single continuous operation without interruption, which has provided more than 1000 hours of stable ion beams for HIRFL.

On Jan. 26<sup>th</sup>, 2019, Annual HIRFL Beam Review Meeting was held in Lanzhou.

From May 19<sup>th</sup> to 20<sup>th</sup>, 2019, the 15<sup>th</sup> Public Science Day was successfully organized with the theme of "S&T Innovation strengthening the Nation and enriching the people" at IMP.

On May 31<sup>st</sup>, 2019, NLHIRFL ion beam irradiation materials academic seminar was held in Lanzhou, China.

From Sept. 1<sup>st</sup> to 6<sup>th</sup>, 2019, the 18<sup>th</sup> International Conference on Ion Sources was successfully held by IMP, in Lanzhou, China.

On Sep. 29<sup>th</sup>, China's first Carbon Ion Cancer Treatment System was approved and registered for market by National Medical Products Administration, which was installed at the Wuwei Tumour Hospital in Wuwei, Gansu Province.

On Dec. 27<sup>th</sup>, the joint commissioning of the first highly charged heavy ion linear accelerator with continuous wave for SSC (SSC-Linac) designed and fabricated by IMP and SSC was accomplished. 5.98MeV/u <sup>40</sup>Ar<sup>7+</sup> ion beam has been successfully extracted. It marks the new era of multi-injectors for HIRFL.

# HIRFL

兰州重离子研究装置

HEAVY ION RESEARCH FACILITY IN LANZHOU

**2019年度报告**

**(附表)**



附表 1 运行单位和用户发表 SCI/EI 论文一览表 (2019 年度)

序号	题名	作者	发表期刊	卷号	期号	页码
1	Selectively Enhanced Ion Transport in Graphene Oxide Membrane/PET Conical Nanopore System	Dong, Yuhua, et al.	ACS APPLIED MATERIALS & INTERFACES	11	16	14960-14969
2	Electrical Field Regulation of Ion Transport in Polyethylene Terephthalate Nanochannels	Li YN, et al.	ACS APPLIED MATERIALS & INTERFACES	11	41	38055-38060
3	Photosynthetic response of Scenedesmus quadricauda to carbon ions irradiation	Wang Jie, et al.	ACTA ASTRONAUTICA	159		27-32
4	Serum microRNA as noninvasive indicator for space radiation	Wei Wenjun, et al.	ACTA ASTRONAUTICA	152		101-104
5	Dosimetric effect of the low dose envelope associated with different beam models for carbon-ion spot scanning beam delivery	Zhang Hui, et al.	ACTA ONCOLOGICA			4
6	Icarin prevents bone loss by inhibiting bone resorption and stabilizing bone biological apatite in a hindlimb suspension rodent model	He Jin-peng, et al.	ACTA PHARMACOLOGICA SINICA	39		1760-1767
7	Analysis and simulation. for Compton camera's imaging resolution	Song Zhang-Yong, et al.	ACTA PHYSICA SINICA	68	11	9
8	Nanoprotusions-Enriched Surface: A Universal and Highly Tolerant Platform for Realizing Uniform Nanoparticles by Sputtering	Xu Guo-Heng, et al.	ADVANCED MATERIALS INTERFACES			9
9	Damaging Intermolecular Energy and Proton Transfer Processes in Alpha-Particle-Irradiated Hydrogen-Bonded Systems	Xu Shenyue, et al.	ANGEWANDTE CHEMIE-INTERNATIONAL EDITION	57		17023-17027
10	Saddle-shaped dose-survival effect, is it a general and valuable phenomenon in microbes in response to heavy ion beam irradiation?	Guo XP, et al.	ANNALS OF MICROBIOLOGY	69	3	221-232
11	microRNA-16-5p enhances radiosensitivity through modulating cyclin D1/E1-pRb-E2F1 pathway in prostate cancer cells	Gan, L.; Wang, F	ANNALS OF ONCOLOGY (会议增刊)	30		-
12	Enhancement of high-LET radiation-induced lung cancer cell apoptosis by Antennapedia proteins (ANTP)-SmacN7	Xie, Y	ANNALS OF ONCOLOGY (会议增刊)	30		-
13	A genome-wide view of mutations in respiration-deficient mutants of Saccharomyces cerevisiae selected following carbon ion beam irradiation	Guo Xiaopeng, et al.	APPLIED MICROBIOLOGY AND BIOTECHNOLOGY	103		1851-1864
14	Current strategies and future prospects for enhancing microbial production of	Hu Wei, et al.	APPLIED MICROBIOLOGY AND	103		201-209

