带电粒子出射核反应实验进展

LPDA实验合作组

Back-n第5次用户研讨会

2021-08-13

提纲

带电粒子出射核反应方向

- **本年度主要成果**
- **本年度研究进展**
- **一点体会**
- **近期研究计划**

1. 本年度主要成果

- 发表论文2篇
- 完成稿件1篇
- 国际专家的评价

发表论文1

n-*p*散射
[^{1}H(*n*, *el*)^{1}H反应]

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THE EUROPEAN PHYSICAL JOURNAL A

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Regular Article - Experimental Physics

Measurement of the relative differential cross sections of the $^1H(n, el)$ reaction in the neutron energy range from 6 MeV to 52 MeV

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n-*p*散射相对微分截面实验测量

- 在6.14 MeV--52.48 MeV能区 23个能点得到了相对微分截面
- 首次采用△*E*-*E* 方法鉴别粒子得到实验结果
- 在6.52 $\leq E_n \leq$ 9.09 MeV, 10.57 $\leq E_n \leq$ 12.43 MeV和 18.05 $\leq E_n \leq$ 20.05 MeV能区首次获得实验结果
- 文章尚未发表，结果已被引用

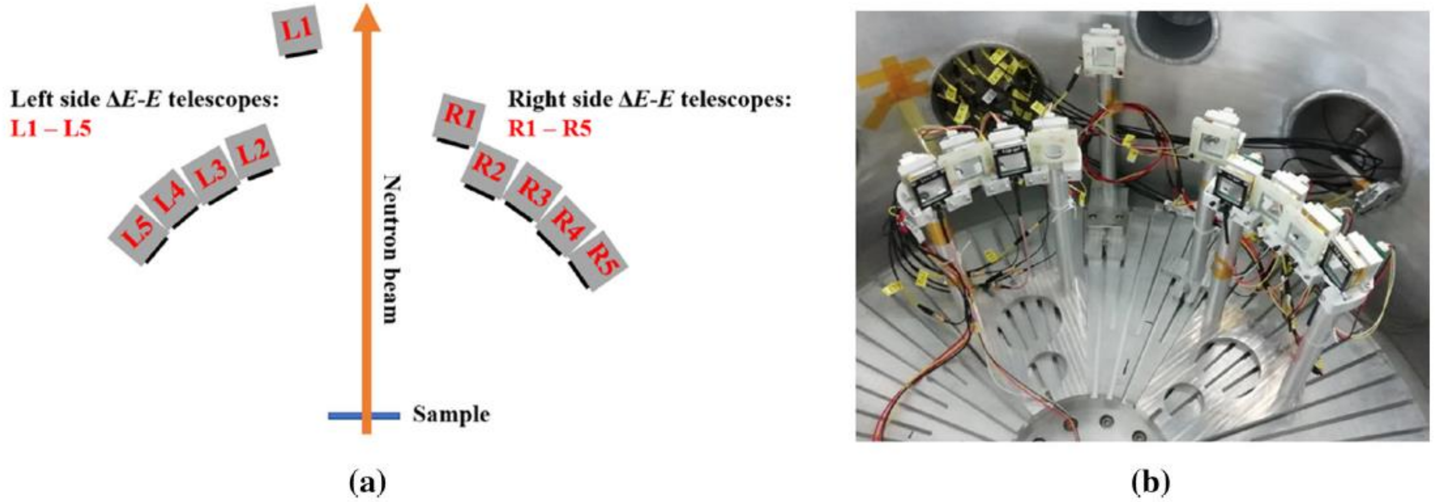

Fig. 3 **a** The sketch of the $\Delta E - E$ telescopes. **b** The photo of the $\Delta E - E$ telescopes inside the vacuum chamber

Haoyu Jiang, Wei Jiang, et al. **Eur. Phys. J. A** (2021) 57:6

Chinese Physics C Vol. 45, No. 6 (2021) 064001

发表论文2

^{12}C(n, xd)反应

Measurement of differential cross sections of neutron-induced deuteron production reactions on carbon from 25 to 52 MeV*

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Minhao Gu(顾旻皓)[2,5] Changcai Han(韩长材)[9] Zijie Han(韩子杰)[8] Guozhu He(贺国珠)[7]
Yongcheng He(何泳成)[2,3] Yang Hong(洪杨)[2,3,4] Hanxiong Huang(黄翰雄)[7] Weiling Huang(黄蔚玲)[2,3]
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Lun Li(李论)[2,3] Qiang Li(李强)[2,3] Xiao Li(李晓)[2,3] Yang Li(李样)[2,3] Rong Liu(刘荣)[8] Shubin Liu(刘树彬)[5,6]
Xingyan Liu(刘星言)[8] Guangyuan Luan(栾广源)[7] Qili Mu(穆奇丽)[2,3] Binbin Qi(齐斌斌)[5,6] Jie Ren(任杰)[7]
Zhizhou Ren(任智洲)[6,8] Xichao Ruan(阮锡超)[7] Zhaohui Song(宋朝晖)[9] Yingpeng Song(宋英鹏)[2,3]
Hong Sun(孙虹)[2,3] Xiaoyang Sun(孙晓阳)[2,3,4] Zhixin Tan(谭志新)[2,3] Hongqing Tang(唐洪庆)[7]
Xinyi Tang(唐新懿)[5,6] Binbin Tian(田斌斌)[2,3] Lijiao Wang(王丽娇)[2,3,4] Pengcheng Wang(王鹏程)[2,3]
Qi Wang(王琦)[7] Taofeng Wang(王涛峰)[11] Zhaohui Wang(王朝辉)[7] Jie Wen(文杰)[8] Zhongwei Wen(温中伟)[8]
Qingbiao Wu(吴青彪)[2,3] Xiaoguang Wu(吴晓光)[7] Xuan Wu(吴煊)[2,3] Likun Xie(解立坤)[5,10] Yiwei Yang(羊奕伟)[8]
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Xianpeng Zhang(张显鹏)[9] Yuliang Zhang(张玉亮)[2,3] Zhiyong Zhang(张志永)[5,6] Yubin Zhao(赵豫斌)[2,3]
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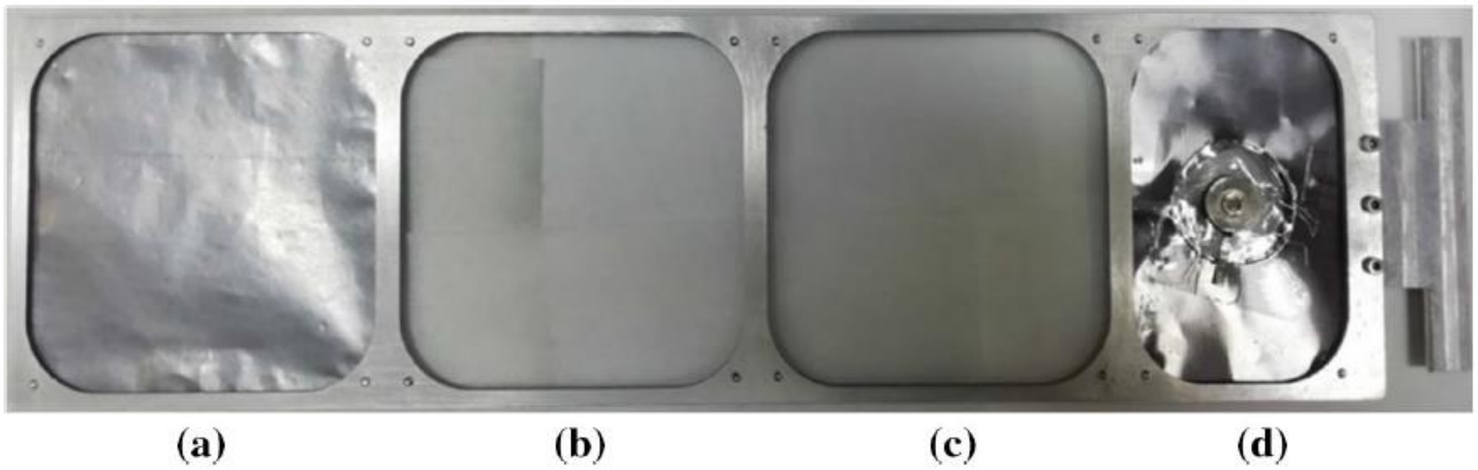
^{12}C(*n*, *xd*)反应氘的相对微分截面

- 在25--52 MeV 6个能点得到了^{12}C(*n*, *xd*)反应氘的相对微分截面
- 首次利用**白光源**在上述能区对该反应进行实验测量
- 是分析^{1}H(*n*, *el*) 反应的本底数据的副产品 (**一次实验获得两个成果**)

Fig. 2 The picture of the sample holder. **a** Graphite foil, **b** empty, **c** low-density polyethylene (LDPE), **d** α sources



Zengqi Cui(崔增琪), et al. **Chinese Physics C** 45(6) (2021) 064001

1篇稿件

n-*d*散射
[^{2}H(*n*, *el*)^{2}H反应]

Measurement of relative differential cross sections of the neutron-deuteron elastic scattering for neutron energy from 13 MeV to 52 MeV

Zengqi Cui[1], Haoyu Jiang[1], Wei Jiang[2,3], Guohui Zhang[1,*], Ruirui Fan[2,3,4,*], Danyang Pang[5], Kang Sun[2,3,5], Huaiyong Bai[1,6], Yiwei Hu[1], Jie Liu[1], Han Yi[2,3], Changjun Ning[2,3], Zhijia Sun[2,3,4], Jingyu Tang[2,3,4,6], Qi An[4,8], Jie Bao[9], Yu Bao[2,3], Ping Cao[4,8], Haolei Chen[4,8], Qiping Chen[10], Yonghao Chen[2,3], Yukai Chen[2,3], Zhen Chen[4,8], Changqing Feng[4,8], Keqing Gao[2,3], Minhao Gu[2,4], Changcai Han[11], Zijie Han[10], Guozhu He[9], Yongcheng He[2,3], Yang Hong[2,3,6], Hanxiong Huang[9], Weiling Huang[2,3], Xiru Huang[4,8], Xiaolu Ji[2,4], Xuyang Ji[4,12], Zhijie Jiang[4,8], Hantao Jing[2,3], Ling Kang[2,3], Mingtao Kang[2,3], Bo Li[2,3], Chao Li[4,8], Jiawen Li[4,12], Lun Li[2,3], Qiang Li[2,3], Xiao Li[2,3], Yang Li[2,3], Rong Liu[10], Shubin Liu[4,8], Xingyan Liu[10], Guangyuan Luan[9], Qili Mu[2,3], Binbin Qi[4,8], Jie Ren[9], Zhizhou Ren[10], Xichao Ruan[9], Zhaohui Song[11], Yingpeng Song[2,3], Hong Sun[2,3], Xiaoyang Sun[2,3,6], Zhixin Tan[2,3], Hongqing Tang[9], Xinyi Tang[4,8], Binbin Tian[2,3], Lijiao Wang[2,3,6], Pengcheng Wang[2,3], Qi Wang[9], Taofeng Wang[13], Zhaohui Wang[9], Jie Wen[10], Zhongwei Wen[10], Qingbiao Wu[2,3], Xiaoguang Wu[9], Xuan Wu[2,3], Likun Xie[4,12], Yiwei Yang[10], Li Yu[2,3], Tao Yu[4,8], Yongji Yu[2,3], Linhao Zhang[2,3,6], Qiwei Zhang[9], Xianpeng Zhang[11], Yuliang Zhang[2,3], Zhiyong Zhang[4,8], Yubin Zhao[2,3], Luping Zhou[2,3,6], Zuying Zhou[9], Danyang Zhu[4,7], Kejun Zhu[2,4,6], Peng Zhu[2,3], the CSNS Back-n Collaboration

