National Nuclear Security Administration

TEXAS A&M UNIVERSITY

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Dynamical production of e^+e^- in strong fields produced by heavy ions

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(***for the experimental part***)

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CENTER FOR EXCELLENCE CENTAUR IN NUCLEAR TRAINING AND UNIVERSITY-BASED RESEARCH

1967 - 2017 50 YEARS OF BEAM exploring the nuclear frontier

CYCLOTRON INSTITUTE TEXAS A&M UNIVERSITY

outline

- background/motivation
- virtual pairs & vacuum polarization
- real pair production in:
    - nuclear scattering & fusion
    - nuclear fission & α decay
- conclusions

Schwinger mechanism [7]

- Dirac particles approximately satisfy the Klein-Gordon Equation

$$\left(p^2 + m^2\right)\psi = \left(i\hbar\frac{\partial}{\partial t} - V(x)\right)^2 \psi$$

- Manipulate into a Schrödinger equation.

$$\left(\frac{p_x^2}{2m_T} + V_{eff}(x)\right)\psi = 0$$

$$V_{eff}(x) = \frac{m_T}{2} - \frac{\left(E - V(x)\right)^2}{2m_T} \qquad m_T = \sqrt{m^2 + p_y^2 + p_z^2}$$

- Negative energy particles in Dirac sea can tunnel through the effective potential and become real.

[7] J. Schwinger, On gauge invariance and vacuum polarization, Phys. Rev. 82 (1951) 664-679.