	citric acid			BIOTECHNOLOGY				
15	Three-Dimensional High-Energy Electron Radiography Method for Static Mesoscale Samples Diagnostics	Zhao QT, et al.		APPLIED SCIENCES-BASEL	9	18	-	
16	Protective effects of phenformin on zebrafish embryonic neurodevelopmental toxicity induced by X-ray radiation	Gan L, et al.		ARTIFICIAL CELLS NANOMEDICINE AND BIOTECHNOLOGY	47	1	4202-4210	
17	Research progress on therapeutic targeting of quiescent cancer cells	Zhang Jinhua, et al.		ARTIFICIAL CELLS NANOMEDICINE AND BIOTECHNOLOGY	47	1	2810-2819	
18	Inhibition of SF3b1 by pladienolide B evokes cycle arrest, apoptosis induction and p73 splicing in human cervical carcinoma cells	Zhang Qianjing, et al.		ARTIFICIAL CELLS NANOMEDICINE AND BIOTECHNOLOGY	47	1	1273-1280	
19	Pretreatment of sweet sorghum straw and its enzymatic digestion: insight into the structural changes and visualization of hydrolysis process	Dong MY, et al.		BIOTECHNOLOGY FOR BIOFUELS	12	1	-	
20	CircRNA CBL-11 suppresses cell proliferation by sponging miR-6778-5p in colorectal cancer	Li Hongbin, et al.		BMC CANCER	19	1	14	
21	Enhancing enzymatic hydrolysis yield of sweet sorghum straw polysaccharides by heavy ion beams irradiation pretreatment	Xu Fuqiang, et al.		CARBOHYDRATE POLYMERS	222		8	
22	Graphene electrical properties modulated by swift heavy ion irradiation	Zeng J, et al.		CARBON	154		244-253	
23	Function, clinical application, and strategies of Pre-mRNA splicing in cancer	Di Cuxia, et al.		CELL DEATH AND DIFFERENTIATION	26		1181-1194	
24	Atomic layer deposition of ZnO thin film on surface modified monolayer MoS2 with enhanced photoresponse	Lv Wenquan, et al.		CERAMICS INTERNATIONAL	44		23310-23314	
25	Lipidomics Studies on Mitochondrial Damage of Saccharomyces cerevisiae Induced by Heavy Ion Beam Radiation	Zhang Miao-Miao, et al.		CHINESE JOURNAL OF ANALYTICAL CHEMISTRY	46		1714-1723	
26	Vibrational modes in LaZrZrO7 pyrochlore irradiated with disparate electrical energy losses	Zhang SX, et al.		CHINESE PHYSICS B	28	11	-	
27	Isospin effect in peripheral heavy-ion collisions at Fermi energies	Guo Ya-Fei, et al.		CHINESE PHYSICS C	42		124106	
28	Centrality Dependence of Charmed-Meson Photoproduction in Ultrarelativistic Heavy Ion Collisions	Yu Gong-Ming, et al.		COMMUNICATIONS IN THEORETICAL PHYSICS	71	5	563-567	
29	The sensitivity of distributed temperature sensor system based on Raman scattering under cooling down, loading and magnetic field	Xin, Caijie; Guan, Mingzhi		CRYOGENICS	100		36-40	
30	Raman Spectra and Microstructure of Zinc Oxide irradiated with Swift Heavy Ion	Song Yin, et al.		CRYSTALS	9	8	8	

31	Heavy-Ion Induced Single Event Upsets in Advanced 65 nm Radiation Hardened FGAs	Cai Chang, et al.		ELECTRONICS	8	3	13	
32	Heavy-ion mutagenesis significantly enhances enduracidin production by Streptomyces fungicidicus	Liu Lu, et al.		ENGINEERING IN LIFE SCIENCES	19		112-120	
33	A digital pulse fitting method for the decay studies of short-lived nuclei	Yang H. B., et al.		EUROPEAN PHYSICAL JOURNAL A	55		5	
34	Possibility of the existence of the rogue wave and the super rogue wave in granular matter	Han, Juan-Fang; et al.		EUROPEAN PHYSICAL JOURNAL E	42		5	
35	Precision mass measurements of short-lived nuclides at HIRFL-CSR in Lanzhou	Sun, Ming-Ze; et al.		FRONTIERS OF PHYSICS	13	6	132112	
36	Research of photosynthesis and genome-wide resequencing on a yellow-leaf Lotus japonicus mutant induced by carbon ion beam irradiation	Cui Tao, et al.		GRASSLAND SCIENCE	65		41-48	
37	Scheme of high-resolution identification and selection of secondary ions for mass measurements with the Rare-RI Ring	Ge Z, et al.		HYPERFINE INTERACTIONS	240	1	-	
38	Laser cooling and precision laser spectroscopy of highly charged ions at the storage ring CSRe and the future HIAF	Wen WQ, et al.		HYPERFINE INTERACTIONS	240		-	
39	Latent Reliability Degradation of Ultrathin Amorphous HfO2 Dielectric After Heavy Ion Irradiation: The Impact of Nano-Crystallization	Li ZZ, et al.		IEEE ELECTRON DEVICE LETTERS	40	10	1634-1637	
40	Online Optimization System for 320-kV Heavy Ion Multidisciplinary Research Facility	Chang, Jianjun; Yuan, Youjun; Zhang, Wei		IEEE TRANSACTIONS ON NUCLEAR SCIENCE	66	7	1782-1789	
41	Assessment of enduracidin production from sweet sorghum juice by Streptomyces fungicidicus M30	Liu Lu, et al.		INDUSTRIAL CROPS AND PRODUCTS	137		536-540	
42	The mechanisms for the radioprotective effect of beta-D-glucan on high linear-energy-transfer carbon ion irradiated mice	Liu Fang, et al.		INTERNATIONAL JOURNAL OF BIOLOGICAL MACROMOLECULES	131		282-292	
43	Nonlinear response of phosphor screen used in velocity map imaging spectrometry	Li Yu-Fan, et al.		INTERNATIONAL JOURNAL OF MASS SPECTROMETRY	442		23-28	
44	Weak space charge effects in laser multiphoton ionization of a rarefied gas beam of heavy species	Zhou Wen-Chang, et al.		INTERNATIONAL JOURNAL OF MASS SPECTROMETRY	440		27-31	
45	Physics design of the superconducting section of the CIADS linac	Liu SH, et al.		INTERNATIONAL JOURNAL OF MODERN PHYSICS A	34	29	-	
46	Measurement of beam steering and RF defocusing effect for a quarter-wave resonator	Qin, Yuanshuai, et al.		INTERNATIONAL JOURNAL OF MODERN PHYSICS E	28	3	11	



