第三届“粤港澳”核物理会议

alpha decay and cluster radioactivity in extreme laser fields

汇报人：王慧
指导老师：苏军

2024.11.18

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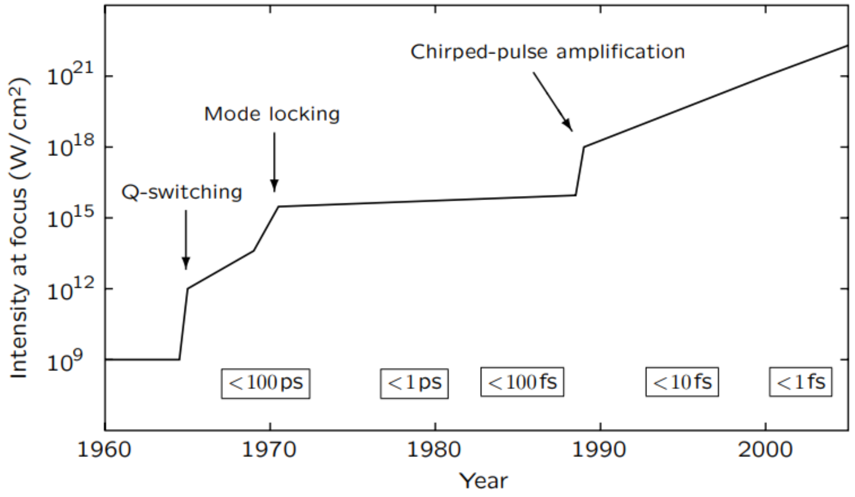
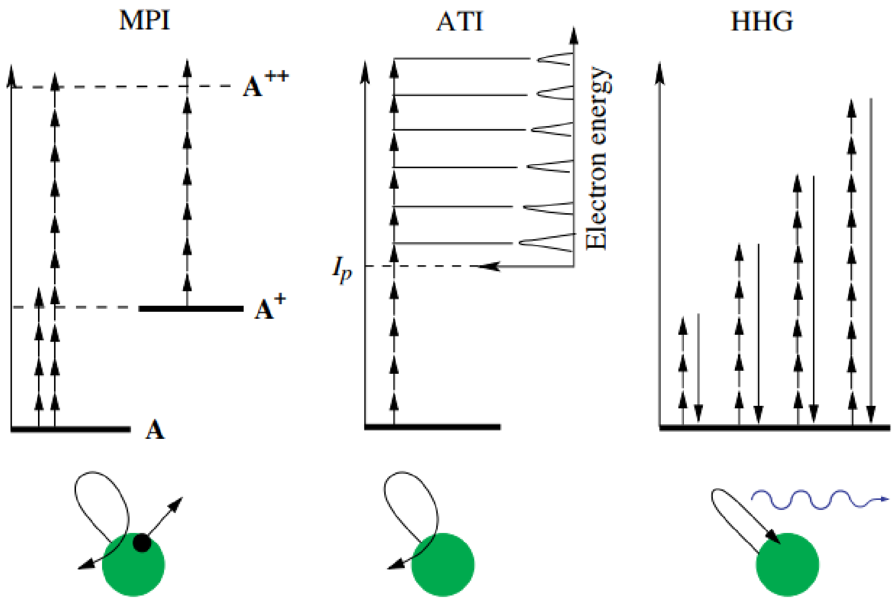
研究背景与现状

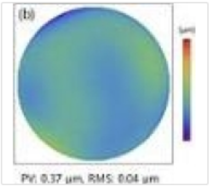
激光





Only 10 months

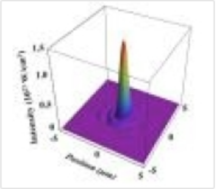
Optics Express Vol. 27, Issue 15, pp. 20412-20420 (2019) • https://doi.org/10.1364/OE.27.020412



Achieving the laser intensity of 5.5×10^{22} W/cm^2 with a wavefront-corrected multi-PW laser

Jin Woo Yoon, Cheonha Jeon, Junghoon Shin, Seong Ku Lee, Hwang Woon Lee, Il Woo Choi, Hyung Taek Kim, Jae Hee Sung, and Chang Hee Nam

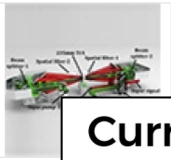
Optica Vol. 8, Issue 5, pp. 630-635 (2021) • https://doi.org/10.1364/OPTICA.420520



Realization of laser intensity over 10^{23} W/cm^2

Jin Woo Yoon, Yeong Gyu Kim, Il Woo Choi, Jae Hee Sung, Hwang Woon Lee, Seong Ku Lee, and Chang Hee Nam

Author Information ▾ Find other works by these authors ▾



339 J high-energy Ti:sapphire chirped-pulse amplifier for 10 PW laser facility

Current status and highlights of the ELI-NP research program

Cite as: Matt
Submitted:
Published O

K. A. Tanaka
M. Cuciuc,
D. G. Ghita,
D. Stutman
and N. V. Za

Eur. Phys. J. Special Topics **223**, 1105–1112 (2014)
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DOI: 10.1140/epjst/e2014-02161-7

THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

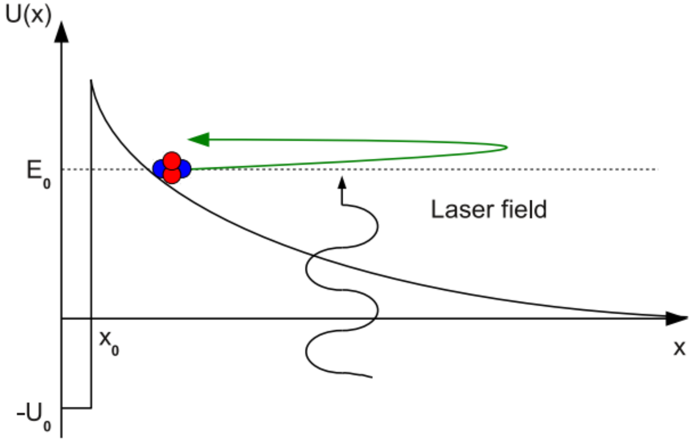
Review

New horizons for extreme light physics with mega-science project XCELS

A.V. Bashinov[1,2], A.A. Gonoskov[1,2,3], A.V. Kim[1,2], G. Mourou[2,4], and A.M. Sergeev[1,2,a]

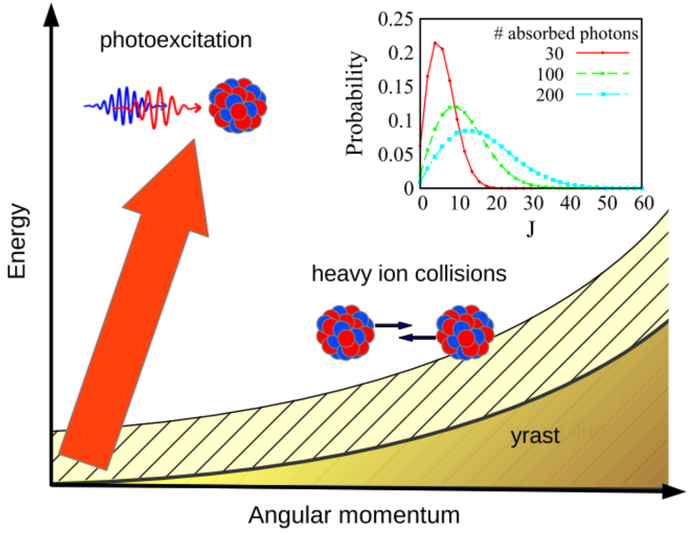
研究背景与现状

- 诱发核反弹



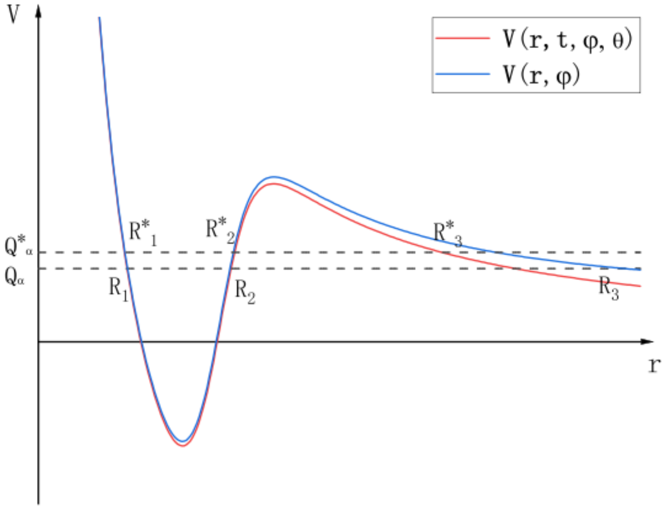
Cortés H M C, Müller C, Keitel C H, et al. Physics Letters B, 2013, 723(4-5): 401-405.

- 激发原子核



Pálffy A, Weidenmüller H A. Physical Review Letters, 2014, 112(19): 192502.

- 影响衰变、裂变、熔合



Delion D S, Ghinescu S A. Physical Review Letters, 2017, 119(20): 202501.

Bai D, Deng D, Ren Z. Nuclear Physics A, 2018, 976: 23-32.

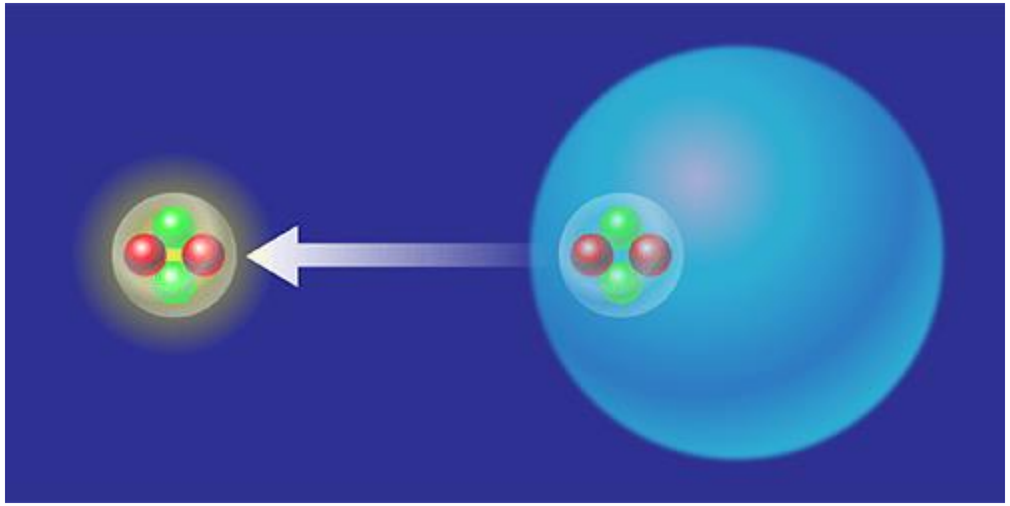
Qi J, Li T, Xu R, et al. Physical Review C, 2019, 99(4): 044610.