maximum energy of created particle

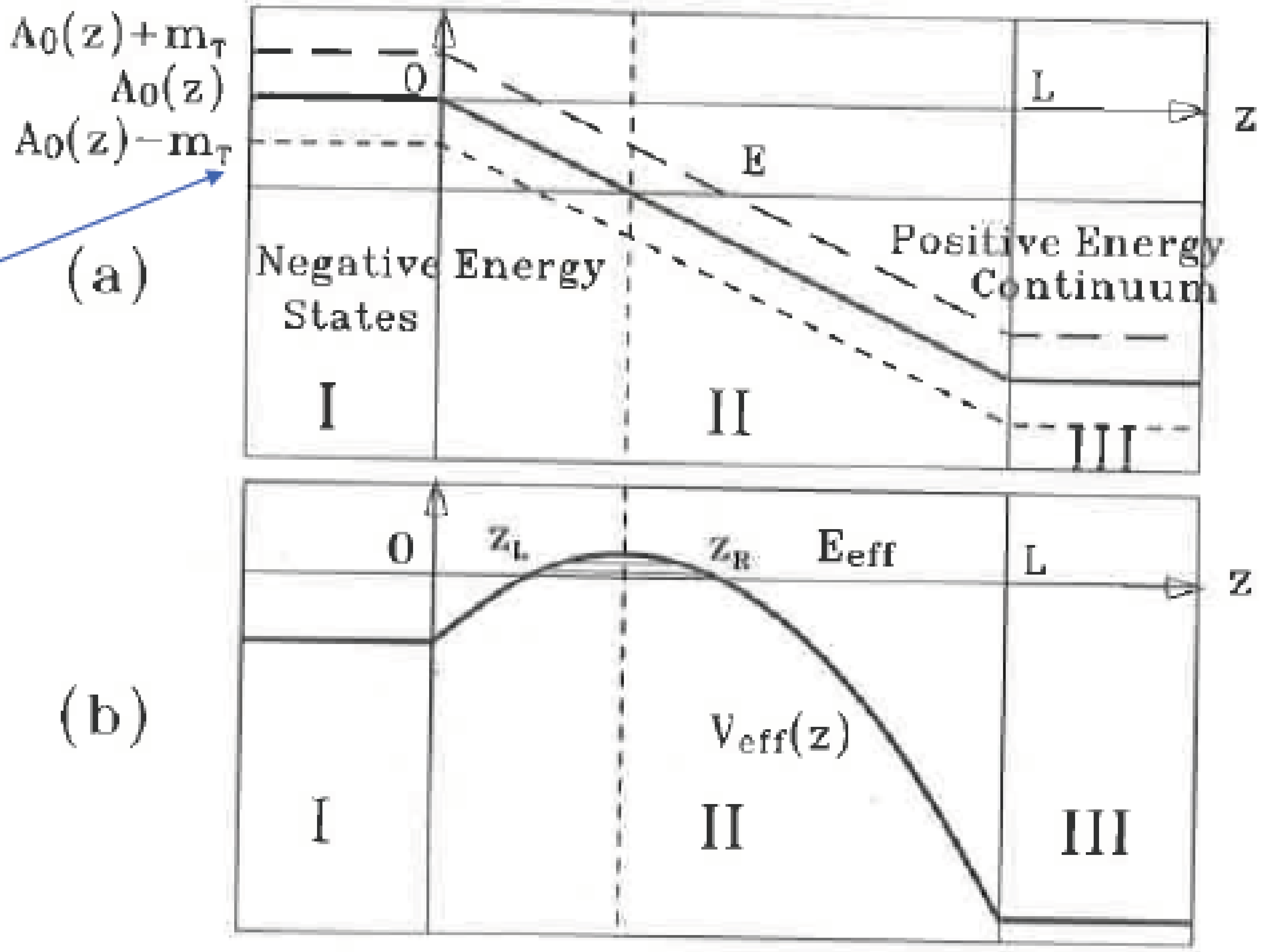


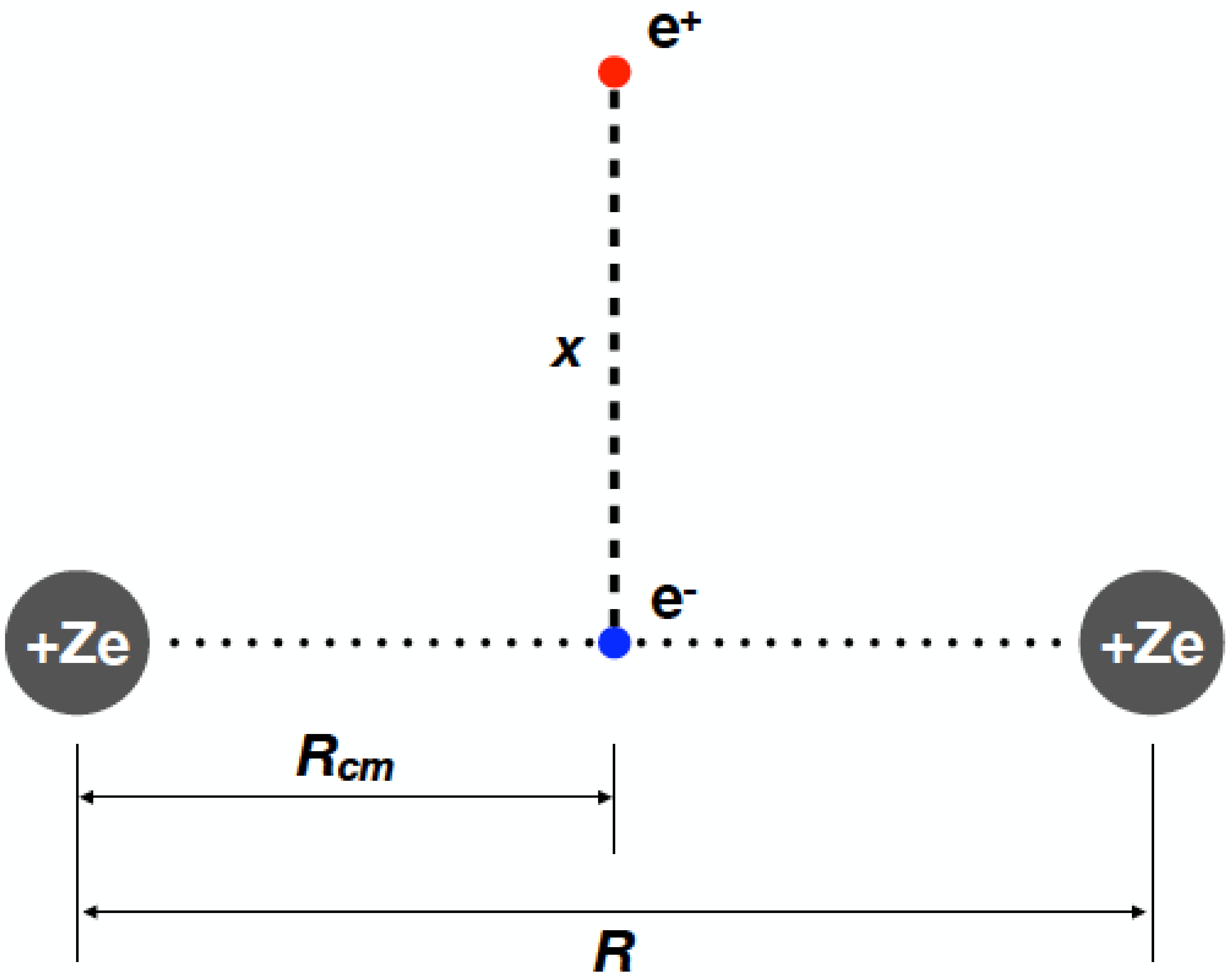
Fig. 5.3(*a*) The potential $A_0(z)$ for the Dirac or the Klein-Gordon equation. (*b*) The corresponding $V_{\rm eff}$ for the equivalent Schrödinger equation (5.13).