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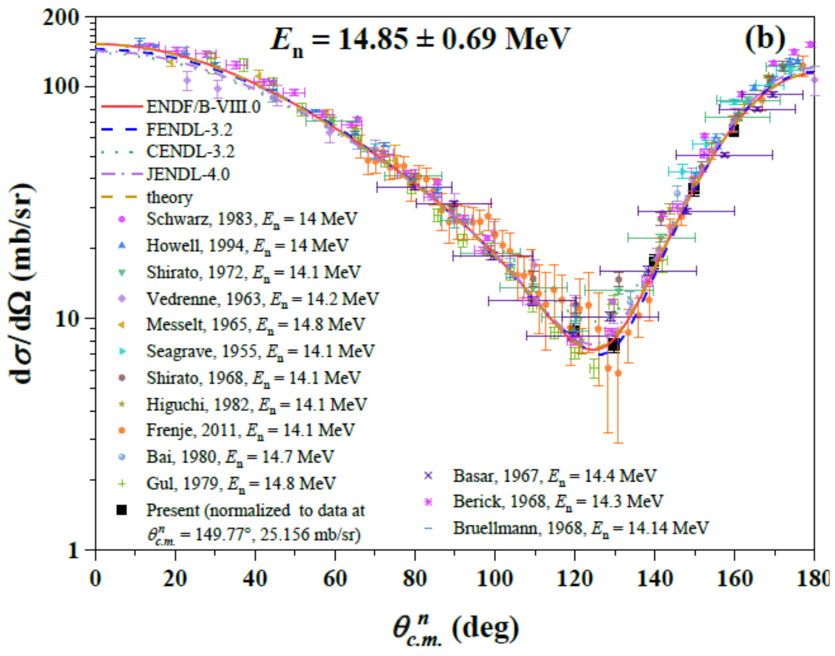
n-d 散射相对微分截面实验测量

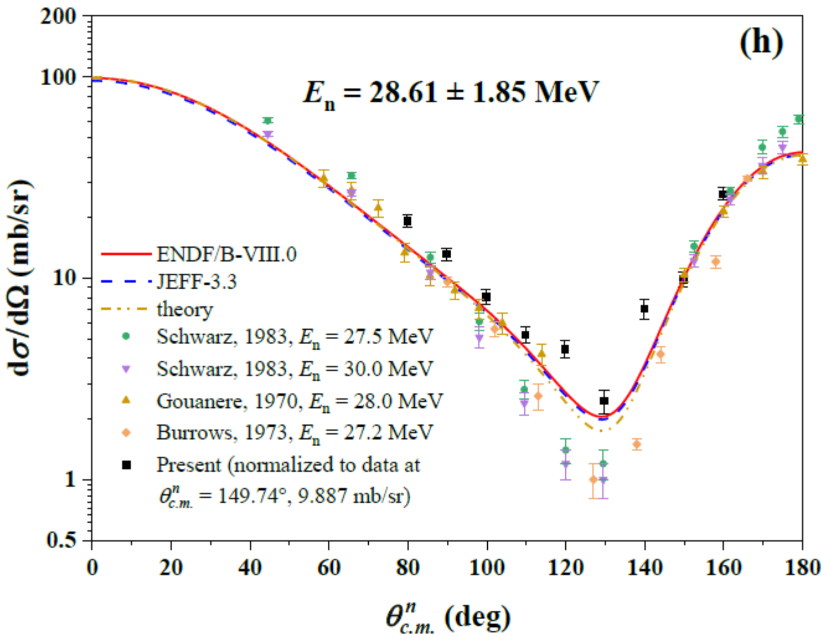
- 稿件已投EPJA 经过合作组修改
- 在13.56--52.48MeV能区12个能点测量了*n-d*散射相对微分截面
- 开展了理论计算(解Faddeev方程)
- 首次用白光源在30 MeV< $E_n \le 55$ MeV能区得到*n-d*散射实验结果
- 已开展*p*, *d*, *t*, α 四种粒子的测量

Fig. 1. The samples used in the present work. From left to right: CH_2 sample, graphite sample, CD_2 sample, and α sources.

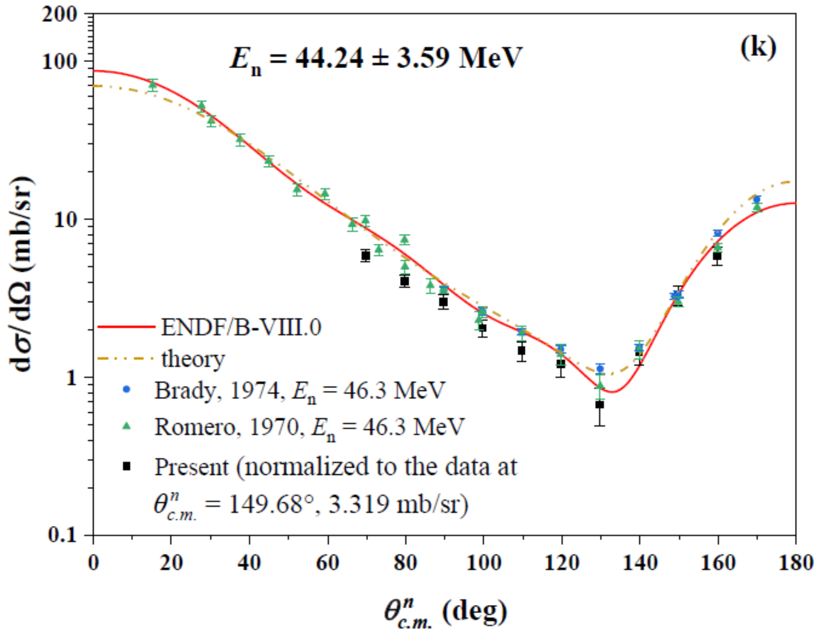
*n-d*散射部分实验结果



E_n = 14.85 ± 0.69 MeV
(b)
ENDF/B-VIII.0
FENDL-3.2
CENDL-3.2
JENDL-4.0
theory
Schwarz, 1983, E_n = 14 MeV
Howell, 1994, E_n = 14 MeV
Shirato, 1972, E_n = 14.1 MeV
Vedrenne, 1963, E_n = 14.2 MeV
Messelt, 1965, E_n = 14.8 MeV
Seagrave, 1955, E_n = 14.1 MeV
Shirato, 1968, E_n = 14.1 MeV
Higuchi, 1982, E_n = 14.1 MeV
Frenje, 2011, E_n = 14.1 MeV
Bai, 1980, E_n = 14.7 MeV
Gul, 1979, E_n = 14.8 MeV
Present (normalized to data at $\theta^n_{c.m.}$ = 149.77°, 25.156 mb/sr)
Basar, 1967, E_n = 14.4 MeV
Berick, 1968, E_n = 14.3 MeV
Bruellmann, 1968, E_n = 14.14 MeV
dσ/dΩ (mb/sr)
$\theta^n_{c.m.}$ (deg)



(h)
E_n = 28.61 ± 1.85 MeV
ENDF/B-VIII.0
JEFF-3.3
theory
Schwarz, 1983, E_n = 27.5 MeV
Schwarz, 1983, E_n = 30.0 MeV
Gouanere, 1970, E_n = 28.0 MeV
Burrows, 1973, E_n = 27.2 MeV
Present (normalized to data at $\theta^n_{c.m.}$ = 149.74°, 9.887 mb/sr)
dσ/dΩ (mb/sr)
$\theta^n_{c.m.}$ (deg)



E_n = 44.24 ± 3.59 MeV
(k)
ENDF/B-VIII.0
theory
Brady, 1974, E_n = 46.3 MeV
Romero, 1970, E_n = 46.3 MeV
Present (normalized to the data at $\theta^n_{c.m.}$ = 149.68°, 3.319 mb/sr)
dσ/dΩ (mb/sr)
$\theta^n_{c.m.}$ (deg)

IAEA NEUTRON DATA STANDARDS

#	Reaction	Energy Range
1	H(n,n)	1 keV to 20 MeV
2	^{6}Li(n,t)	1e-5 eV to 4 MeV (Standard range up to 1 MeV)
3	^{10}B(n,α);(n,α$_1$γ)	1e-5 eV to 1 MeV
4	^{nat}C(n,n)	up to 6.45 MeV
5	^{197}Au(n,γ)	2.5 keV to 2.8 MeV
6	^{235}U(n,f)	150 eV to 200 MeV
7	^{238}U(n,f)	0.5 to 200 MeV
8	Thermal Neutron Constants: ^{233}U, ^{235}U, ^{239}Pu, ^{241}Pu, ^{252}Cf	0.0253 eV (2200 m/s)
9	^{197}Au(n,γ)	MACS (30 keV)= 620(11) mb
10	^{235}U(n,f)	Integral from 7.8 eV to 11 eV = 247.5(3.3) b*eV^{3}

2019 05 24 ND2019
with Allan D Carlson

• 标准核反应截面测量数据的质量是核反应实验水平的重要标志

国际专家的评价

国际中子标准截面工作组

A.D.Carlson NIST USA

Haoyu Jiang, et al. **Eur. Phys. J. A** (2021) 57: 6

Recent Work on Neutron Standards

Allan D. Carlson

Presented at

The IAEA Consultancy (Virtual) Meeting on Neutron Data Standards

Oct 12-16, 2020

H(n,n)H Angular Distribution Work at the China Spallation Neutron Source (CSNS) by Jiang et al.江浩雨

- Measurements were made from 10 to 55 degrees (10 angles) in the laboratory system. All angles were measured simultaneously. Uncertainties vary from 1 to 8%.

文章尚未发表，结果已被引用

- The measurements extend from 6 MeV to 52 MeV with 23 energy points. Plans have been made to use multi-wire proportional counters in the E-DE telescopes so it should be possible to obtain data to considerably lower energies (possibly as low as 0.5 MeV). They are also considering measurements at higher energies.

期待向更低能区、更高能区拓展

^{10}B(n,α) and ^{10}B(n,$α_1$) Measurements at CSNS by Jiang et al. 江浩雨

Haoyu Jiang(江浩雨), et al. **Chinese Physics C** 43(12) (2019) 124002

Recent Work on Neutron Standards

Allan D. Carlson

Presented at

The IAEA Consultancy (Virtual) Meeting on Neutron Data Standards

Oct 12-16, 2020

- There are a number of cases where both the ^{10}B(n,$α_1$) and ^{10}B(n,α) differential cross section data are somewhat low compared with the standard. The integrated ^{10}B(n,$α_1$) cross section data are in good agreement with the standard values. The integrated ^{10}B(n,α) cross section data are in largely in good agreement but somewhat low in the several hundred keV energy region compared with the standard.

- This work could provide the data necessary for a smooth transition from the H(n,n) standard to the ^{10}B(n,α) standards with sufficient overlap.

^{6}Li(n,t) Measurements at the CSNS by Bai et al.白怀勇

Huaiyong Bai(白怀勇), et al. **Chinese Physics C** 44 (1) (2020) 014003

Recent Work on Neutron Standards

Allan D. Carlson

Presented at

The IAEA Consultancy (Virtual) Meeting on Neutron Data Standards

Oct 12-16, 2020

The agreement with the standard in many regions is relatively good. More work is planned.

This work could provide the data necessary for a smooth transition from the H(n,n) standard to the ^{6}Li(n,t) standard with sufficient overlap.

^{6}Li(n,t) Measurements at the CSNS by Bai et al.白怀勇

Huaiyong Bai(白怀勇), et al.
Chinese Physics C 44 (1) (2020) 014003

Recent LANL Work on Reactions in the ^{7}Li System

LA-UR-20-28120

Los Alamos NATIONAL LABORATORY EST.1943

Gerry Hale and Mark Paris
12 October 2020

- A large data set added was the recent measurement by Bai et al. of the differential cross section for the ^{6}Li(n,t)^{4}He reaction at energies up to 3 MeV.

- The data for most reactions are fit well, including the extensive new CSNS data set of Bai et al., which may be overall the most complete, and best-quality, set of relative differential cross sections for the ^{6}Li(n,t)^{4}He reaction that presently exists at energies below 3 MeV.