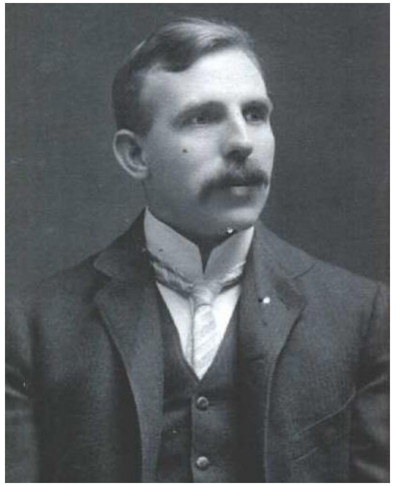
Pálffy A, Popruzhenko S V. Physical Review Letters, 2020, 124(21): 212505.

Cheng J H, Zhang W Y, Xiao Q, et al. Physics Letters B, 2024, 848: 138322.

研究背景与现状

对原子核α衰变认识的发展





Ernest Rutherford

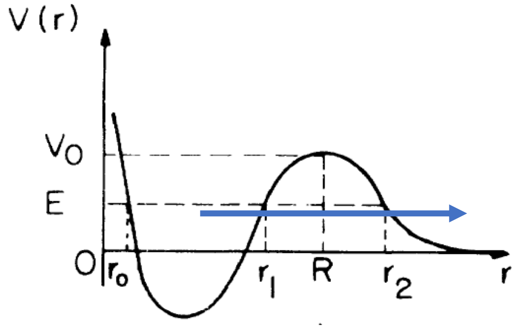
Frederic Soddy

trifuges). In one attempt, Rutherford [3] actually used a bomb to produce temperatures of 2,500°C and pressures of 1,000 bar albeit for a short period of time. No effect on the decay constant was detected.

E. Rutherford, J.E. Petavel: Br. Assoc. Advan. Sci. Rep. A 456 (1906)

the case. The fractional change in the decay constant is $\delta k/k \approx 10^{-8}$ per bar. At pressures of 100 kbar, which can be relatively easily produced in laboratory conditions, $\delta k/k = 10^{-3}$ and the change in the decay constant is still small. Extrapolation to very high pressures would give $\delta k/k \approx 10$ at 1 Gbar

H. Mazaki: J. Phys. E, Sci. Instrum. 11, 739–741 (1978) 7. K. Ader, G. Bauer, V. Raff: Helv. Phys. Acta 44, 514 (1971)



量子隧穿

Gurvitz S A, Kalbermann G. Physical review letters, 1987, 59(3): 262.

激光对α衰变的影响

PRL **119,** 202501 (2017) PHYSICAL REVIEW LETTERS week ending 17 NOVEMBER 2017

Geiger-Nuttall Law for Nuclei in Strong Electromagnetic Fields

D. S. Delion[1,2,3] and S. A. Ghinescu[1,4]
[1]"Horia Hulubei" National Institute of Physics and Nuclear Engineering, 30 Reactorului, POB MG-6, RO-077125 Bucharest-Măgurele, Romania
[2]Academy of Romanian Scientists, 54 Splaiul Independenţei, RO-050085 Bucharest, Romania
[3]Bioterra University, 81 Gârlei, RO-013724 Bucharest, Romania
[4]Department of Physics, University of Bucharest, 405 Atomiştilor, POB MG-11, RO-077125 Bucharest-Măgurele, Romania
(Received 29 June 2017; published 16 November 2017)

spherical nuclei. As a consequence, the contribution of the monopole term increases the barrier penetrability by 2 orders of magnitude, while the total contribution has an effect of 6 orders of magnitude at $D \sim 3D_{crit}$. In the case of deformed nuclei, the electromagnetic field increases the penetrability by an additional order of magnitude for a quadrupole deformation $\beta_2 \sim 0.3$. The influence of the electromagnetic field can be expressed in terms of a shifted Geiger-Nuttal law by a term depending on S_0 and deformation.

Delion D S, Ghinescu S A. Physical Review Letters, 2017, 119(20): 202501.
Bai D, et al. Nuclear Physics A, 2018, 976: 23-32.

多大的激光强度能显著影响
α衰变/结团放射性过程?

PHYSICAL REVIEW LETTERS **124,** 212505 (2020)

Can Extreme Electromagnetic Fields Accelerate the α Decay of Nuclei?

Adriana Pálffy[1] and Sergey V. Popruzhenko[2,3]
[1]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
[2]Prokhorov General Physics Institute of the Russian Academy of Sciences, Vavilov Str. 38, 119991 Moscow, Russia
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(Received 16 September 2019; revised manuscript received 7 March 2020; accepted 29 April 2020; published 28 May 2020)

theoretically. Using both analytic arguments based on the Wentzel-Kramers-Brillouin approximation and numerical calculations for the imaginary time method applied in the framework of the α decay precluster model, we show that no experimentally detectable modification of the α decay rate can be observed with super-intense lasers at any so-far-available wavelength. Comparing our predictions with those reported in several recent publications, where a considerable or even giant laser-induced enhancement of the decay rate has been claimed, we identify there the misuse of a standard approximation.

Pálffy A, Popruzhenko S V. Physical Review Letters, 2020, 124(21): 212505.
Qi J, Li T, Xu R, et al. Physical Review C, 2019, 99(4): 044610.
Cheng J H, Zhang W Y, Xiao Q, et al. Physics Letters B, 2024, 848: 138322.