- notice the force must be repulsive!
- don't let me move on without saying this!
- it will be important later!

[8] C. Wong, *Introduction to High-Energy Heavy-Ion Collisions*, World Scientific Publishing, Singapore, 1994.

Our model

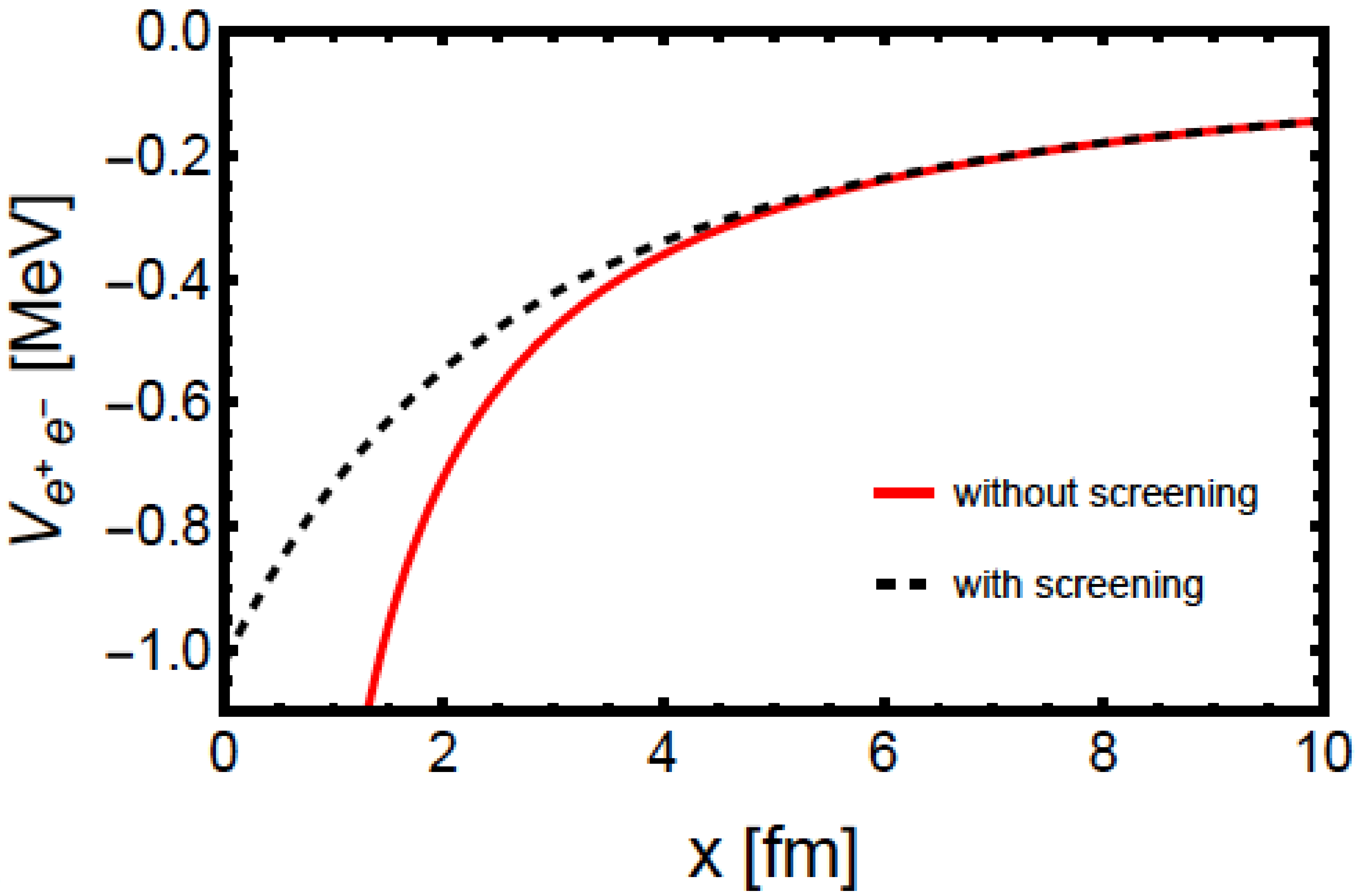
- The two nuclei come together with impact parameter zero.
- Suppose the e^- is created at the center of mass of the two nuclei and the e^+ is on an axis perpendicular to the beam axis [9].
- Symmetric and energetically favorable.
- The ions get accelerated by the e^- in the middle, encouraging fusion.