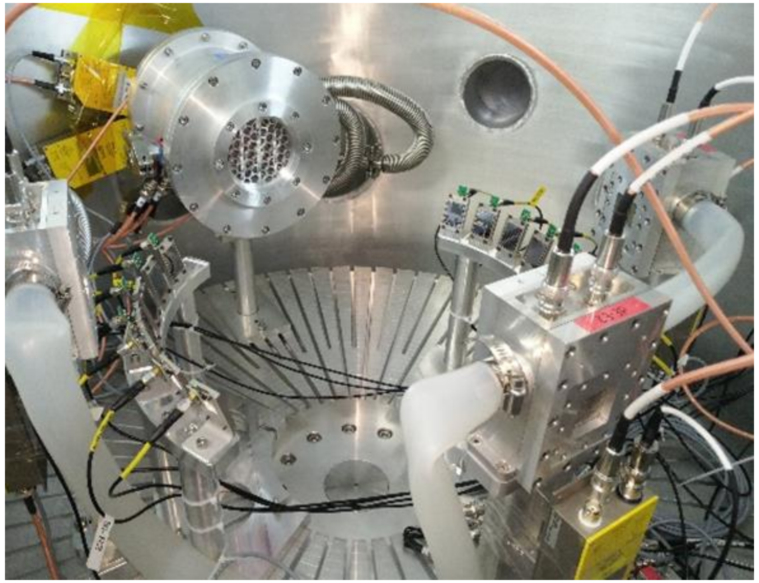
2. 本年度主要进展

两条线索 (详见易晗的报告)

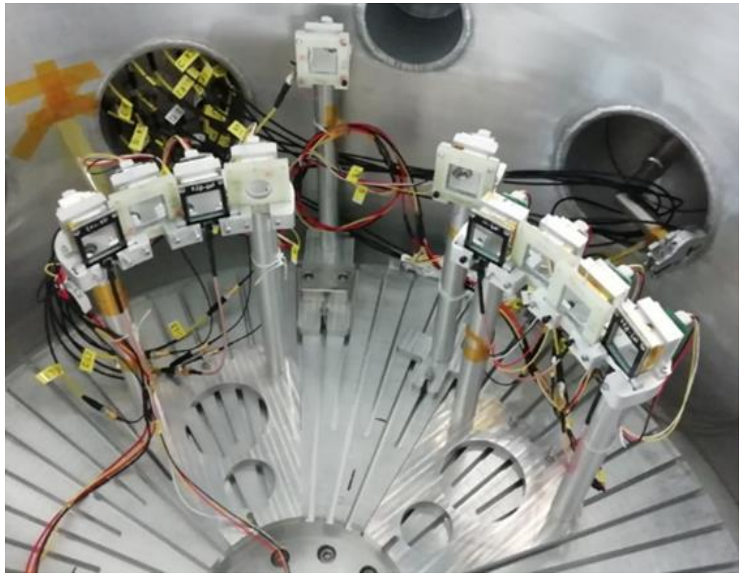
- LPDA探测系统
- TPC探测器

第3组分组报告1
易晗: “2020-2021白光中子源带电粒子实验研究进展”

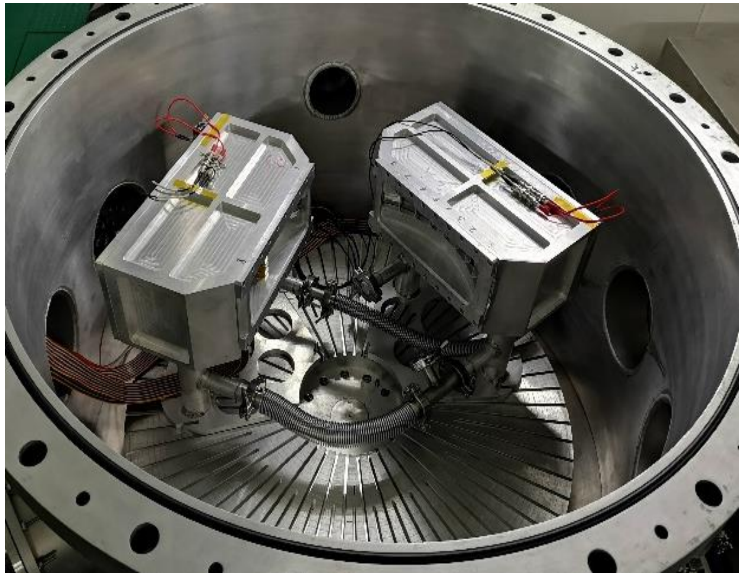
LPDA进展



LPDA-v1
(16*Si)



LPDA-v2
10*Si+CsI

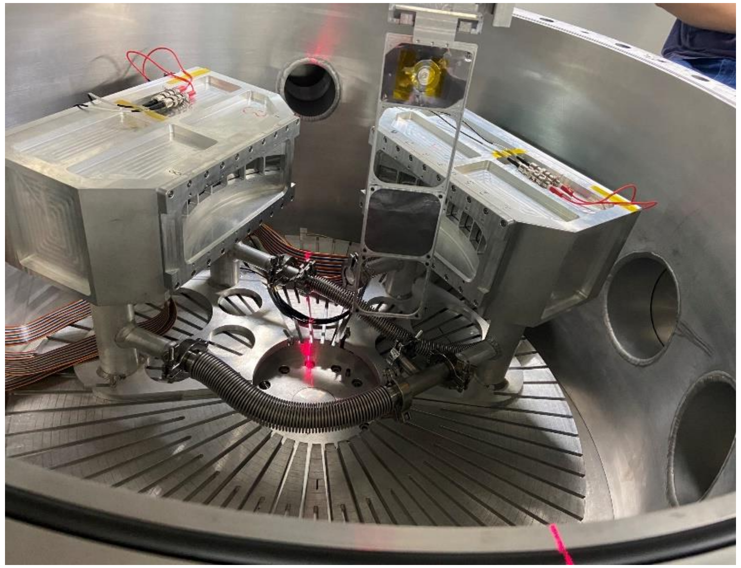


LPDA-v3
16* MWPC+Si+CsI

详见孙康报告：白光中子源LPDA谱仪设计与束流结果

LPDA进展

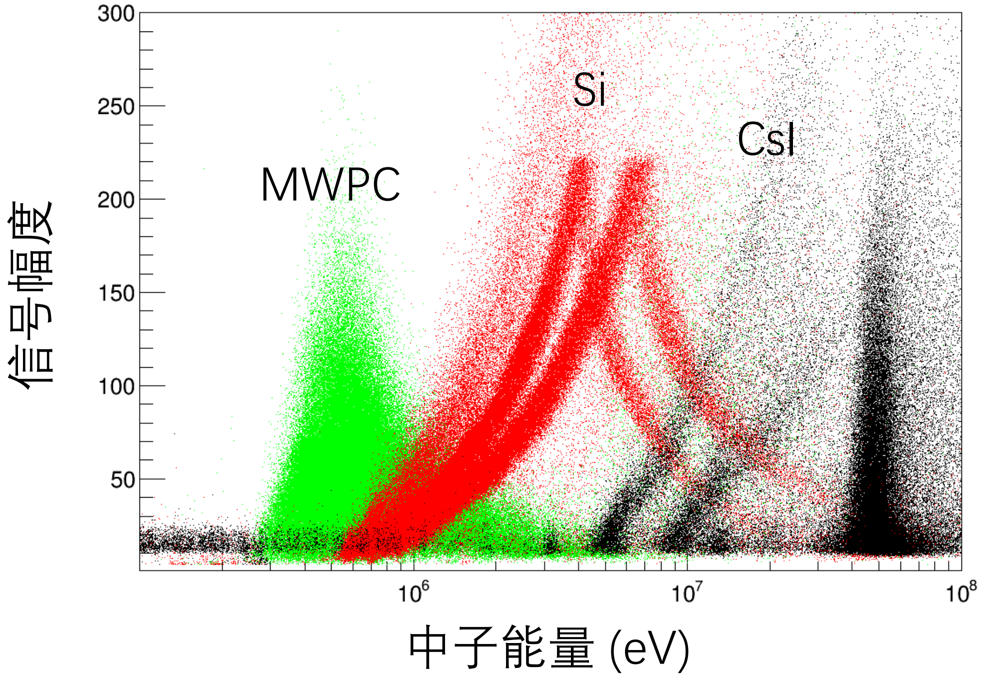
- LPDA探测系统2020年11月通过验收各项指标合格



A套8号望远镜3个探测器

HV=730V C_3H_6样品

三级探测器信号



LPDA主要设计参数和考核指标

参数	设计指标	考核指标	测试/认定方式	测试/认定结果
探测单元数量	16	16	1	16
探测器覆盖能区（质子）	0.5-100 MeV	0.5-100 MeV	2	0.5-100 MeV
探测效率或覆盖立体角	1.7%（0.216 sr）	1.7%（0.216 sr）	3	1.74%（0.22 sr）
探测器粒子分辨	氢、氦、锂等	氢、氦、锂等	2	^{1}H、^{3}H、^{4}He、^{7}Li 分辨

LPDA探测器有关文章

1. Wei Jiang et al, Application of a silicon detector array in (n, lcp) reaction cross-section measurements at the CSNS Back-n white neutron source, Nuclear Inst. and Methods in Physics Research, A 973 (2020) 164126
2. Ruirui Fan et al, Detection of low-energy charged-particle using the ΔE-E telescope at the Back-n white neutron source, Nuclear Inst. and Methods in Physics Research, A 981 (2020) 164343
3. 蒋伟 江浩雨 易晗 樊瑞睿* 等，基于反角白光中子源次级质子的探测器标定[J]，物理学报. 2021, 70(8): 082901.
4. Y. Wang, Z. Sun, X. Wang, H. Yi, W. Jiang, R. Fan(*), et al, Characterization of low-pressure MWPC from 1E3 to 1E5 Pa, 2021 JINST 16 T04003

LPDA进展

- 基于LPDA开展了实验
  - 蒋伟: 低能n-p散射实验

    探索: 束斑问题 气体探测器问题 电子学问题
  - **刘龙祥：$n+^{12}C$核反应实验研究**
  - **李云居：$^{17}O(n,\alpha)$实验研究($W^{17}O_3$样品，LPDA靶室，SiC探测器)**

    详见刘龙祥、李云居的报告

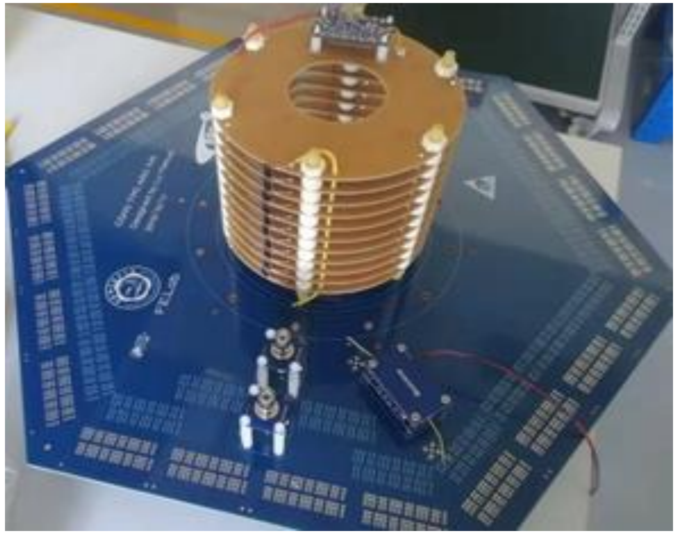
TPC进展

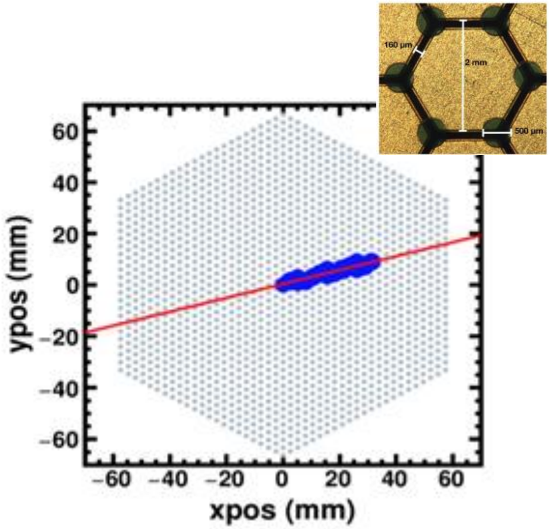
- **完成样机:**

  硬件1519阳极pad

  软件(分析模拟)