47	Genetic polymorphisms in mutagenesis progeny of <i>Arabidopsis thaliana</i> irradiated by carbon-ion beams and gamma-rays irradiations	Chen X, et al.	INTERNATIONAL JOURNAL OF RADIATION BIOLOGY			-
48	Induction of cancer stem-like cells in A549 cells after exposure to carbon ions and X-rays	Chen Y., et al.	INTERNATIONAL JOURNAL OF RADIATION RESEARCH	17	1	25-35
49	Radiation damage in $\gamma$ -Ga2O3 induced by swift heavy ions	Al WS, et al.	JAPANESE JOURNAL OF APPLIED PHYSICS	58	12	-
50	Early embryonic exposure of ionizing radiations disrupts zebrafish pigmentation	Wang Yupei, et al.	JOURNAL OF CELLULAR PHYSIOLOGY	234		940-949
51	Transforming growth factor beta signaling pathway: A promising therapeutic target for cancer	Chen Yuhong, et al.	JOURNAL OF CELLULAR PHYSIOLOGY			12
52	Mitochondrial proteomics reveals the mechanism of spermatogenic cells apoptosis induced by carbon ion radiation in zebrafish	Li HY, et al.	JOURNAL OF CELLULAR PHYSIOLOGY	234	12	22439-22449
53	microRNA-16-5p enhances radiosensitivity through modulating Cyclin D1/E1-pRb-E2F1 pathway in prostate cancer cells	Wang Fang, et al.	JOURNAL OF CELLULAR PHYSIOLOGY	234	8	13182-13190
54	Dynamic recognition and repair of DNA complex damage	Yan Junfang, et al.	JOURNAL OF CELLULAR PHYSIOLOGY	234	8	13014-13020
55	The biological mechanisms of butanol tolerance and the application of solvent-tolerant bacteria for environmental protection	Gao Y, et al.	JOURNAL OF CHEMICAL TECHNOLOGY AND BIOTECHNOLOGY			-
56	Efficient L-lactic acid production from purified sweet sorghum juice coupled with soybean hydrolysate as nitrogen source by <i>Lactobacillus thermophilus</i> A69 strain	Tian Xue-jiao, et al.	JOURNAL OF CHEMICAL TECHNOLOGY AND BIOTECHNOLOGY	94	6	1752-1759
57	Development of 2.45 GHz ECR ion sources at IMP	Wu Q, et al.	JOURNAL OF INSTRUMENTATION	14		-
58	Spectral property of SrLaAlO4 by 350 MeV Fe-56(21+) ion beam irradiation	Song Y, et al.	JOURNAL OF LUMINESCENCE	216		-
59	Spin-orbit splitting in the ground state of tungsten monosulfide	Zhang JC, et al.	JOURNAL OF MOLECULAR SPECTROSCOPY	366		-
60	Laser-induced fluorescence spectroscopy of jet-cooled WO in 18, 900-23, 500 cm(-1)	Zhang Jicai, et al.	JOURNAL OF MOLECULAR SPECTROSCOPY	360		7-12
61	Laser-induced fluorescence spectroscopic study of the [21.2]0(+)-X0(+) and [22.2]0(+)-X0(+) electronic transitions of tungsten monoxide	Zhang Jicai, et al.	JOURNAL OF MOLECULAR SPECTROSCOPY	355		96-100
62	Electronic transport in MoSe2 FETs modified by latent tracks created by swift heavy ion irradiation	Zhang S. X., et al.	JOURNAL OF PHYSICS D-APPLIED PHYSICS	52		125102
63	Determination of the density region of the symmetry energy probed by the pi(-)/pi(+) ratio	Yong Gao-Chan, et al.	JOURNAL OF PHYSICS G-NUCLEAR AND PARTICLE PHYSICS	46	10	10