[9] T. Settlemyre, H. Zheng, A. Bonasera, Dynamical pair production at sub-barrier energies for light nuclei, Particles 5 (2022) 580-588.

Screening

- To prevent arbitrarily negative energies, introduce a cutoff as x->0
- $$V_{e^+e^-} = -\left(1 - \exp\left[-\frac{x}{x_s}\right]\right)\frac{e^2}{x}$$
- $$x_s = \frac{e^2}{2m_T}$$
- Energy is $-2m_T$ when x=0, the energy needed to extract the pair from the vacuum.
- Factor in exponent is a free parameter to be determined by experiment.



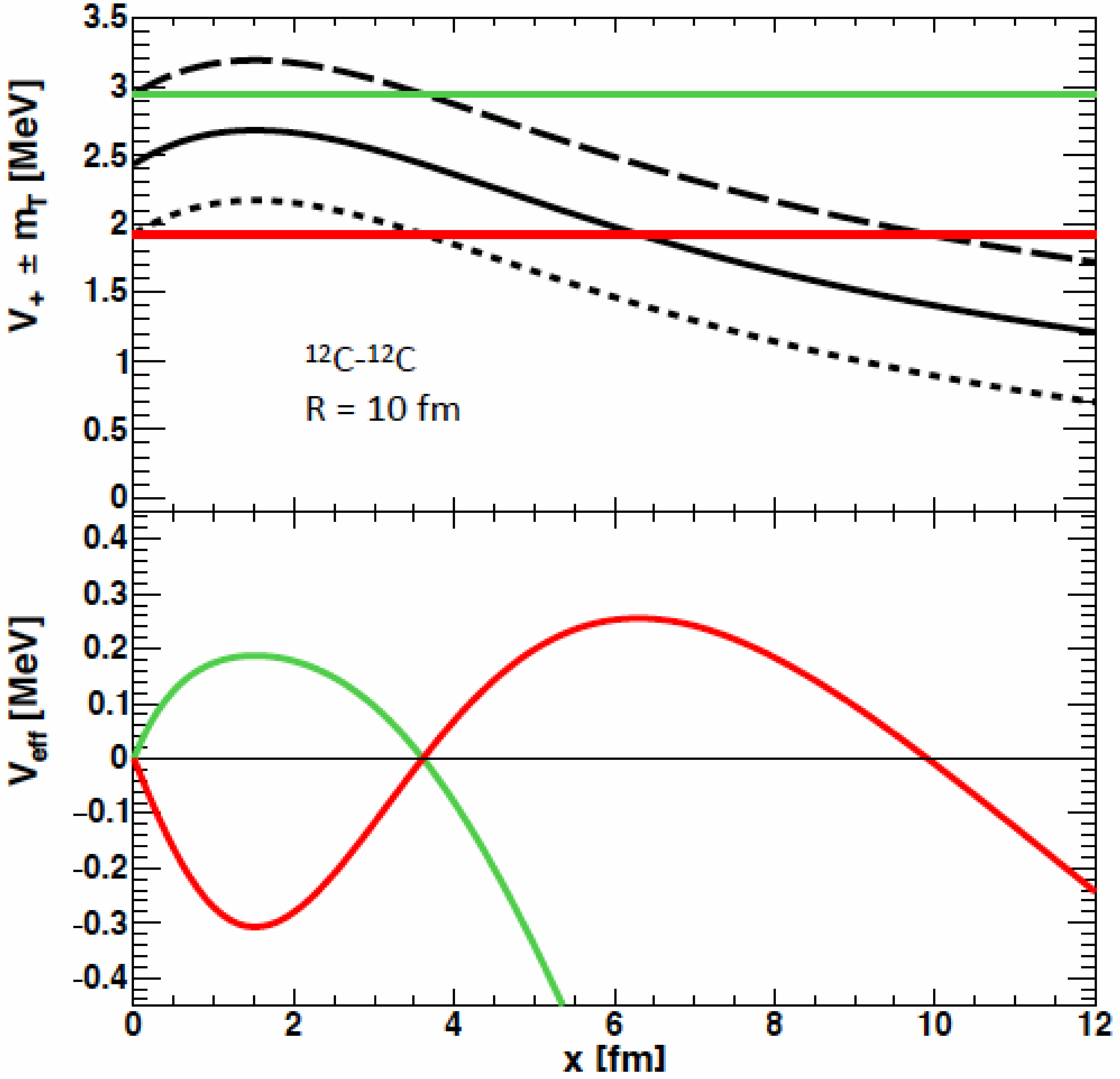
Effective potential

- Potential energy of positron

$$V_+(R,x) = \frac{2Ze^2}{\sqrt{\left(\frac{R}{2}\right)^2 + x^2}} - S(x)\frac{e^2}{x},$$

- Effective potential

$$V_{eff}(x) = \frac{m_T}{2} - \frac{(E_+ - V_+(R,x))^2}{2m_T},$$



Energy conservation

- The kinetic energy of the ions can change.