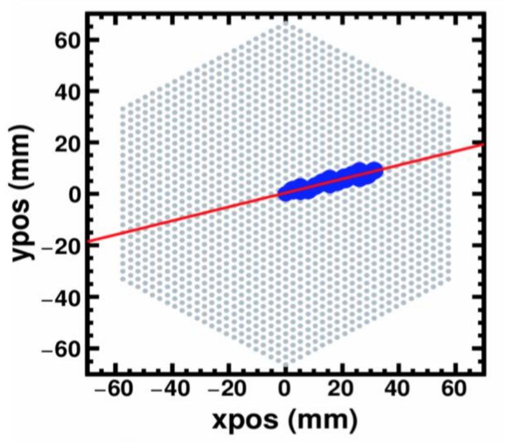
  电子学

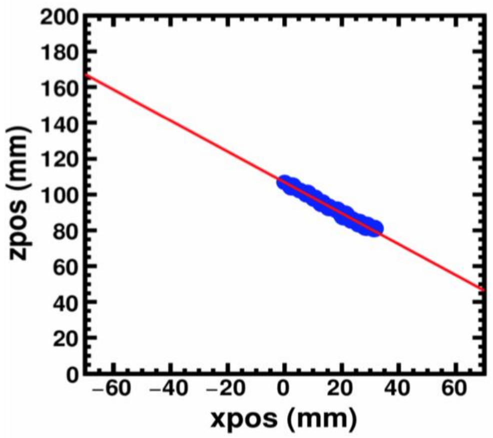


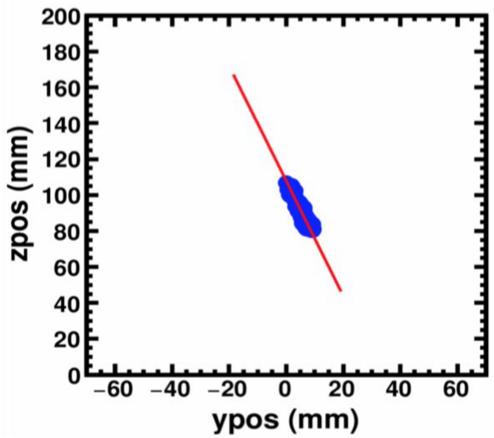


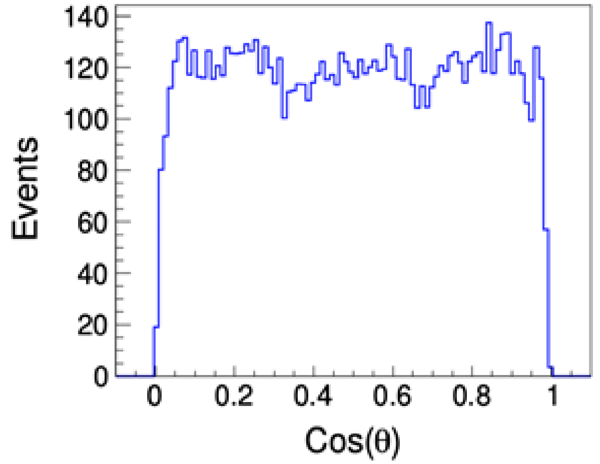
- **α源测试:** 工作电压 增益均匀性 验证各向同性 求电子漂移速率 (详见白浩帆的分组报告)
- **北大单能源测试:** 典型测量事件 模拟分析 (详见孙艳坤的报告)
- **白光源测试:** $^{14}N(n,p)$反应 TOF确定中子能量 (详见易晗的报告)
- 今后改进: 改变工作气压, 增阳极pad数, 背对背双TPC

4能量α源模拟计算 (详见孙艳坤的报告)