64	Theoretical investigation of electron-ion recombination processes of Li-like tungsten ions	Dou Li-Jun, et al.	JOURNAL OF QUANTITATIVE SPECTROSCOPY & RADIATIVE TRANSFER	220		162-171
65	Determining survival fractions of <i>Saccharomyces cerevisiae</i> in response to ionizing radiation in liquid culture	Guo Xiaopeng, et al.	JOURNAL OF RADIATION RESEARCH	59		760-764
66	Shallow Embedded Strain Measurements and Analysis for a NbTi Superconducting Sextupole Coil During Cooling, Excitation, and Quench	Xin, Camjie; Guan, Mingzhi	JOURNAL OF SUPERCONDUCTIVITY AND NOVEL MAGNETISM	32	2	175-183
67	Microstructure property study of ZnO single crystal irradiated with 200 MeV86 Kr(17+) ions	Song Yin, et al.	MATERIALS RESEARCH EXPRESS	6		
68	Technical Note: Effect of magnetic fields on the microdosimetry of carbon-ion beams	Dai Tianyuan, et al.	MEDICAL PHYSICS	46	8	3746-3750
69	Nanodosimetric quantities and RBE of a clinically relevant carbon-ion beam	Dai TY, et al.	MEDICAL PHYSICS			-
70	Effects of total ionizing dose on single event effect sensitivity of FRAMs	Ji Qinggang, et al.	MICROELECTRONICS RELIABILITY	95		1-7
71	Heavy-ion induced radiation effects in 50 nm NAND floating gate flash memories	Yin YN, et al.	MICROELECTRONICS RELIABILITY	102		-
72	Microstructure of SiC fibers by swift heavy ion beam irradiation	Song Yin, et al.	MODERN PHYSICS LETTERS B	33	20	7
73	Transcriptional response of murine bone marrow cells to total-body carbon-ion irradiation	Liu Fang, et al.	MUTATION RESEARCH-GENETIC TOXICOLOGY AND ENVIRONMENTAL MUTAGENESIS	839		49-58
74	Radiosensitizing Effect of Gadolinium Oxide Nanocrystals in NSCLC Cells Under Carbon Ion Irradiation	Li FF, et al.	NANOSCALE RESEARCH LETTERS	14	1	-
75	The investigation of a new fast timing system based on DRS4 waveform sampling system	Zhang Xiuling, et al.	NUCLEAR ENGINEERING AND TECHNOLOGY	51	2	432-438
76	Design and simulation of a LINAC for high energy electron radiography research	Zhu Yunliang, et al.	NIM A	911		74-78
77	A method to measure the transition energy gamma(t) of the isochronously tuned storage ring (vol 898, pg 111, 2018)	Chen RJ, et al.	NIM A	915		116-116
78	The charged fragment detector system of the External Target Facility	Sun Y. Z., et al.	NIM A	927		390-395
79	Particle identification and revolution time corrections for the isochronous mass spectrometry in storage rings	Xing Y. M., et al.	NIM A	941		9
80	Characterization of a double Time-Of-Flight detector system for accurate	Yan Xin-Liang, et al.	NIM A	931		52-59

	velocity measurement in a storage ring using laser beams							
81	Study of eddy current effect in BRing at HIAF	Chen XQ, et al.	NIM A	920				37-42
82	Low-level radio-frequency system upgrade for the IMP Heavy Ion Reach Facility in Lanzhou (HIRFL)	Cong Yan, et al.	NIM A	925				76-86
83	Phase stabilization design for radio-frequency system of the IMP HIRFL-SSC	Cong Yan, et al.	NIM A	927				240-249
84	Experimental investigation of the transition energy gamma(t) in the isochronous mode of the HIRFL-CSRe	Ge W. W., et al.	NIM A	908				388-393
85	The design and implementation of the beam diagnostics control system for HIMM	Li Min, et al.	NIM A	919				27-35
86	The collimation system design for the Booster Ring in the HIAF project	Li Peng, et al.	NIM A	920				14-21
87	RF design of radio-frequency quadrupole accelerator for heavy ion medical machine	Wang K. D., et al.	NIM A	927				375-381
88	Stochastic cooling experiments for CSRe at IMP	Zhu G. Y., et al.	NIM A	932				83-89
89	Longitudinal modulation of electron-cooled C-12(6+) and O-16(8+) ion beams at heavy ion storage ring CSRe	Wang H. B., et al.	NIM A	908				244-249
90	A new alignment method for HIMM magnetic field measurement system	Chen W. J., et al.	NIM A	944				5
91	Charge trapping effect in HfO2-based high-k gate dielectric stacks after heavy ion irradiation: The role of oxygen vacancy	Li ZZ, et al.	NIM B	459				143-147
92	Molecular dynamics simulation studies of displacement cascade induced defects in gold nanotubes	Liu WQ, et al.	NIM B	461				142-148
93	Beam optics of upgraded high energy heavy ion microbeam in Lanzhou	Ponomarov A, et al.	NIM B	461				10-15
94	Damage and recovery behavior of 4H-SiC implanted with He ions	Yang Yitao, et al.	NIM B	449				54-57
95	Fine structure of swift heavy ion track in rutile TiO2	Zhai Pengfei, et al.	NIM B	457				72-79
96	Microstructure damage in silicon carbide fiber induced by 246.8-MeV Ar-ion irradiation	Zhang LQ, et al.	NIM B	435				169-173
97	Radiation protection considerations in radioactive ion beam facilities	Yang Yao, et al.	NIM B	455				96-107
98	Optical emission from the interaction of highly charged Xe <sup>q+</sup> (6 ≤ q ≤ 23) ions with GaAs surface	Xu Q. M., et al.	NIM B	436				74-77