$$\Delta E_k = E'_k - E_k = -\left(E_+ + m_T - \frac{4Ze^2}{R}\right)$$

- The requirement

$$E_+ \ \leq \ V_+(R,0) - m_T$$

- implies

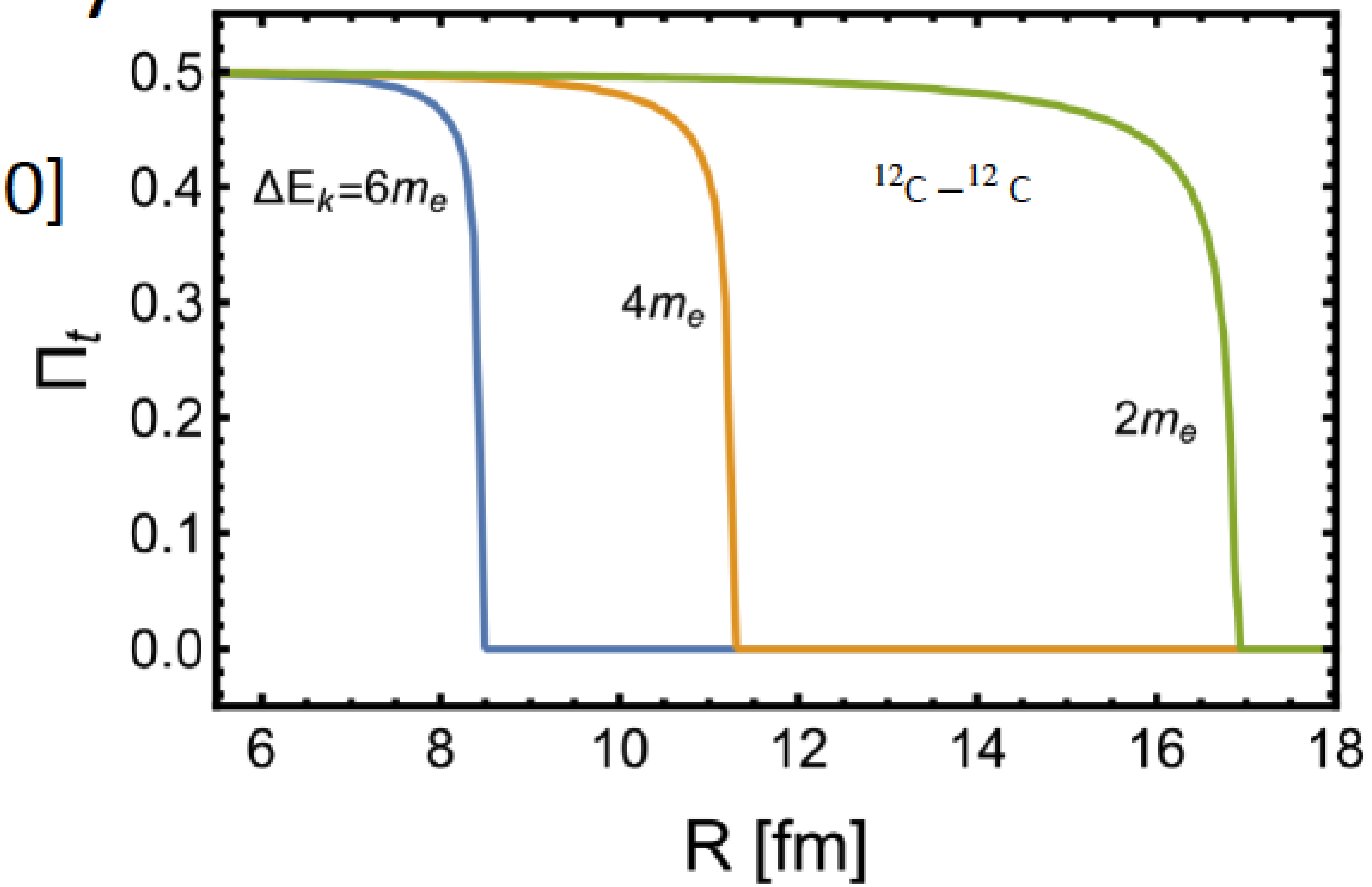
$$\Delta E_k \ \geq \ 2m_T$$

Tunneling probability

$$\Pi_t = [1 + \exp(2A)]^{-1} \text{ [10]}$$

- Probability is essentially 1/2 for R less than the critical value

$$R_x = \frac{4Ze^2}{\Delta E_k + 2m_T},$$

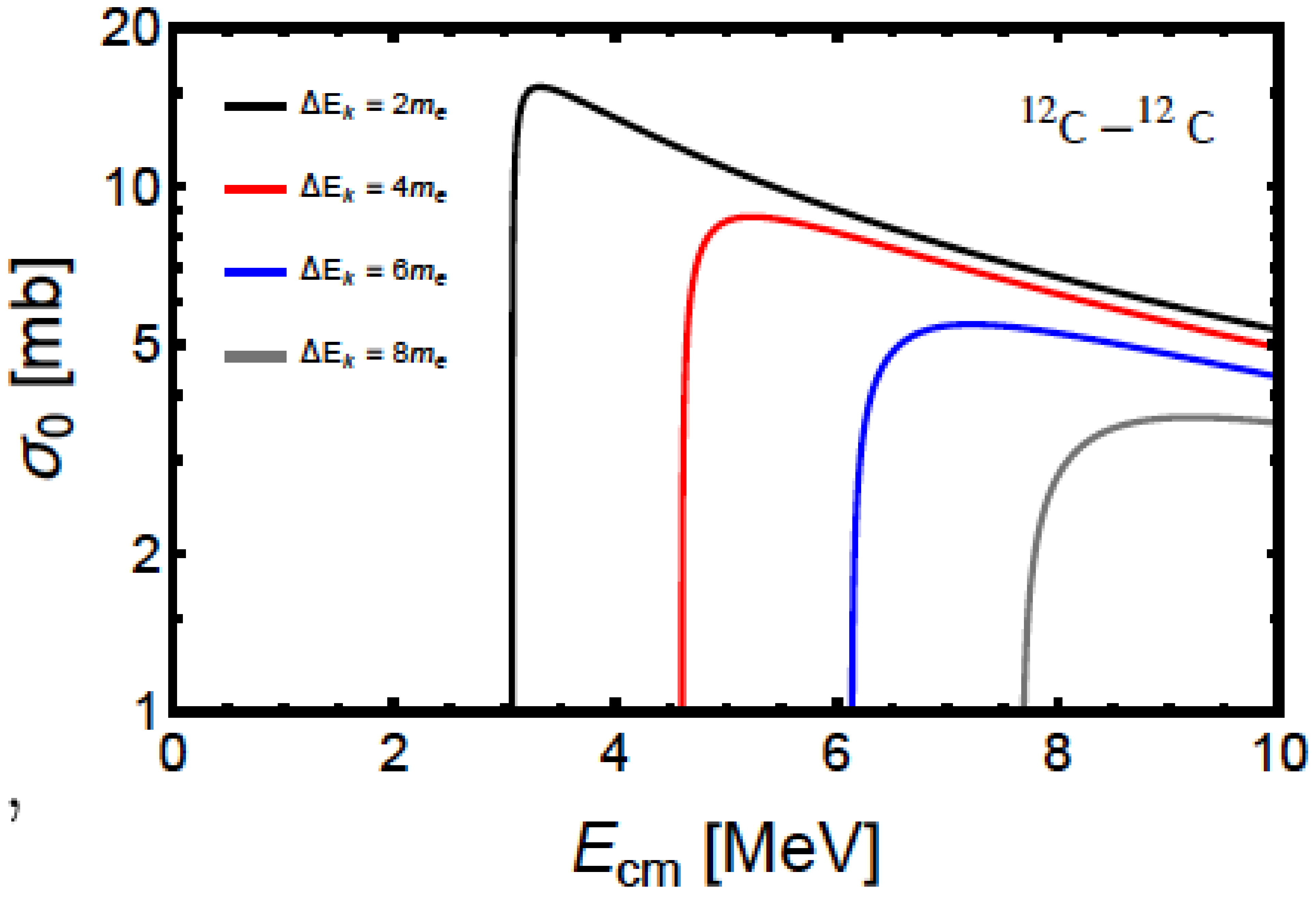


[10] Edwin C. Kemble. "A Contribution to the Theory of the B. W. K. Method". In: Phys. Rev. 48 (6 Sept. 1935), pp. 549–561. DOI:10 . 1103 / PhysRev . 48 . 549

Cross section of pair production

$$\sigma(E_{c.m.}) = \frac{\pi\hbar^2}{2\mu E_{c.m.}} \sum_{l=0}^{n} (2l+1)\Pi_l P_H\,.$$

$$P_H = 1 - \exp(-\tau/\Delta\tau) \qquad \Delta\tau = \frac{\hbar}{2m_T},$$



- Square root in σ gives minimum value for E_{cm}
- Model dependent

$$\sigma_0(E_{c.m.}) = \frac{\pi\hbar^2}{2\mu E_{c.m.}} 0.5 \left(1 - \exp\left[-\frac{\tau}{\Delta\tau}\right]\right)$$

$$\tau = \sqrt{2\mu}\left(\frac{R_x}{E_{cm}}\sqrt{E_{cm} - \frac{Z^2e^2}{R_x}} + \frac{Z^2e^2}{E_{cm}^{3/2}}\text{arctanh}\sqrt{1 - \frac{Z^2e^2}{R_x E_{cm}}}\right)$$

dN/dE

probability of creating a pair in time dt:

$$dN = \Pi_t \frac{dt}{\Delta\tau}$$

change of variables:

$$\frac{dN}{dE_+} = \frac{\Pi_t R^2}{2\Delta\tau \left|\frac{dR}{dt}\right| Z_{tot} e^2}$$