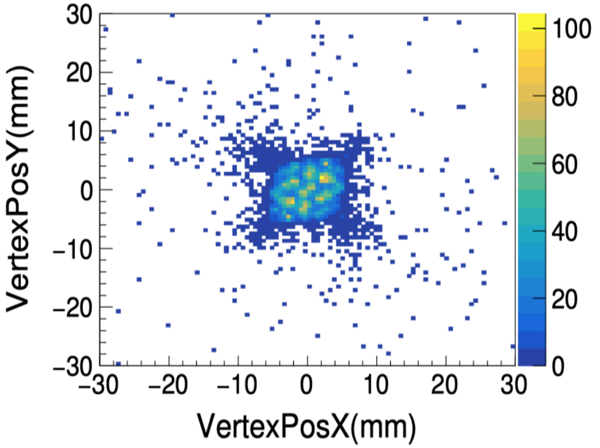


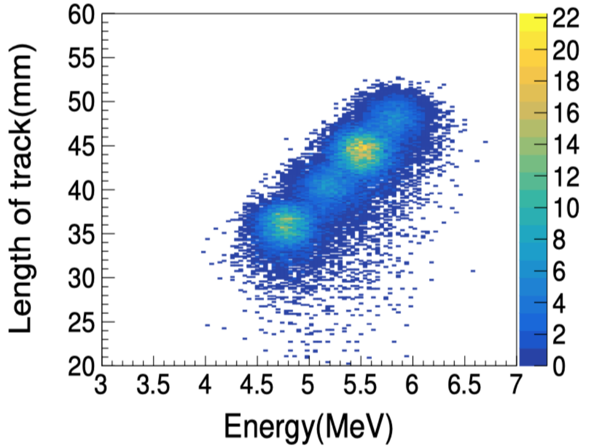


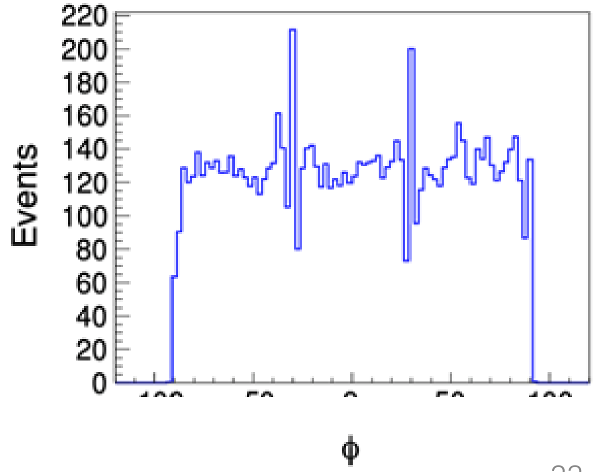




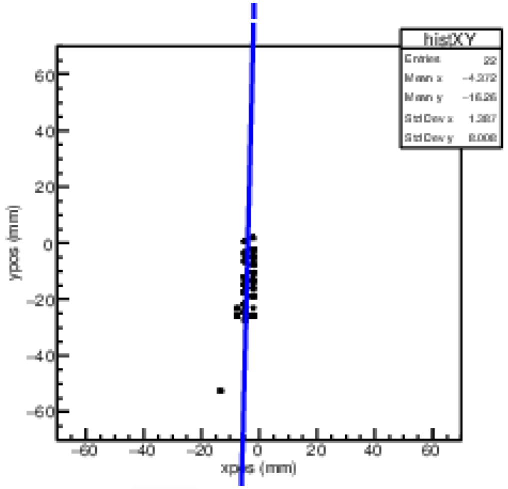
4能量混合α源

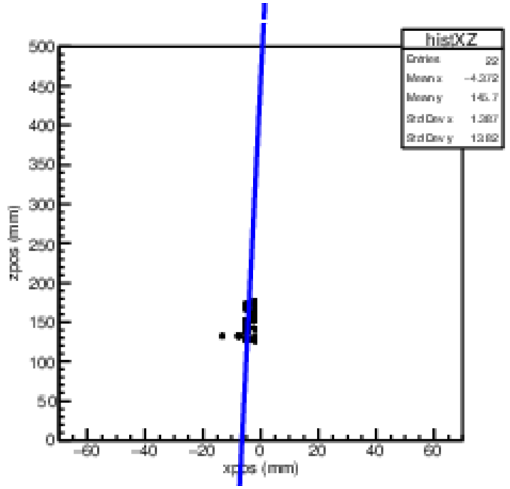


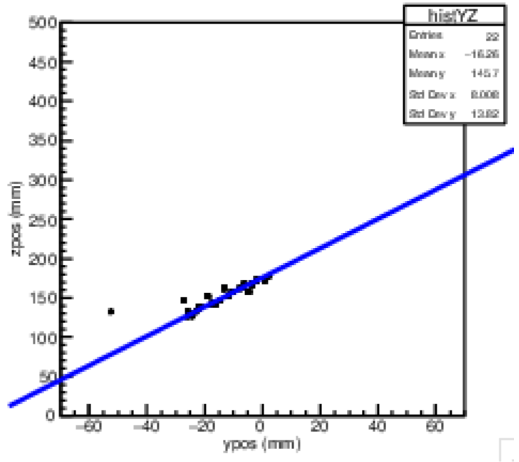


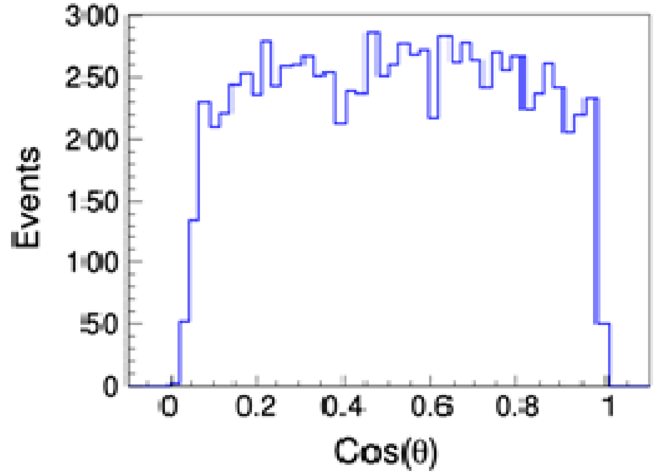


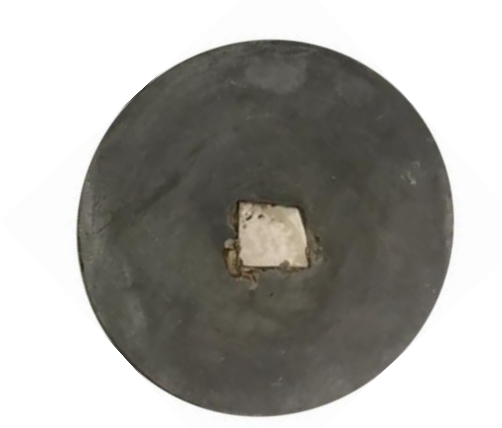
4能量α源实验测量数据分析



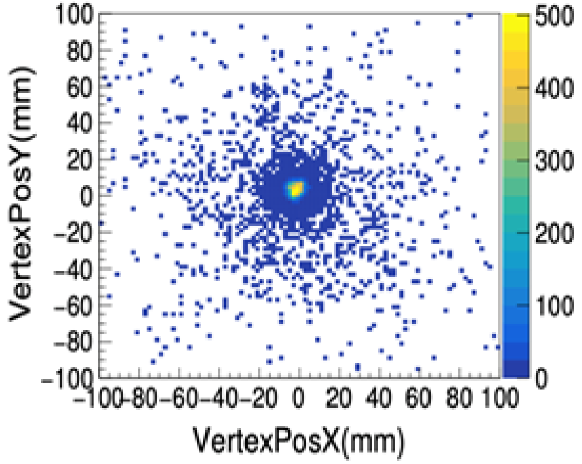


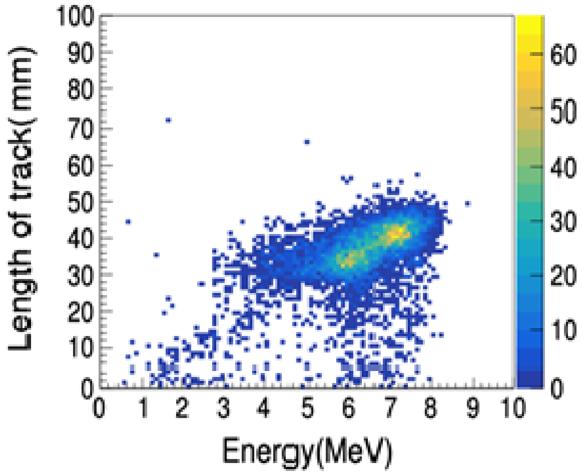


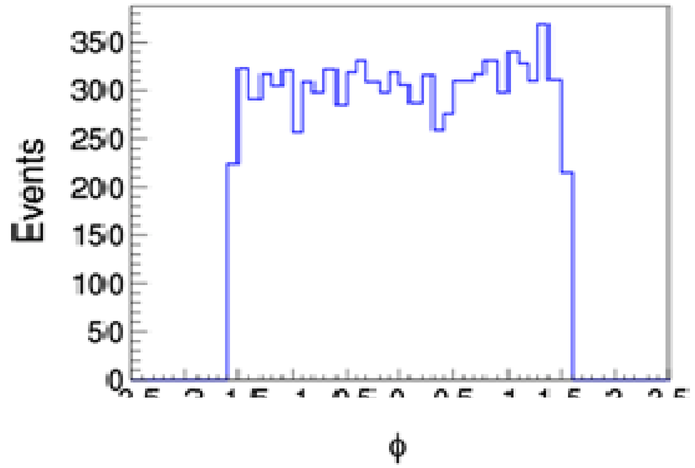




4能量混合α源

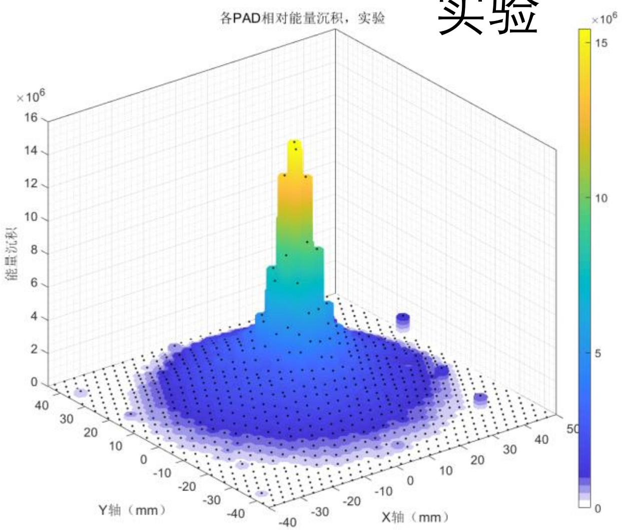






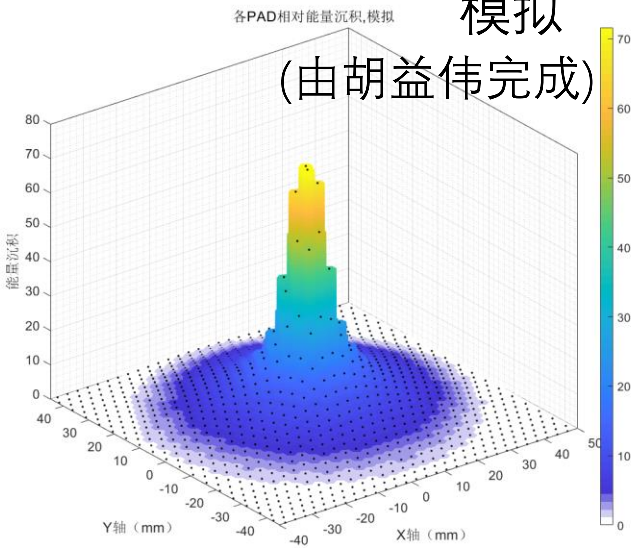
4能量α源测量及模拟--增益均匀性

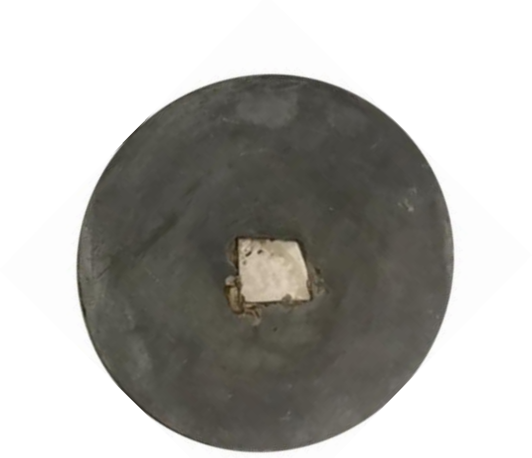
实验



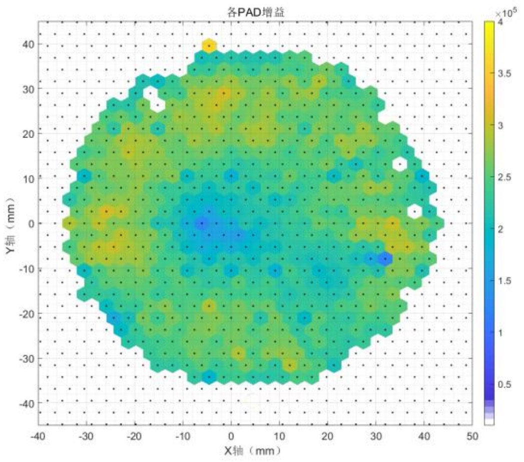
模拟

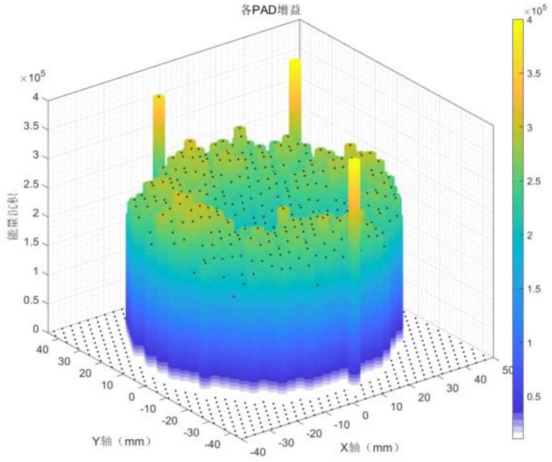
(由胡益伟完成)

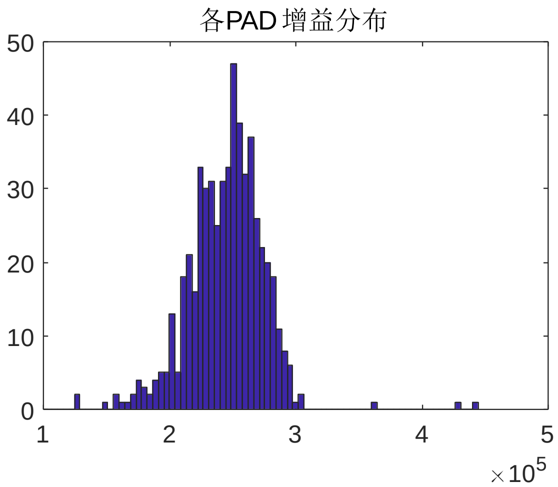




4能量混合α源

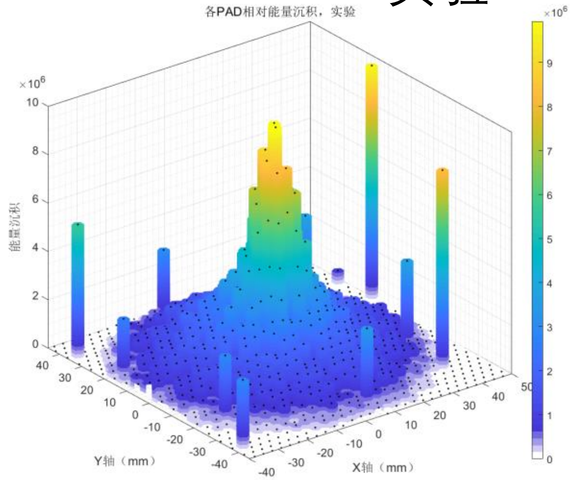




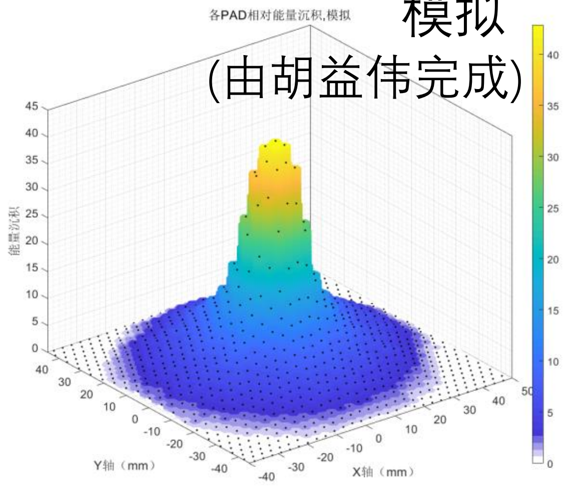


单能α源测量及模拟--增益均匀性

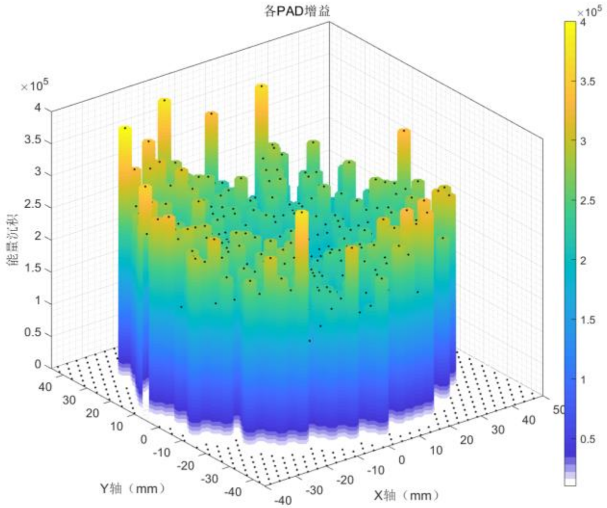
实验

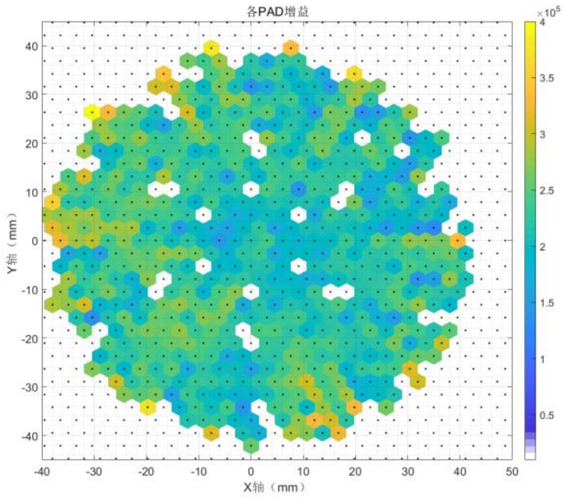


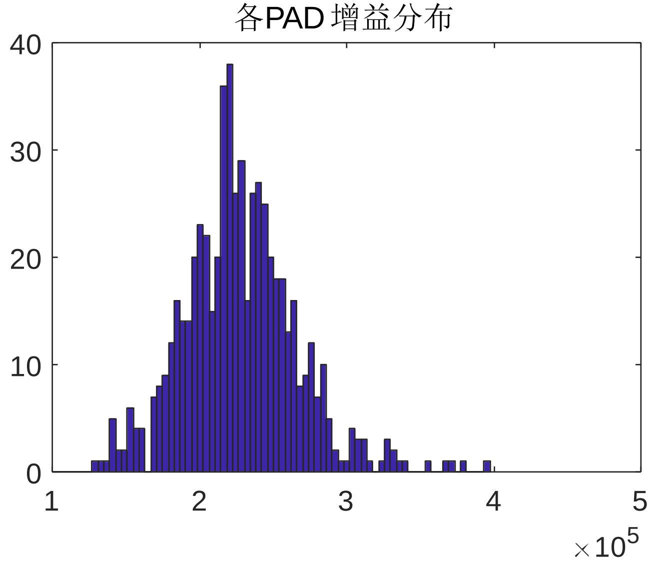
模拟
(由胡益伟完成)