99	An effective Coulomb interaction in nuclear energy density functionals	Dong J. M., et al.	NUCLEAR PHYSICS A	983				133-144
100	Nonexotic-exotic bipartite mode entanglements of an SU(3) baryon	Xia Zheng-Tong	NUCLEAR PHYSICS A	989				97-116
101	Heavy-ion and pulsed-laser single event effects in 130-nm CMOS-based thin/thick gate oxide anti-fuse PROMs	Cai C, et al.	NUCLEAR SCIENCE AND TECHNIQUES	30	5			-
102	Nuclear dynamics in multinucleon transfer reactions near Coulomb barrier energies	Chen Peng-Hui, et al.	NUCLEAR SCIENCE AND TECHNIQUES	29				
103	Stellar reaction rate of Ni-55(p, gamma)Cu-56 in Type I X-ray bursts	Ma Shao-Bo, et al.	NUCLEAR SCIENCE AND TECHNIQUES	30	9			9
104	Temperature dependence of CsI:TI coupled to a PIN photodiode and a silicon photomultiplier	Sun Yu, et al.	NUCLEAR SCIENCE AND TECHNIQUES	30	2			9
105	An efficient method for mapping the C-12+C-12 molecular resonances at low energies	Tang Xiao-Dong, et al.	NUCLEAR SCIENCE AND TECHNIQUES	30	8			7
106	Transverse emittance measurement for the heavy ion medical machine cyclotron	Feng YC, et al.	NUCLEAR SCIENCE AND TECHNIQUES	30	12			-
107	Fast-bunching design of compact heavy ion RFQ linac	Wang Ke-Dong, et al.	NUCLEAR SCIENCE AND TECHNIQUES	29				
108	Neutron penetration in labyrinths under different beam losses	Yang Y, et al.	NUCLEAR SCIENCE AND TECHNIQUES	30	8			-
109	Optimization of a pretreatment and hydrolysis process for the efficient recovery of recycled sugars and unknown compounds from agricultural sweet sorghum bagasse stem pith solid waste	Jiang Ting-Ting, et al.	PEERJ	6				
110	Fabrication and temperature dependent magnetic properties of Co-Ni nanotube arrays	Chen Yonghui, et al.	PHYSICA E-LOW-DIMENSIONAL SYSTEMS & NANOSTRUCTURES	110				123-126
111	A novel pencil beam model for carbon-ion dose calculation derived from Monte Carlo simulations	Zhang H, et al.	PHYSICA MEDICA-EUROPEAN JOURNAL OF MEDICAL PHYSICS	55				15-24
112	Energy dependence of the reduced single-particle strength for strongly-bound proton removal on C-16	Wang S. T., et al.	PHYSICA SCRIPTA	94				
113	Dissociation of [HCCH] <sup>2+</sup> to H-2(+) and C-2(+): a benchmark reaction involving H migration, H-H combination, and C-H bond cleavage	Xu Shenyue, et al.	PHYSICAL CHEMISTRY CHEMICAL PHYSICS	20				27725-27729
114	Electron transfer plus double ionization in slow He2+ + Ar collisions	Gao Y., et al.	PHYSICAL REVIEW A	98				-
115	Laser-assisted binary-encounter emission in relativistic ion-atom collisions	Wang Z, et al.	PHYSICAL REVIEW A	100	5			-
116	Heavy ion accelerator facility front end design and commissioning	Yang Y, et al.	PHYSICAL REVIEW ACCELERATORS AND BEAMS	22	11			-