研究方法

激光场影响衰变

- WKB方法计算隧穿概率：

$$P(t,\theta,I)=\frac{1}{2}\int_0^{\pi}P(t,\phi,\theta,I)\mathrm{sin}\phi d\phi,$$

$$P(t,\phi,\theta,I)=\exp[-\frac{2(2\mu)^{1/2}}{\hbar}\int_{R_{\mathrm{in}}}^{R_{\mathrm{out}}}k(r,t,\phi,\theta,I)dr],$$

$$k(r,t,\phi,\theta,I)=\sqrt{|V(r,t,\phi,\theta,I)-Q_e|},$$

1. 改变势场：

$$V(r,t,\phi,\theta)=V_N(r,\phi)+V_c(r,\phi)+V_l(r)+V_i(r,t,\phi,\theta,I),$$

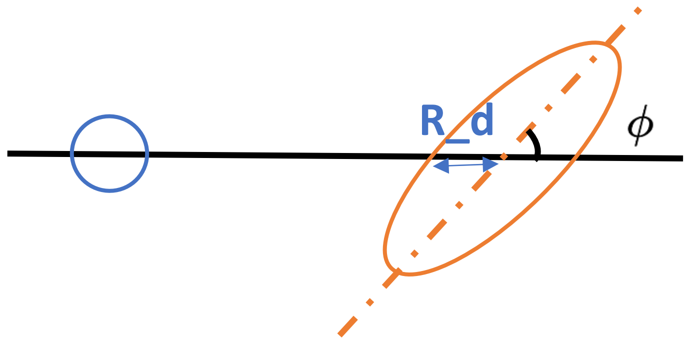
$$V_i(r,t,\phi,\theta,I)=-Q_{\mathrm{eff}}\boldsymbol{r}\boldsymbol{E}(t),$$

$$Q_{\mathrm{eff}}=\frac{Z_eA_d-Z_dA_e}{A_e+A_d},$$

2. 改变粒子衰变能：

$$Q_e^*=Q_e+\Delta Q_e.$$

$$\Delta Q_e=eZ_e\boldsymbol{R}_d(\phi)\boldsymbol{E}(t)$$



- 计算核核相互作用势: Frozen Hatree-Fock方法

$$V_{\mathrm{FHF}}(\boldsymbol{R})=\int H[\rho_1(\boldsymbol{r})+\rho_2(\boldsymbol{r}-\boldsymbol{R})]d\boldsymbol{r}-E[\rho_1]-E[\rho_2]$$

- 激光电场强度

$$\boldsymbol{E}(t)=E_0\mathrm{sin}(\frac{2\pi ct}{\lambda})\boldsymbol{e}_r(\text{linear polarization}),$$

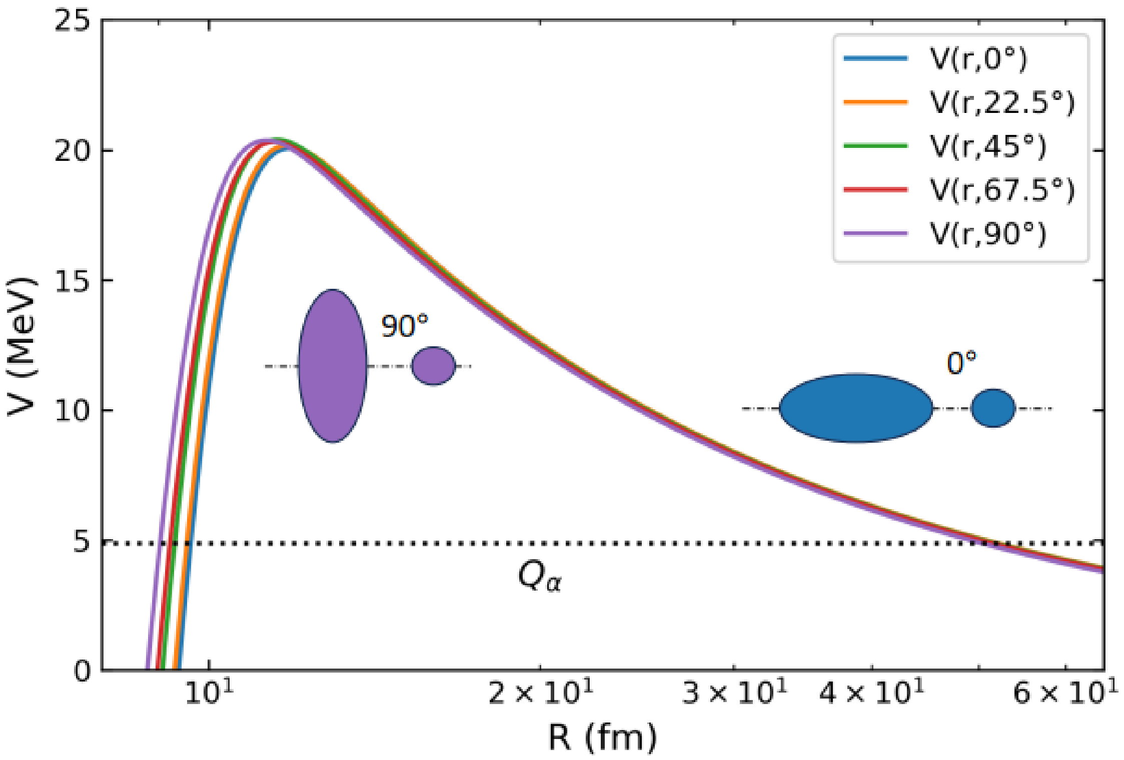
$$\boldsymbol{E}(t)=E_0(\mathrm{sin}(\frac{2\pi ct}{\lambda})\boldsymbol{e}_x+\cos(\frac{2\pi ct}{\lambda})\boldsymbol{e}_y)(\text{circular polarization}),$$