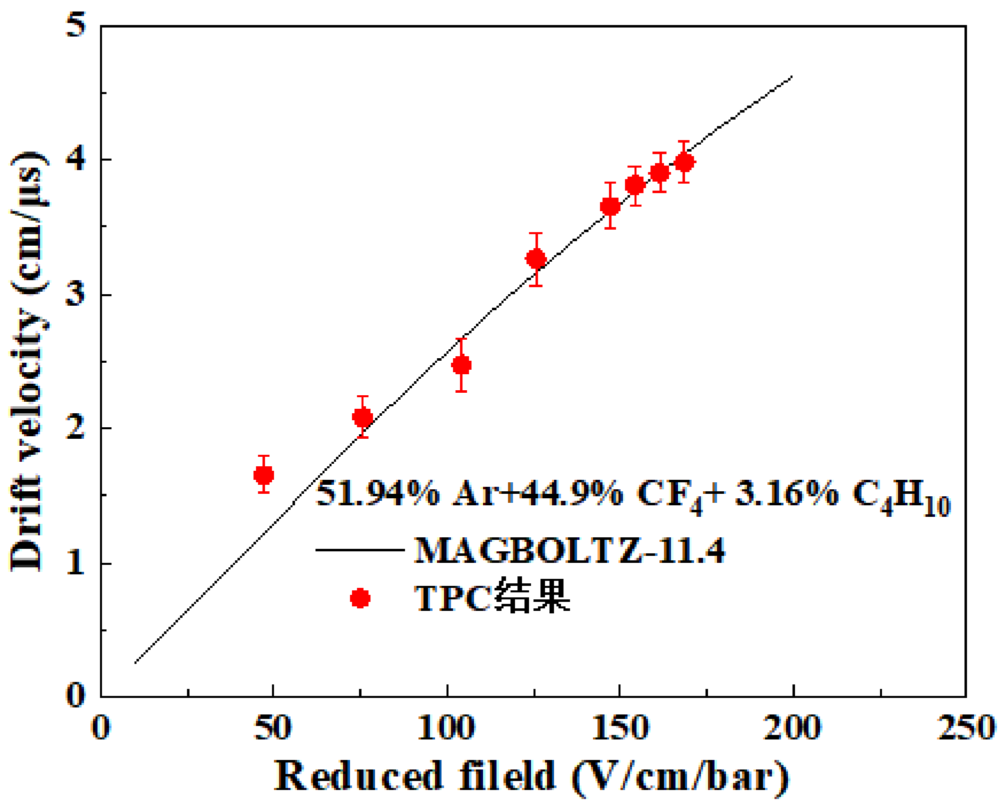
^{241}Am α源

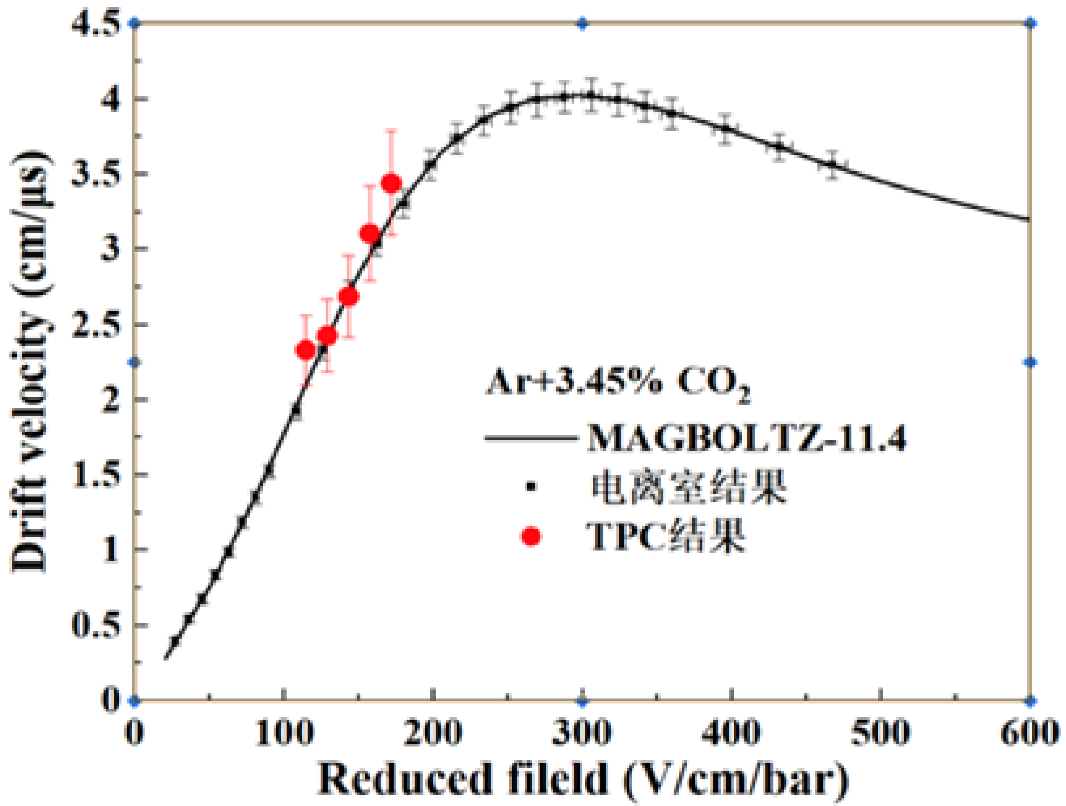






用TPC测量电子的漂移速率



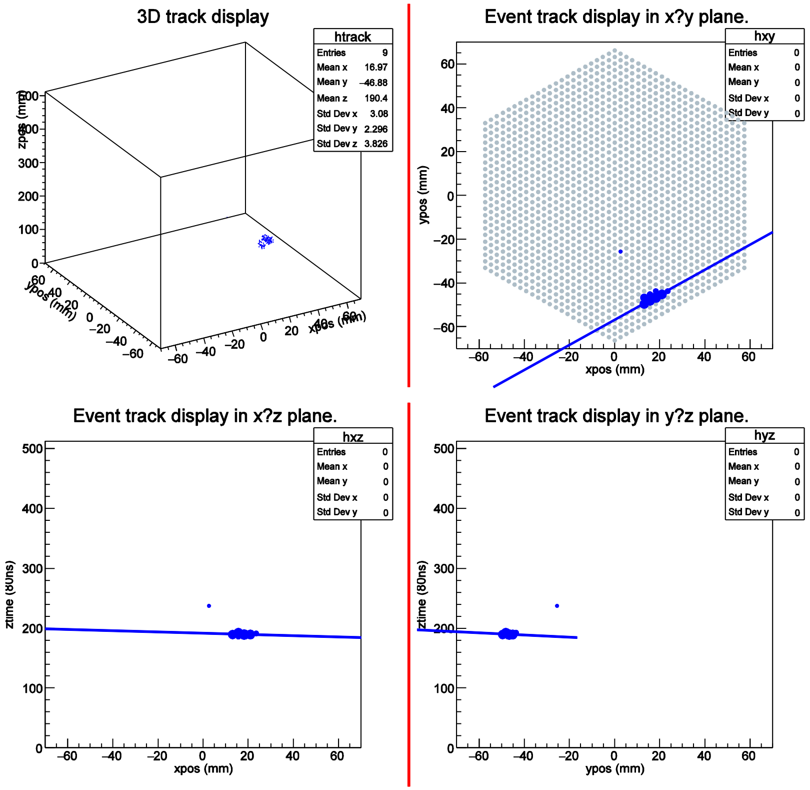


Jie Liu, et al., Improved method to measure the electron drift velocity using the Frisch-grid ionization chamber, **Nucl. Instrum. Methods Phys. Res. A** 1004 (2021) 165363