117	One-proton knockout from C-16 at around 240 MeV/nucleon	Zhao YX, et al.	PHYSICAL REVIEW C	100	4	-
118	Beyond Wigner's isobaric multiplet mass equation: Effect of charge-symmetry-breaking interaction and Coulomb polarization	Dong J. M., et al.	PHYSICAL REVIEW C	99		014319
119	Beyond Wigner's isobaric multiplet mass equation: Effect of charge-symmetry-breaking interaction and Coulomb polarization	Dong JM, et al.	PHYSICAL REVIEW C	99	1	-
120	Neutron-proton pairing in nuclear matter	Fan Xiao-Hua, et al.	PHYSICAL REVIEW C	99	6	6
121	Probing nuclear bubble configurations by proton-induced reactions	Fan, Xiao-Hua; et al.	PHYSICAL REVIEW C	99	4	4
122	High p(t) squeezed-out n/p ratio as a probe of K-sym of the symmetry energy	Guo, Ya-Fei; Yong, Gao-Chan	PHYSICAL REVIEW C	100	1	5
123	Isomer yield ratios in Re-184 from the Be-9+Ta-181 reaction	Li G. S., et al.	PHYSICAL REVIEW C	99	5	6
124	Fusion reactions in the Be-9+Au-197 system above the Coulomb barrier	Li GS, et al.	PHYSICAL REVIEW C	100	5	-
125	Identification of high-K rotation in Ba-130: Testing the consistency of electromagnetic observables	Qiang Y. H., et al.	PHYSICAL REVIEW C	99		
126	Two-neutron removal cross sections from C-15( $\gamma$ )16 at around 240 MeV/nucleon	Sun Y. Z., et al.	PHYSICAL REVIEW C	99		024605
127	Nucleon momentum distributions in asymmetric nuclear matter	Yang ZX, et al.	PHYSICAL REVIEW C	100	5	-
128	Measurement of Ni-58(p, p)Ni-58 elastic scattering at low momentum transfer by using the HIRFL-CSR heavy-ion storage ring	Yue K, et al.	PHYSICAL REVIEW C	100	5	-
129	Dark compact objects: An extensive overview	Deliyergiyev Maksym, et al.	PHYSICAL REVIEW D	99	6	17
130	Denoising scheme based on singular-value decomposition for one-dimensional spectra and its application in precision storage-ring mass spectrometry	Chen X. C., et al.	PHYSICAL REVIEW E	99	6	10
131	New Isotope Np-220: Probing the Robustness of the N=126 Shell Closure in Neptunium	Zhang ZY, et al.	PHYSICAL REVIEW LETTERS	122	19	192503
132	Blind spots of probing the high-density symmetry energy in heavy-ion collisions	Yong GC	PHYSICS LETTERS B	786		422-425
133	Cellulase production by <i>Aspergillus fumigatus</i> MS13.1 mutant generated by heavy ion mutagenesis and its efficient saccharification of pretreated sweet sorghum straw	Dong Miaoyin, et al.	PROCESS BIOCHEMISTRY	84		22-29
134	Alignment of heavy ion therapy center vertical terminal	Chen Wenjun, et al.	RADIATION EFFECTS AND DEFECTS IN SOLIDS			10

135	STUDY OF NEUTRON RADIATION FIELD AT THE FIRST RADIOACTIVE ION BEAM LINE IN LANZHOU	Yang Y, et al.	RADIATION PROTECTION DOSIMETRY	183	3	312-318
136	miR-454-3p regulates cellular radio-sensitivity by targeting to BTG1 in renal carcinoma cells	Wang, J.	RADIODTHERAPY AND ONCOLOGY	133		S1194-S1195
137	Downregulation of Nrf2 promotes radiation-induced apoptosis in non-small cell lung cancer cells	Zhang, H.	RADIODTHERAPY AND ONCOLOGY	133		S1194-S1194
138	Design of a Superconducting Gantry Dipole Magnet Based on Tilted Solenoids	Liang Yu, et al.	RARE METAL MATERIALS AND ENGINEERING	47		3444-3450
139	Magnetic properties and hydrides precipitation observation of nitrogen doping niobium used for accelerator applications	Yang Ziqin, et al.	RESULTS IN PHYSICS	12		2155-2163
140	A beam profile monitor for picampere low-energy ion beams	Li Xiaoxiao	REVIEW OF SCIENTIFIC INSTRUMENTS	90	7	3
141	Multiple ionization state of Arq <sup>+</sup> ions during collisions near the Bohr velocity	Zhou Xianming, et al.	SCIENTIFIC REPORTS	9		6
142	Discharge Assisted Laser Ablation Source for Gas Phase Metal Compound Molecules and Ions	Zhang Ji-cai, et al.	SPECTROSCOPY AND SPECTRAL ANALYSIS	38		3941-3945
143	Effects of Different Stem Skin and Marrow Root Mesh Sizes in Sweet Sorghum Bagasse on the Release of Sugar in Hydrolysis	Jiang Ting-Ting, et al.	SUGAR TECH	21	3	421-436
144	Investigations of nano-defect morphology and vibrational spectra of swift heavy ion irradiated muscovite mica	Zhang SX, et al.	SURFACE & COATINGS TECHNOLOGY	355		186-190
145	Endocytosis-mediated mitochondrial transplantation: Transferring normal human astrocytic mitochondria into glioma cells rescues aerobic respiration and enhances radiosensitivity	Sun Chao, et al.	THERANOSTICS	9	12	3595-3607
146	Effects of ionizing radiation and HLY78 on the zebrafish embryonic developmental toxicity	Si Jing, et al.	TOXICOLOGY	411		143-153
147	Dynamic vacuum simulation for the Booster Ring in the high-intensity heavy ion accelerator facility	Li Peng, et al.	VACUUM	163		15-25
148	Repair characteristics and time-dependent effects in <i>Saccharomyces cerevisiae</i> cells after X-ray irradiation	Guo Xiaopeng, et al.	WORLD JOURNAL OF MICROBIOLOGY & BIOTECHNOLOGY	35		
149	基于脂质代谢组学研究重离子束辐射诱导的酿酒酵母线粒体损伤	张苗等	分析化学	46	11	1714-1723
150	放电辅助激光溅射气相金属化合物分子和离子的产生装置	张吉才等	光谱学与光谱分析	38	12	3941-3945
151	康普顿相机的成像分辨分析与模拟	宋张勇等	物理学报	68	11	269-277