$$E_0=27.44\sqrt{I}.$$

研究进展

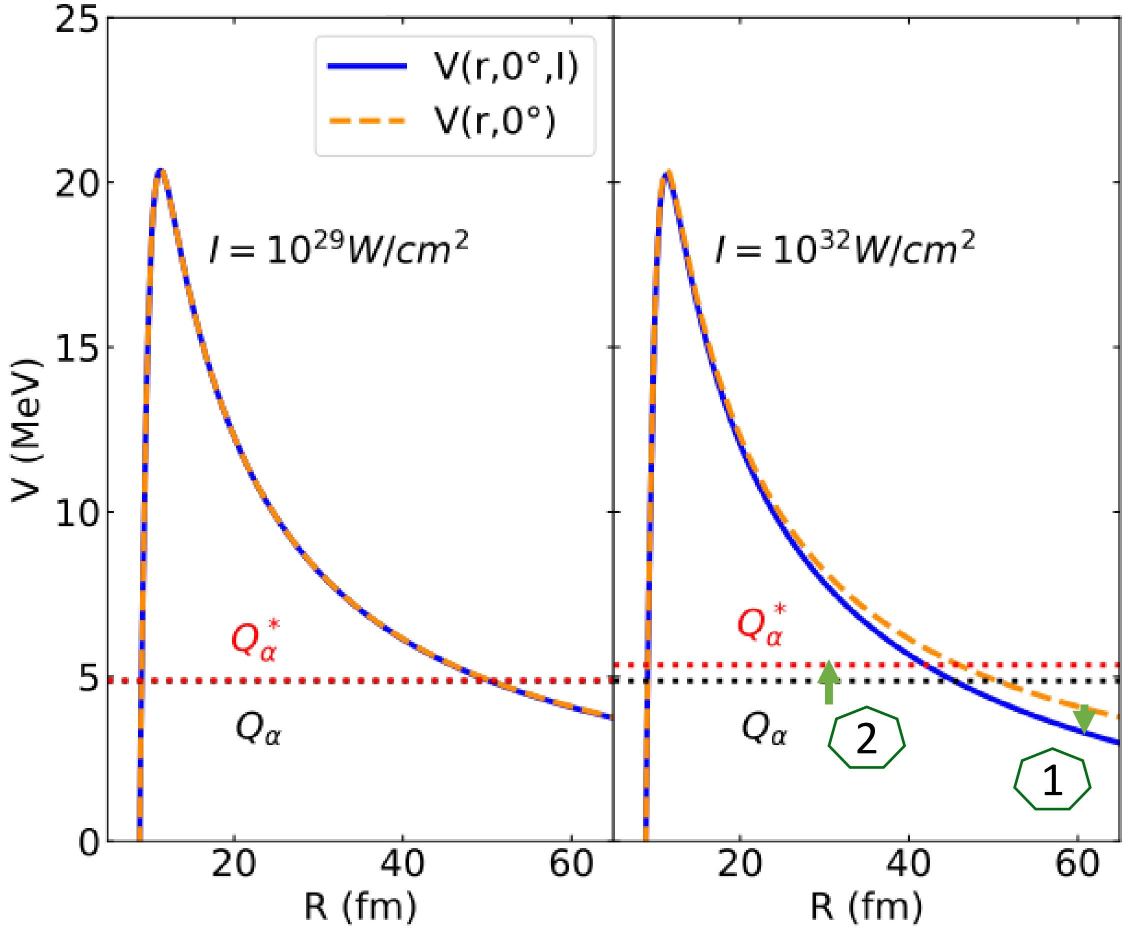
Decay channel	Q_e(MeV)	l	$\log_{10}T_{\rm exp}$
^{144}Nd $\to$ ^{140}Ce+α	1.90	0	22.86
^{226}Ra $\to$ ^{222}Rn+α	4.87	0	10.70
^{238}U $\to$ ^{234}Th+α	4.27	0	17.15
^{242}Cm $\to$ ^{238}Pu+α	6.23	0	7.15
^{147}Sm $\to$ ^{143}Nd+α	2.31	0	18.53
^{213}Po $\to$ ^{209}Pb+α	8.54	0	-5.43
^{235}U $\to$ ^{231}Th+α	4.68	1	16.35
^{239}Pu $\to$ ^{235}U+α	5.25	3	11.88
^{222}Ra $\to$ ^{208}Pb+^{14}C	33.05	0	11.22
^{223}Ra $\to$ ^{209}Pb+^{14}C	31.83	4	15.04
^{224}Ra $\to$ ^{210}Pb+^{14}C	30.53	0	15.87
^{226}Ra $\to$ ^{212}Pb+^{14}C	28.20	0	21.20