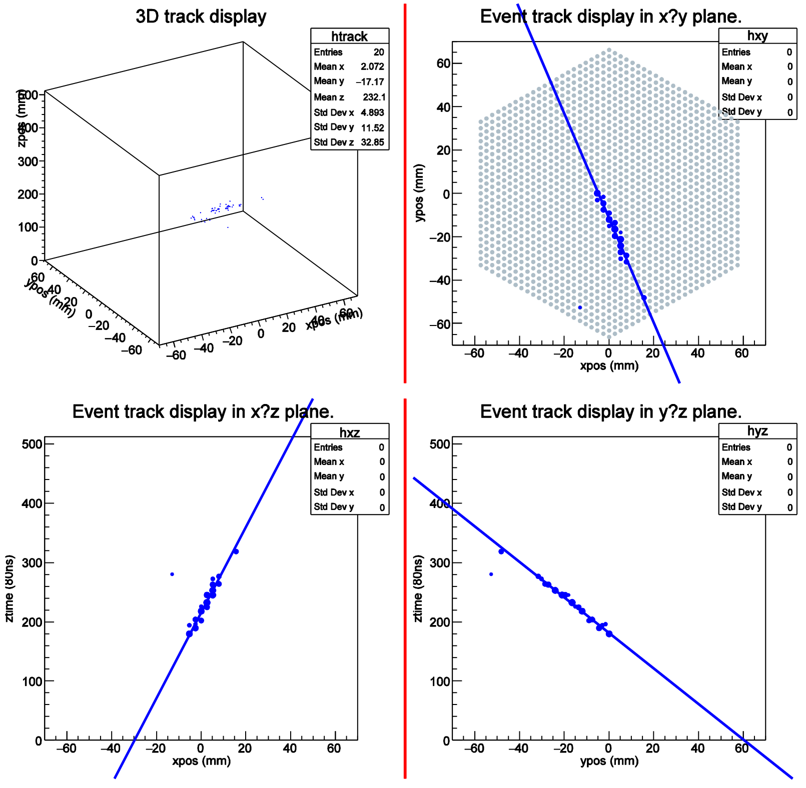
利用北大单能源进行测试 2021 05

利用北大单能源进行测试

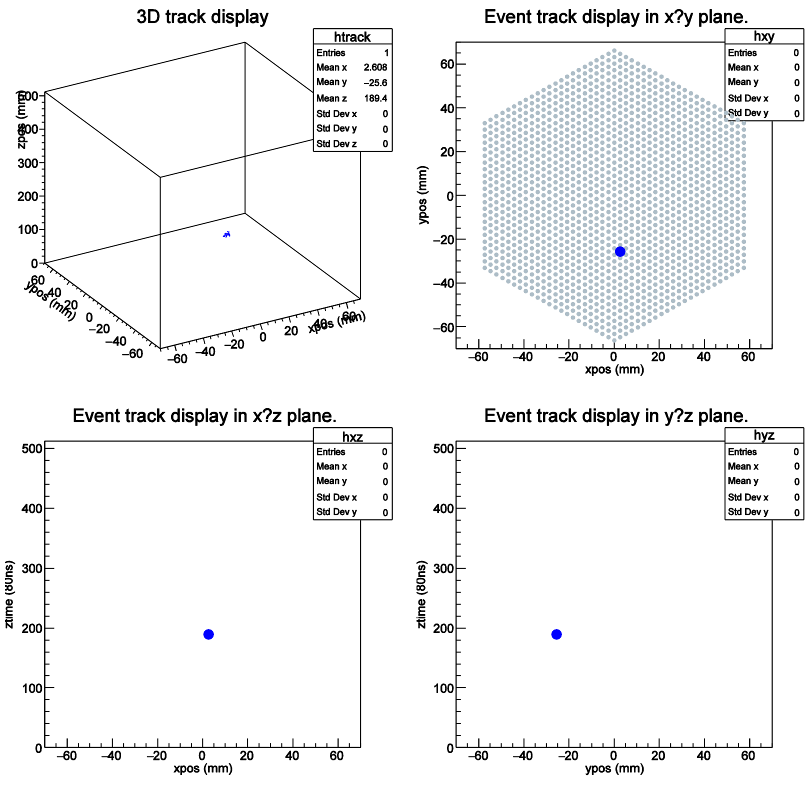
$^{19}F(n,\alpha)$事例



$^{36}Ar(n,\alpha)$事例

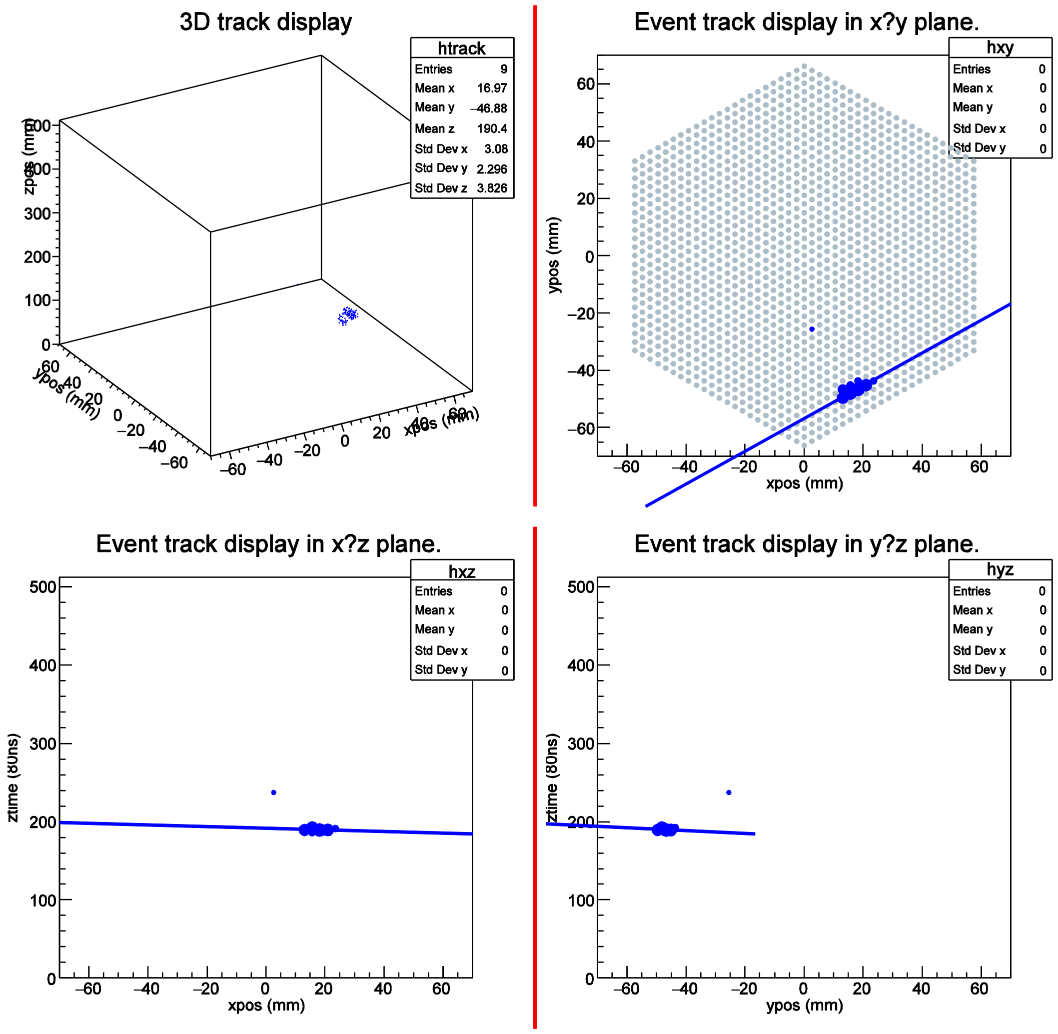


反冲核事例

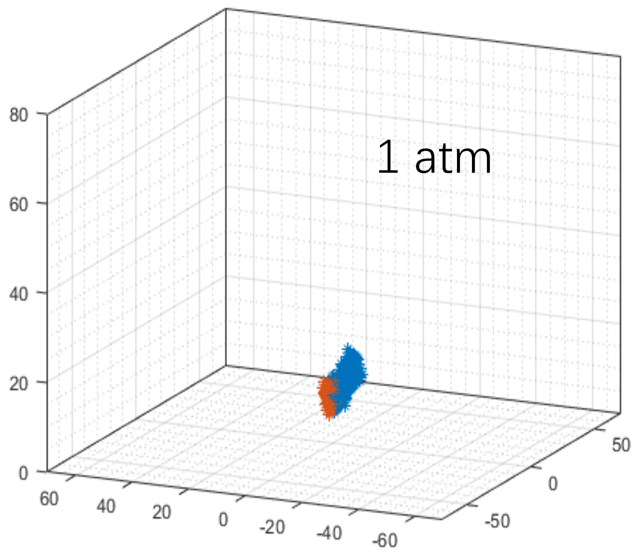


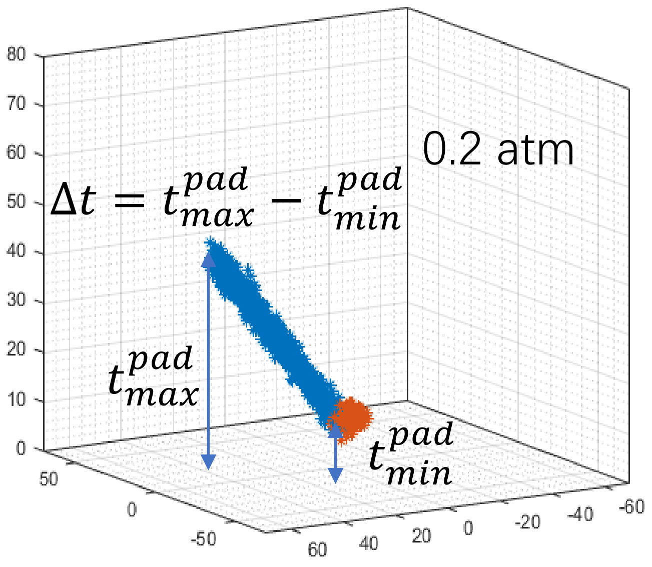
Ar(51.94%)+CF_4(44.90%)+C_4H_{10}(3.16%)混合气体作为工作气体 E_n= 4.5 MeV

$^{19}F(n,\alpha)^{16}N$测量事例



$^{19}F(n,\alpha)^{16}N$模拟事例



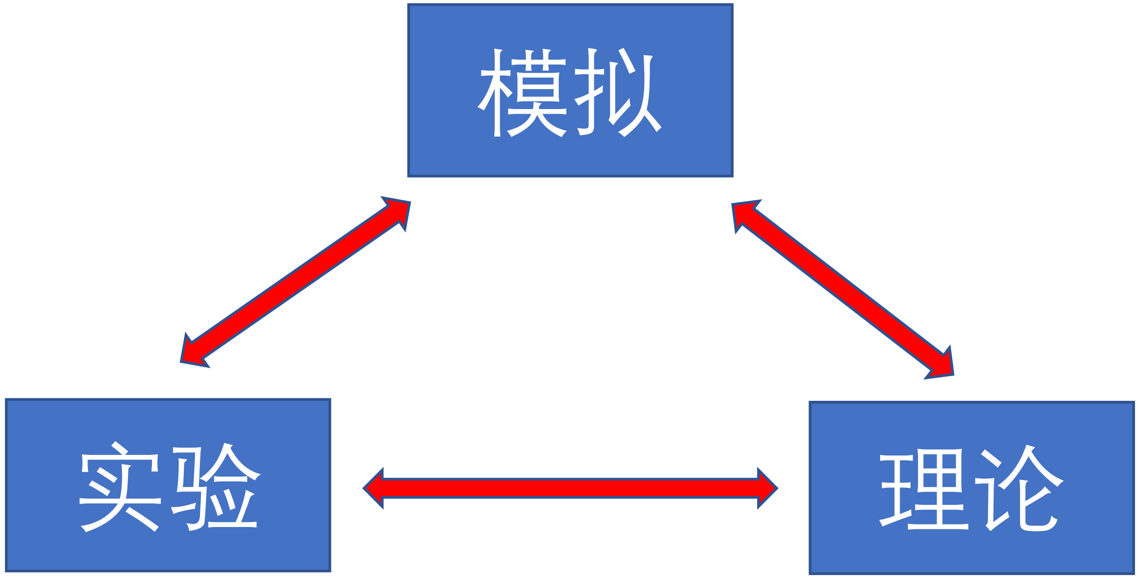


径迹短 见不到反冲核(蝌蚪头)
是因为1 atm工作气压较高

0.2 atm理想工作气压

3. 一点体会

模拟计算在核反应实验中的作用



- 有机结合 三位一体
- 充分利用所有可以得到的信息：已有实验 评价库 理论 模拟
- 利用所有可用的手段：计算机 大数据 人工智能 …

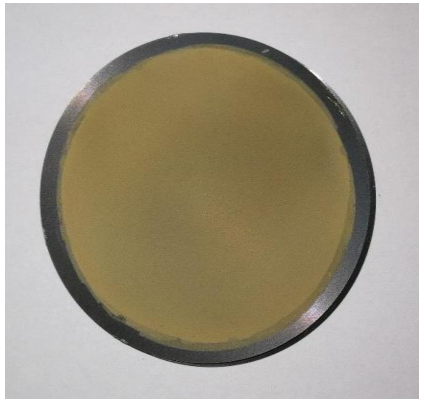
模拟计算在核反应实验中的作用

- **模拟计算与实验测量互相印证**
- “**实验为主 模拟先行**”
  - 实验前　获得最佳实验条件 确定详细实验方案
  - 实验中　发现探测器与电子学问题 发现原来没有考虑到的因素
  - 实验后　实验数据处理 探测器效率修正 其他修正

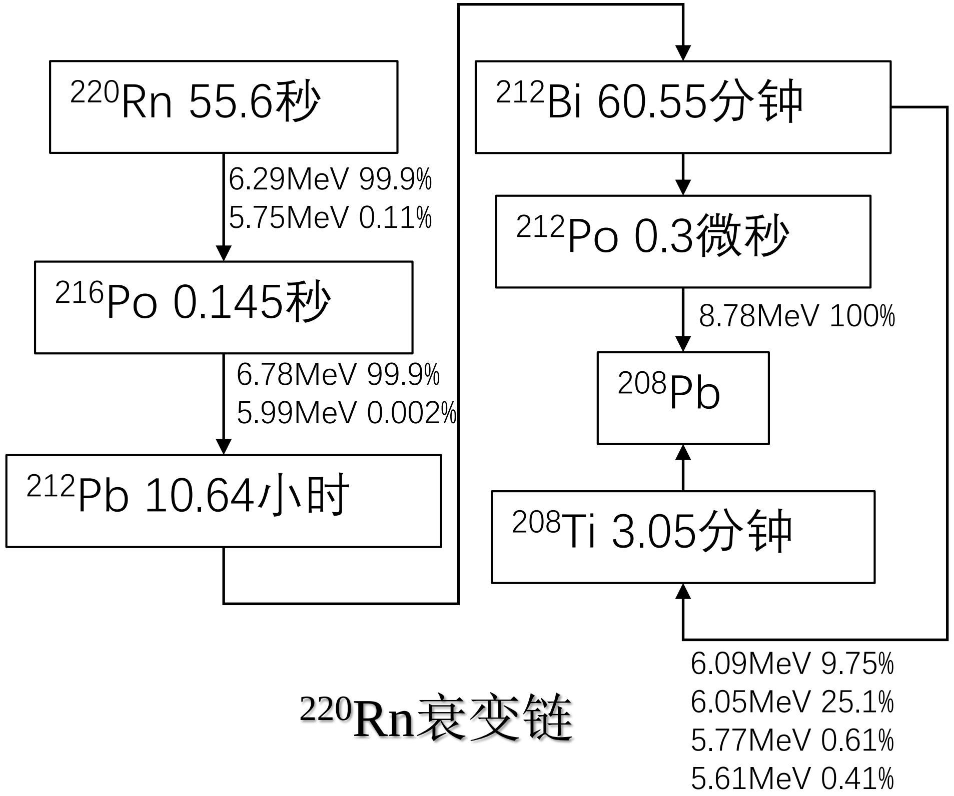
模拟计算与实验测量互相印证--实例

用屏栅电离室测量气体α源及其模拟

带样品转换器的屏栅电离室



$^{232}Th(OH)_4$样品 (从换样器缝隙得到气体^{220}Rn)