序号	专利名称	当前权利人	发明人	专利类型	授权日
152	基于斜螺线管型超导 Gantry 二极磁体设计	梁羽等	稀有金属材料与工程	47	3444-3450
153	Optimizing parallel section length for small tensile specimen with fabrication non-uniformity in thickness	Haiting Liu, et al.	Fusion Engineering and Design	147	2019 111244(1-10)
154	A new method to reliably determine elastic strain of various crystal structures from atomic-resolution images	J. S. Chen, et al.	Scientific Reports	9	2019 16399
155	Latent tracks and novel infrared waveguide formation in lithium tantalate irradiated with swift heavy ions	Liu Yong, et al.	Journal of Physics D: Applied Physics	2019	534
156	Ion tracks formation through synergistic energy processes in strontium titanate under swift heavy ion irradiation: Experimental and theoretical approaches	Liu Yong, et al.		7	2019 100402
157	HMGBl mediated autophagy protects glioblastoma cells from carbon-ion beam irradiation injury	Runhong Lei, et al.	Acta Astronautica	166	628-634
158	Quantitative proteomics reveals mitochondrial respiratory chain as a dominant target for carbon ion radiation: Delayed reactive oxygen species generation caused DNA damage.	Fan PC, et al.	Free Radical Biology and Medicine	130	2019 436-445
159	Improvement of charge resolution for radioactive heavy ions at relativistic energies using a hybrid detector system	J.W. Zhao, et al.	Nuclear Inst. and Methods in Physics Research, A	930	2019 95-99
160	Reduced blister quantity in damaged tungsten exposed to deuterium plasma	Xiu-Li Zhu, et al.	SCIENCE CHINA Physics, Mechanics & Astronomy	62	5 957021

附表 2 运行单位和用户获授权发明专利一览表(2019 年度收到)

序号	专利名称	当前权利人	发明人	专利类型	授权日
1	一种核燃料小球的制备装置及制备方法	中国科学院近代物理研究所	田伟;秦芝;曼努埃尔·亚历山大·普冲	发明专利;发明专利	20190726
2	将反应堆从次临界状态转换到临界状态的方法	中国科学院近代物理研究所	詹文龙;杨磊	发明专利;发明专利	20190924
3	用于去除辐照表面钝镀层的化学退镀液和退镀方法	中国科学院近代物理研究所	初青伟;谭腾;何源;郭浩;熊平然;游志明	发明专利;发明专利	20191008
4	靶系统和具有靶系统的用于产生中子和/或中微子的系统	中国科学院近代物理研究所	杨磊;高笑菲;林平;张晟;詹文龙	发明专利;发明专利	20190927
5	高温辐射蠕变装置	中国科学院近代物理研究所	李炳生;王志光;魏孔芳;申铁龙	发明专利;发明专利	20191018
6	一种上旋式液态金属无窗散裂靶构件	中国科学院近代物理研究所	杨伟峰;张雪莹	实用新型	20191115
7	功率输入耦合器	中国科学院近代物理研究所	王若旭;李永明;蒋天才;何源;张生虎	发明专利;发明专利	20191115
8	一种真空密封用不锈钢法兰	中国科学院近代物理研究所	王若旭;郭浩;黄玉璐;谭腾;何源	实用新型	20200107
9	一种光电倍增管高压电源模块	中国科学院近代物理研究所	王彦瑜;尹俊;张亚鹏;倪发福	发明专利;发明专利	20200124
10	双热窗型的功率输入耦合器	中国科学院近代物理研究所	李永明;王若旭;蒋天才;何源;张生虎	发明专利;发明专利	20200221
11	一种高温高压水气流体效应模拟装置的使用方法	中国科学院近代物理研究所	王志光;马志伟;姚存峰;刘超	发明专利;发明专利	20191206
12	轮盘提升机	中国科学院近代物理研究所	杨磊;张建荣;高笑菲;杨阳阳;刘伟明;张延师;麻礼东	实用新型	20191115
13	束流自适应校正器件及校正电极板	中国科学院近代物理研究所	于得洋;薛迎利	发明专利;发明专利	20191115
14	一种直接分离二氧化铀或者乏燃料中稀土元素的方法	中国科学院近代物理研究所; 厦门稀土材料研究所	范芳丽;秦芝;詹文龙;杨帆;赵志钢	发明专利;发明专利	20200124
15	磁力提升装置	中国科学院近代物理研究所	詹文龙;杨磊;张学智;张延师;高笑菲	实用新型	20190927
16	高压电缆接头及其使用方法	中国科学院近代物理研究所	李明睿;高大庆;上官靖斌;高杰;冯秀明;封安辉;孙鹏;钱其三; 李继强;孙志强;陈晓明;肖野;张帅;李晓辉;陈皓;赵江	发明专利;发明专利	20190625
17	反应堆燃料组件的锁紧与提升机构以及锁紧与提升方法	中国科学院近代物理研究所	朱彦雷;顾龙;于毅;蔡义林;彭天骥;王大伟;李金阳;秦长平;刘璐;盛鑫;唐延泽;张璐;田旺盛;冯丽	发明专利;发明专利	20190719