^{222}Rn+α



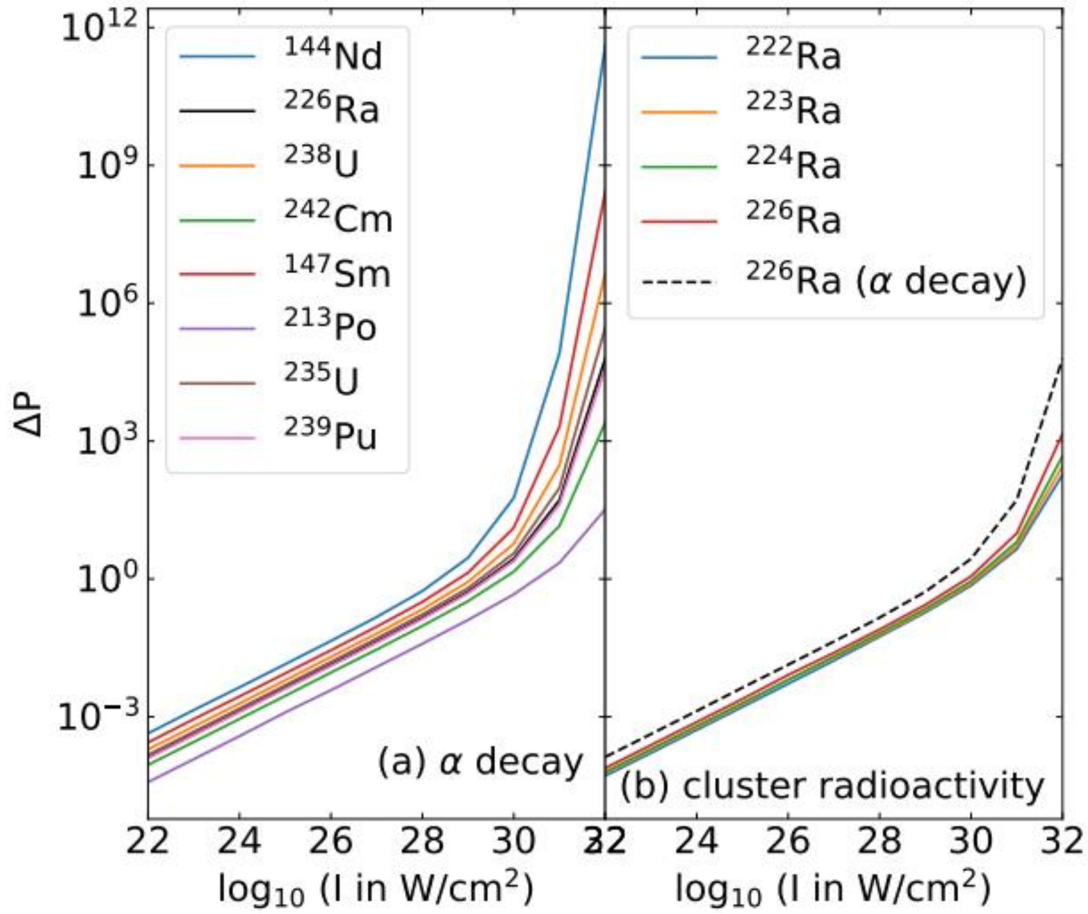
研究进展

^{222}Rn+α



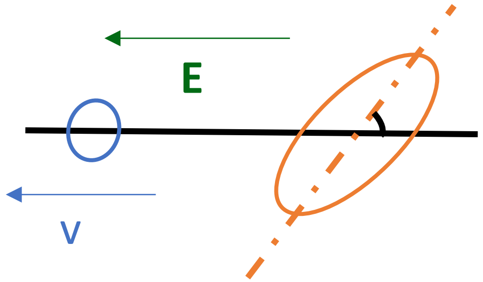
1. 改变势的库伦部分
2. 影响衰变能

$$\Delta P(t,\theta,I) = \frac{P(t,\theta,I) - P(t,\theta,I=0)}{P(t,\theta,I=0)}.$$