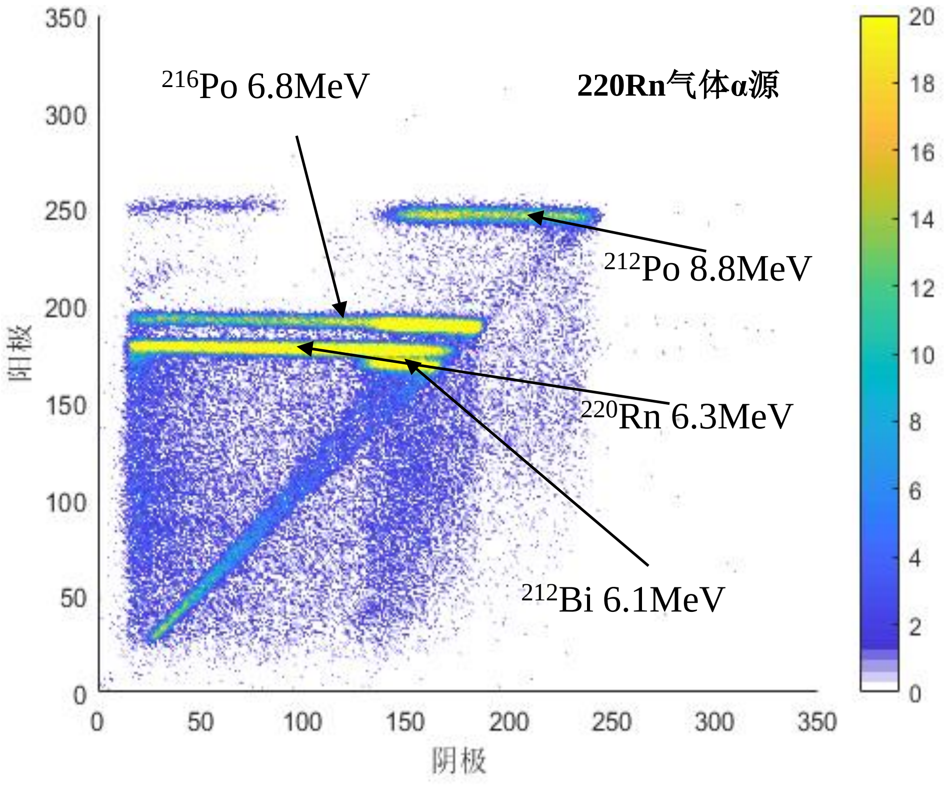


^{220}Rn衰变链

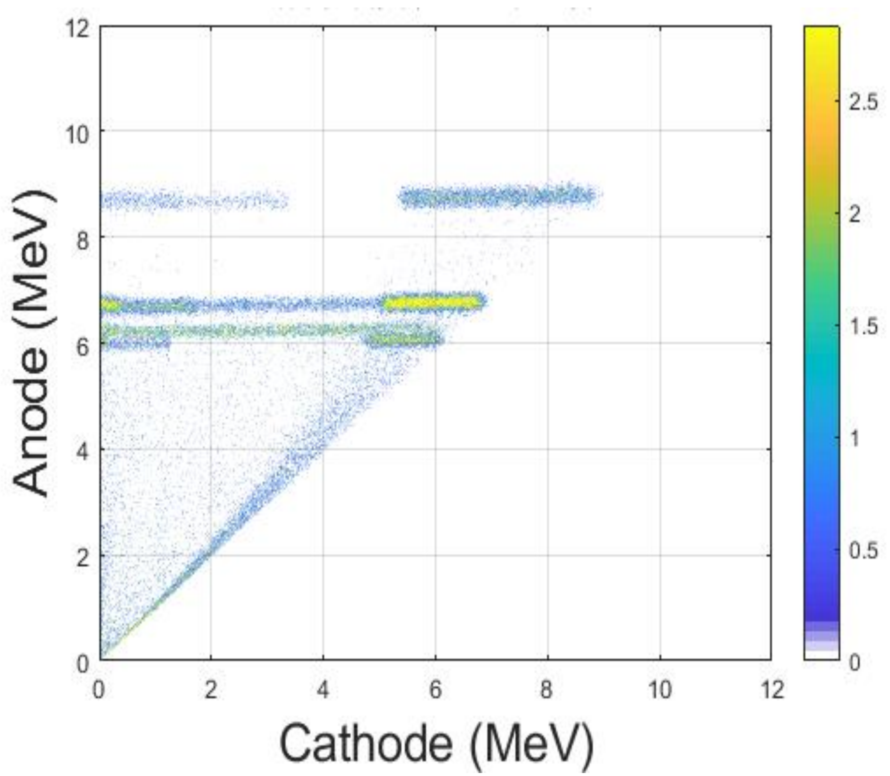
模拟计算与实验测量互相印证--实例

用屏栅电离室测量气体α源及其模拟

实验测量



模拟计算



4. 近期实验计划

2.5个实验 束流申请

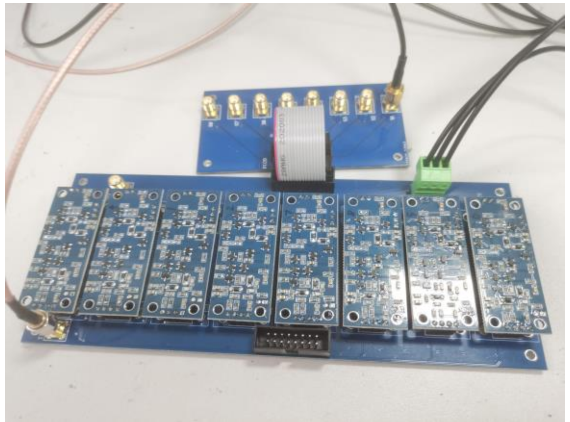
- **樊瑞睿：1.5-10 MeV n-p散射微分截面测量**
- **易晗：基于TPC的$^{14}N/^{6}Li$中子反应截面测量**
- **陈永浩：相对n-p散射的$^{235}U/^{238}U$裂变截面测量**

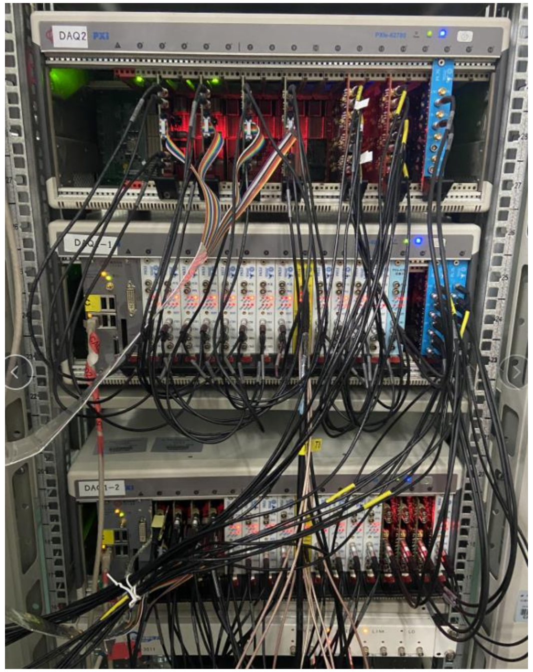
实验难度增加 需要更长的束流时间

详见樊瑞睿、易晗、陈永浩束流申请报告

1.5-10 MeV n-p散射微分截面测量-樊瑞睿

- 完善实验条件 (基于LPDA)
  - 小束斑
  - 完善气路
  - 完善电子学
- 预计束流时间 450小时
  - 8月电子学测试
  - 9月探测器隧道测试
  - 10月开展实验





基于TPC的^{14}N/^{6}Li中子反应截面测量-易晗

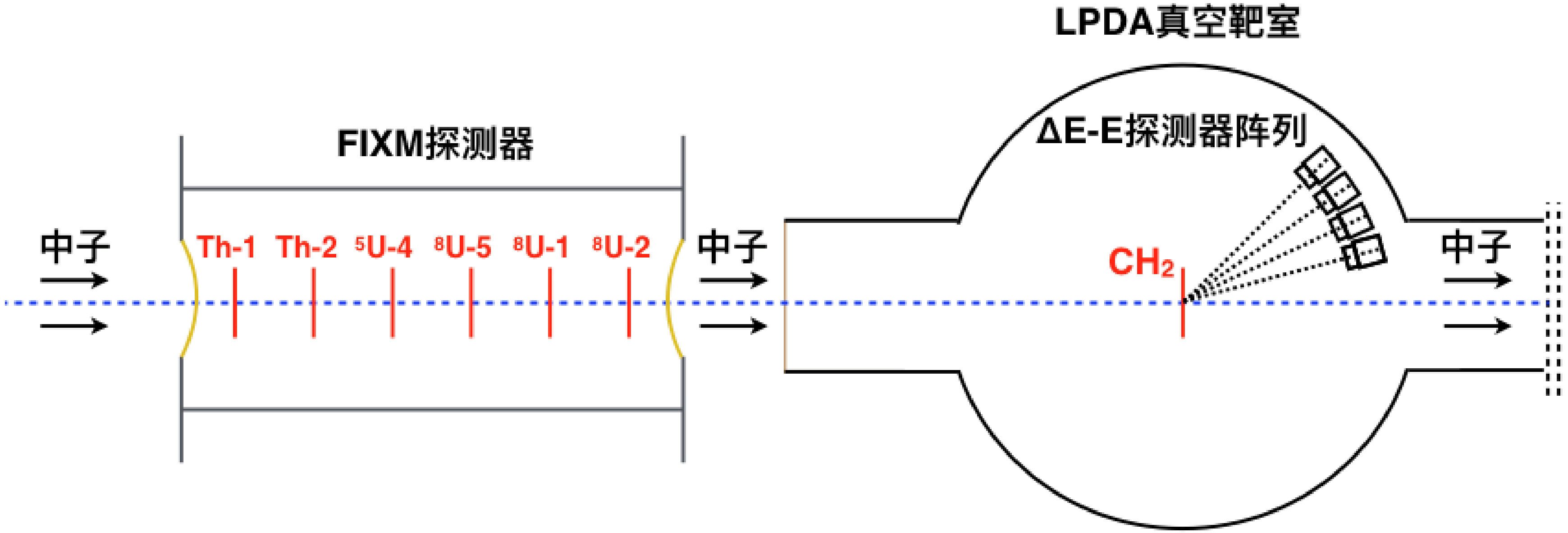
- 以^{6}Li为标准截面进行1MeV以下^{14}N(n,p)^{14}C截面测量
- 0.1MeV以下能区测截面和对角度的微分截面
  0.1MeV~1MeV能区测量截面

- **预计束流时间370小时**

- 2020年底用TPC进行了^{14}N(n,p)测试;
- 得到了^{14}N(n,p)反应事例，径迹可以甄别，
  验证了TPC装置测量该反应的可行性
- TPC与电子学已用白光束流进行了联合测试
  TPC具备粒子径迹测量能力、粒子鉴别能力和TOF测量能力

相对n-p散射的^{235}U/^{238}U裂变截面测量-陈永浩

- 在1-100MeV能区测量^{235}U、^{238}U裂变截面



2021下半年拟开展实验 预计束流时间：400小时

机时分配：

- ΔE-E 探测器： PE膜 (200小时) + 纯碳膜 (150小时) + 空靶 (50小时)
- FIXM探测器： 400小时

展望

- **有机结合**

  - **实验** 实验难度增加 探索性与挑战性 需要更长的束流时间
  - **理论** 不断提高理论水平 基于物理目标开发探测器 向理论家学习
  - **模拟** 充分认识与发挥模拟计算在核反应实验测量中的重要作用

- **加强合作**

  国际-国内合作 老-中-青合作 研究所-高校合作 实验-理论合作

总结

本报告介绍了带电粒子出射核反应方向

- **一年来取得的主要成果** 受到国际专家的重视与认可
- **一年来的主要研究进展** LPDA 和 TPC 两条线索
- **一点体会** 模拟计算在核反应实验测量中的作用非常重要
- **研究计划与展望** 实验难度增加 需要更长的束流时间 前途光明

- **感谢LPDA团队全体成员的大力协作与不懈努力！**
- **感谢各位专家的指导、帮助、建议与支持！**

第3分会场报告安排

内容涉及本年度总体实验进展，实验测量数据分析，探测系统设计与探测器测试等

1) 易晗：2020-2021白光中子源带电粒子实验研究进展
2) 孙康：白光中子源LPDA谱仪设计与束流结果
3) 孙艳坤：白光中子源多用途TPC测试与实验
4) 白浩帆：TPC测量α源初步结果
5) 李云居：基于散裂中子源的$^{17}O(n,\alpha)$实验研究
6) 刘龙祥：$n+^{12}C$核反应实验研究

第一个报告15分钟，其他报告各约10分钟，加上讨论共~1.5小时

(n,lcp)反应研究的意义

- 中子核反应标准的完善
- 中子探测器的研发、标定、模拟计算
- 中子的防护设计 宇航员防护 辐射生物学
- 材料辐射损伤计算 核燃料与核材料开发
- 核能与核工程应用 造氚反应(聚变) 癌症治疗 单粒子效应
- 基础核物理研究 核天体物理与核素合成