18	高温铝熔体中自动化空氧/腐蚀装置及方法	中国科学院近代物理研究所	常海龙;王志光;姚存峰;孙建荣;张宏鹏;李炳生;盛彦斌;魏孔芳;徐珊珊	发明专利;发明专利	20190726
19	电荷测量电路	中国科学院近代物理研究所	杨海波;孔洁;千奕;苏弘;赵红赞;余乾顺;牛晓阳;蒲天磊;马晓利	发明专利;发明专利	20191220
20	汽车用锂电池隔膜及其制备方法	中国科学院近代物理研究所	梁伟;莫丹;蔡晓红;袁平;杜榕	发明专利;发明专利	20191206
22	一种离子泵性能测试和优化装置及其测试和优化方法	中国科学院近代物理研究所	杨伟顺;蒲晓建;张喜平;刘建龙;蒙峻	发明专利;发明专利	20200117
23	基于GPU并行架构的束流轰击颗粒的能量沉积仿真方法	中国科学院近代物理研究所	杨磊;田园;高笑菲;林平	发明专利;发明专利	20191220
24	磁环组件和制造磁环组件的方法	中国科学院近代物理研究所	赵红卫;张子民;李家庆;王辉;马保华;孙良华;张雪珍;谢祖祺;翟浩银	发明专利;发明专利	20190830
25	核孔膜大气辐照传动装置	中国科学院近代物理研究所	莫丹;袁平;刘杰;孙友梅;李运杰;姚会军;段敬亮	发明专利;发明专利	20190104
26	一种四翼型RFQ加速器腔体冷模测量装置	中国科学院近代物理研究所	王锋峰;张斌;李晨星;金晓凤;赵博;张周礼;王志军;张军辉;何源;于培炎	发明专利;发明专利	20190528
27	一种用于放射治疗中患者摆位的实时验证装置及方法	中国科学院近代物理研究所	中国盛;李强;陈卫强;姬腾飞;戴中颖;刘新国;马圆圆;贺鹏博;张晖	发明专利;发明专利	20190726
28	一种抑制高阶磁电场的热阴极微波电子枪	中国科学院近代物理研究所	宗阳;曹树春;申晓康;赵全堂;张子民	实用新型	20190827
29	一种用于Gantry磁体的倾斜螺线管	中国科学院近代物理研究所	梁羽;吴巍;梅恩铭;马力楦	发明专利;发明专利	20190827
30	一种用于骨样本试验的机械力装置	中国科学院近代物理研究所	王菊芳;何进鹏;华君瑞;危文俊;张亚楠	实用新型	20191206
31	固态氢靶系统和使用它的激光离子源	中国科学院近代物理研究所	孙良亭;赵环昱;沈叮叮;张俊杰	发明专利;发明专利	20200124
32	高频腔失谐检测单元	中国科学院近代物理研究所; 惠州离子科学研究中心	张瑞峰;许哲;王贤武;丛岩;李世龙;韩小东	实用新型	20190712
33	ECR离子源感应炉	中国科学院近代物理研究所	卢旺;钱程;孙良亭;李立彬;黄维	实用新型	20200103
34	储能发电装置以及间歇式发电系统	中国科学院近代物理研究所	詹文龙;杨磊	实用新型	20190219
35	抗菌型PM2.5复合过滤材料制备方法及其应用	中国科学院近代物理研究所	梁伟;莫丹;蔡晓红;袁平;杜榕	发明专利;发明专利	20190312

36	直线加速器和同步加速器	惠州离子科学研究中心;中国科学院近代物理研究所	殷学军;杜衡;夏佳文;李钟汕;李小妮;杨雅清;王科栋;孔启宇;张翔;杨鹏;姚庆高	实用新型	20190308
37	靶系统和具有靶系统的用于产生中子和/或中微子的系统	中国科学院近代物理研究所	杨磊;张晟;高笑菲;林平;付芬;詹文龙	发明专利;发明专利	20190412
38	控氧液态铅铋腐蚀和离子辐照协作研究实验装置	中国科学院近代物理研究所	姚存峰	实用新型	20190510
39	转盘提升机	中国科学院近代物理研究所	杨磊;杨阳阳;高笑菲;张建荣;刘伟明;张延师	实用新型	20191115
40	一种评估颗粒流集体摩擦磨损行为的实验装置	中国科学院近代物理研究所	庞立龙;王志光;常海龙	实用新型	20191115
41	ECR离子源金属炉测试装置	中国科学院近代物理研究所	卢旺;钱程;孙良亭;李立彬;黄维	实用新型	20200107
42	病毒培养方法	中国科学院代物理研究所;中国疾病预防控制中心病毒病预防控制所	胡步荣;陈亚雄;段招军;潘冬;杜亚蓉;谢广成;庞立丽;宋敬东	发明专利;发明专利	20200131

附表3 运行单位和用户获奖一览表

序号	类别	项目名称	主要完成人
1	甘肃省科技进步一等奖	暗物质粒子探测卫星关键探测器-塑闪阵列探测器	刘杰、余玉洪、孔洁、孙志宇、苏弘、杨雅清、杨鹏、赵红赞、杨海波、方芳、张永杰、莫丹、张胜霞、马新文、肖国青
2	高等学校研究优秀成果技术发明一等奖	超导磁体研制设计中的关键力学方法及应用	周又哲、王省哲、张兴义、关明智、吴巍、马力楦
3	甘肃医学科技三等奖	重离子束精准放疗宫颈癌的应用基础研究	谢清