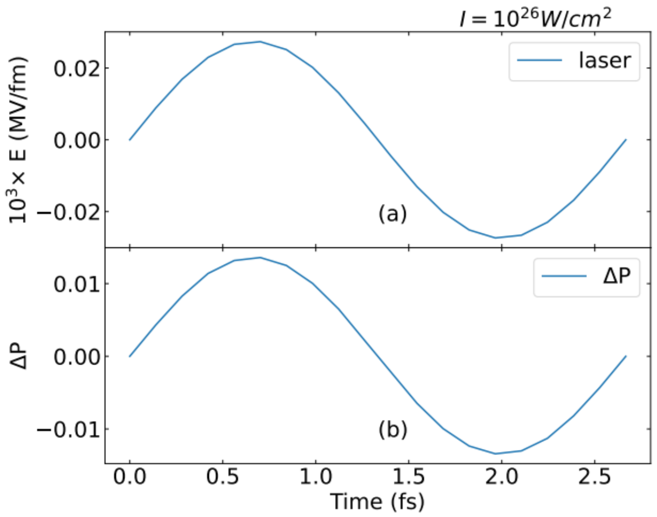


^{144}Nd对激光场的影响最为敏感

研究进展

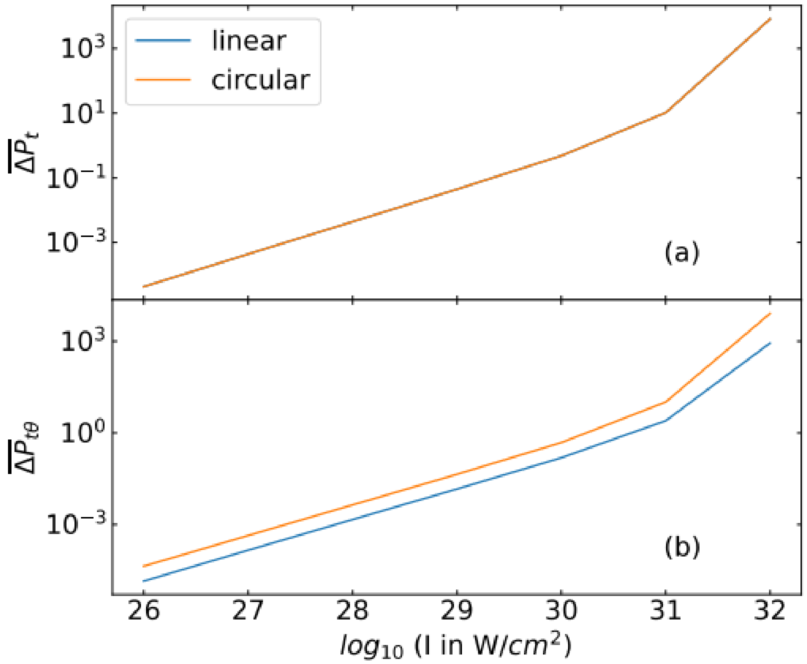


线性偏振

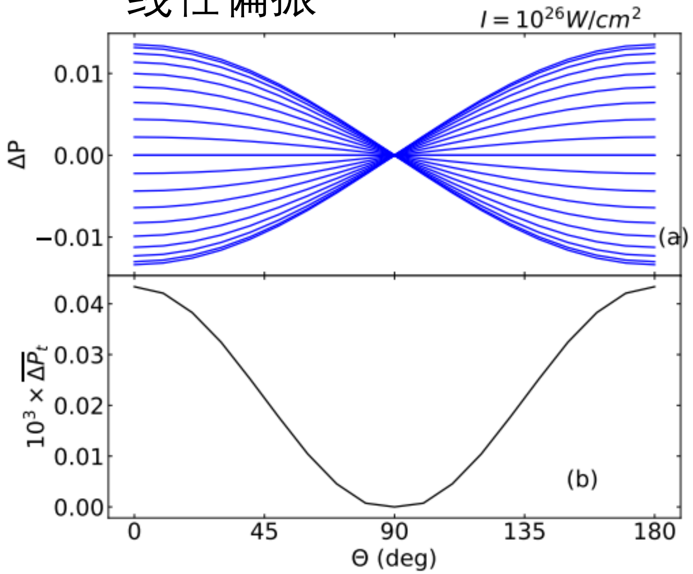


$$\boldsymbol{E}(t) = E_0 \sin(\frac{2\pi ct}{\lambda})\boldsymbol{e}_r(\text{linear polarization}),$$

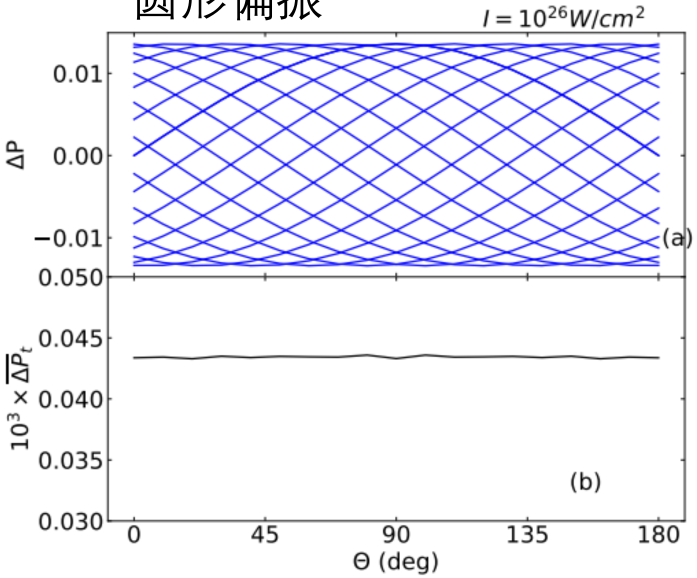
$$\boldsymbol{E}(t) = E_0(\sin(\frac{2\pi ct}{\lambda})\boldsymbol{e}_x + \cos(\frac{2\pi ct}{\lambda})\boldsymbol{e}_y)(\text{circular polarization}),$$



线性偏振

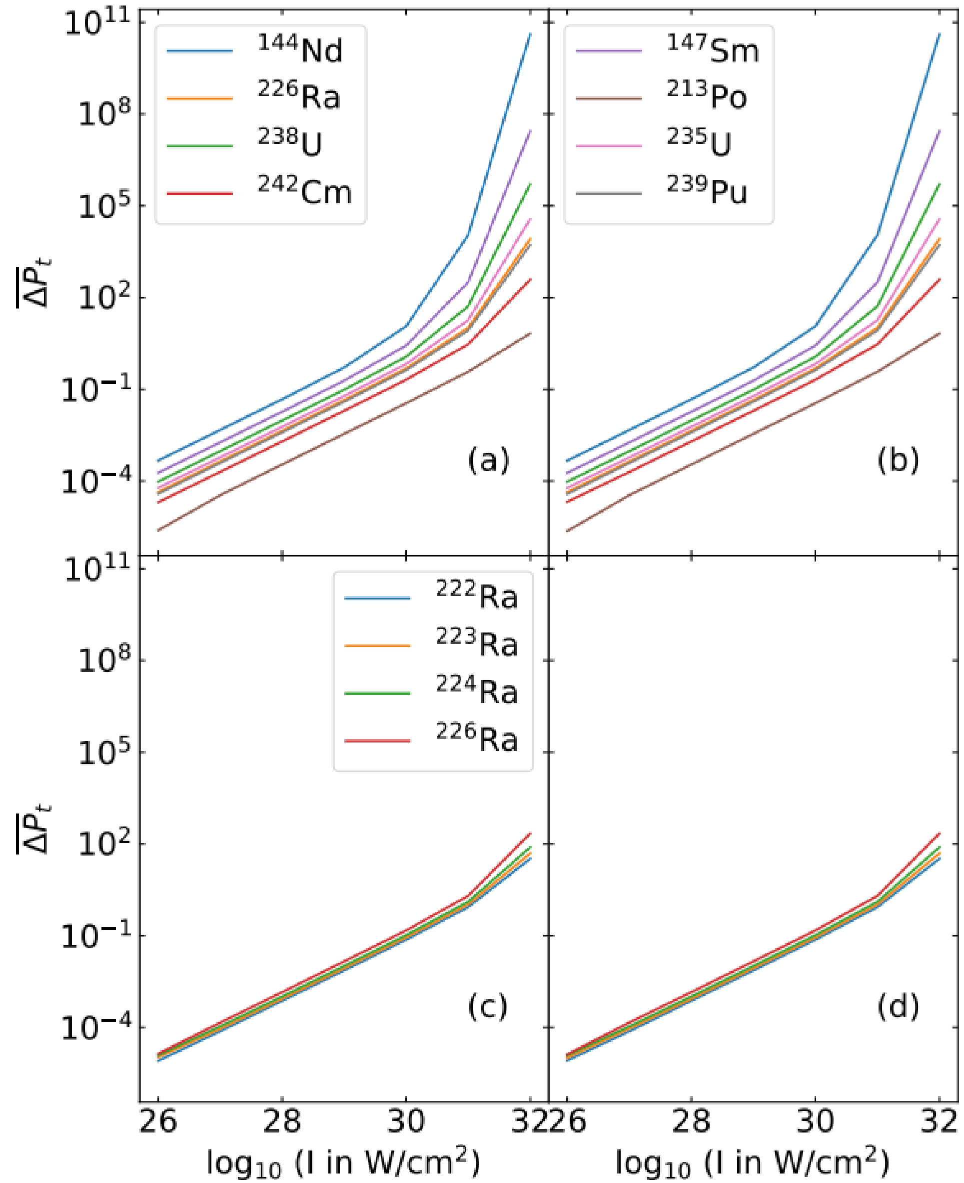


圆形偏振



推荐使用圆形偏振激光
验证激光对衰变的影响

研究进展



Decay channel	$\log_{10}$I	$\overline{\Delta P_{t\theta}}$
^{144}Nd → ^{140}Ce+α	27	4.66×10^{-3}
^{226}Ra → ^{222}Rn+α	28	4.39×10^{-3}
^{238}U → ^{234}Th+α	28	9.51×10^{-3}
^{242}Cm → ^{238}Pu+α	28	1.97×10^{-3}
^{147}Sm → ^{143}Nd+α	27	1.84×10^{-3}
^{213}Po → ^{209}Pb+α	29	3.48×10^{-3}
^{235}U → ^{231}Th+α	28	5.92×10^{-3}
^{239}Pu → ^{235}U+α	28	3.89×10^{-3}
^{222}Ra → ^{208}Pb+^{14}C	29	7.28×10^{-3}
^{223}Ra → ^{209}Pb+^{14}C	29	8.58×10^{-3}
^{224}Ra → ^{210}Pb+^{14}C	28	1.03×10^{-3}
^{226}Ra → ^{212}Pb+^{14}C	28	1.43×10^{-3}

目前的激光场强度为10^{23} W/cm^2

在现有的激光条件下无法观测到激光场对α衰变或结团放射性的影响

总结与展望

总结

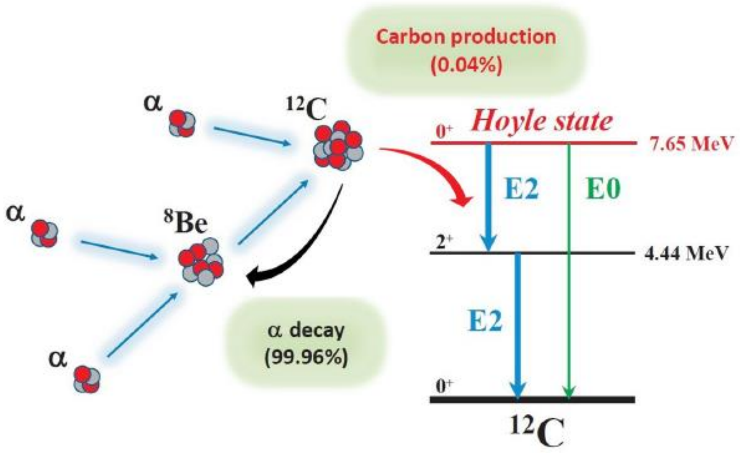
1. ^{144}Nd对激光场的影响最为敏感，这归因于其较小的衰变能

2. 在同等激光强度下，圆形偏振激光的效果比线性偏振激光的大两三倍，因此推荐使用圆形偏振激光验证激光对衰变的影响

3. 除非拥有极端强度的激光和更精确的实验探测器，否则不可能观测到激光对衰变过程的影响

展望

➢ 研究高密天体环境下，α粒子形成的库仑场对形成12C反应率的影响



Eriksen T K et al. Physical Review C, 2020, 102(2): 024320.

敬请各位老师批评指正！

2024.11.18