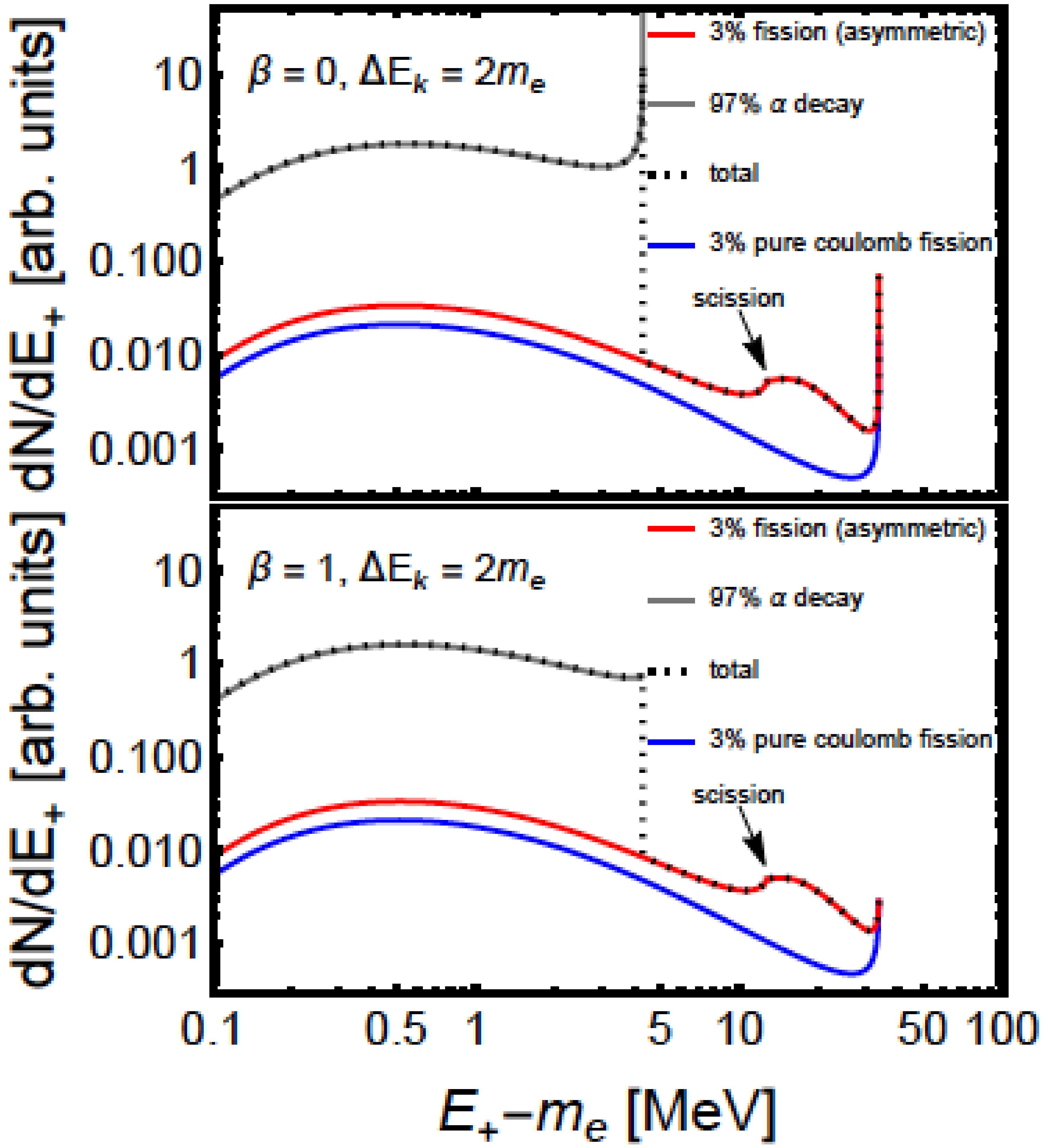
which value of dR/dt? before or after ΔE_k? Introduce parameter β (depends on tunneling).

result for pure coulomb repulsion:

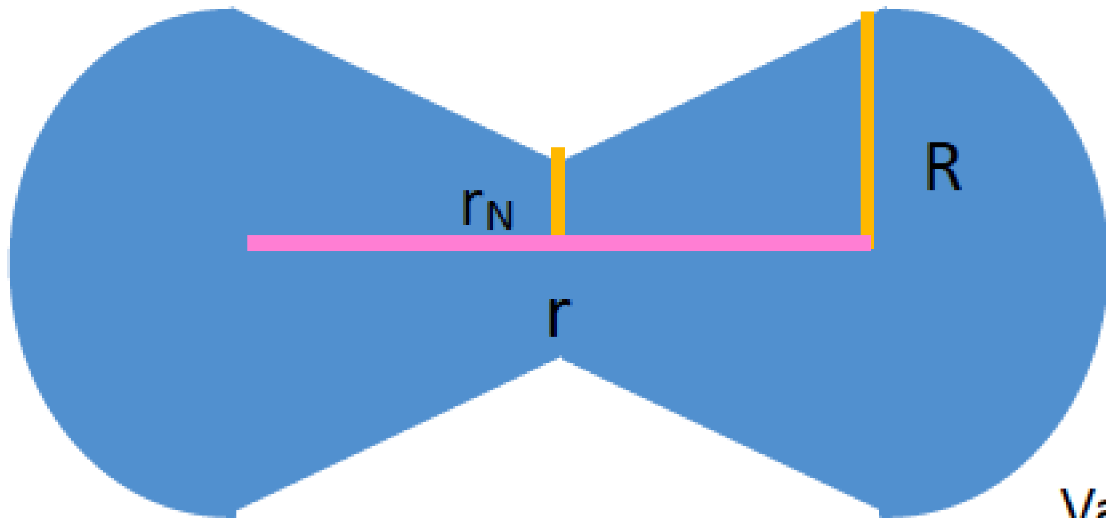
$$\frac{dN}{dE_+} = \frac{\Pi_t \sqrt{2\mu} Z_{tot} e^2}{\Delta\tau (E_+ + m_T + \Delta E_k)^2} \left(E_{cm} + \beta \Delta E_k - \frac{Z_1 Z_2}{2 Z_{tot}} (E_+ + m_T + \Delta E_k) \right)^{-1/2}$$

pair production as probe of alpha decay and fission dynamics [12]

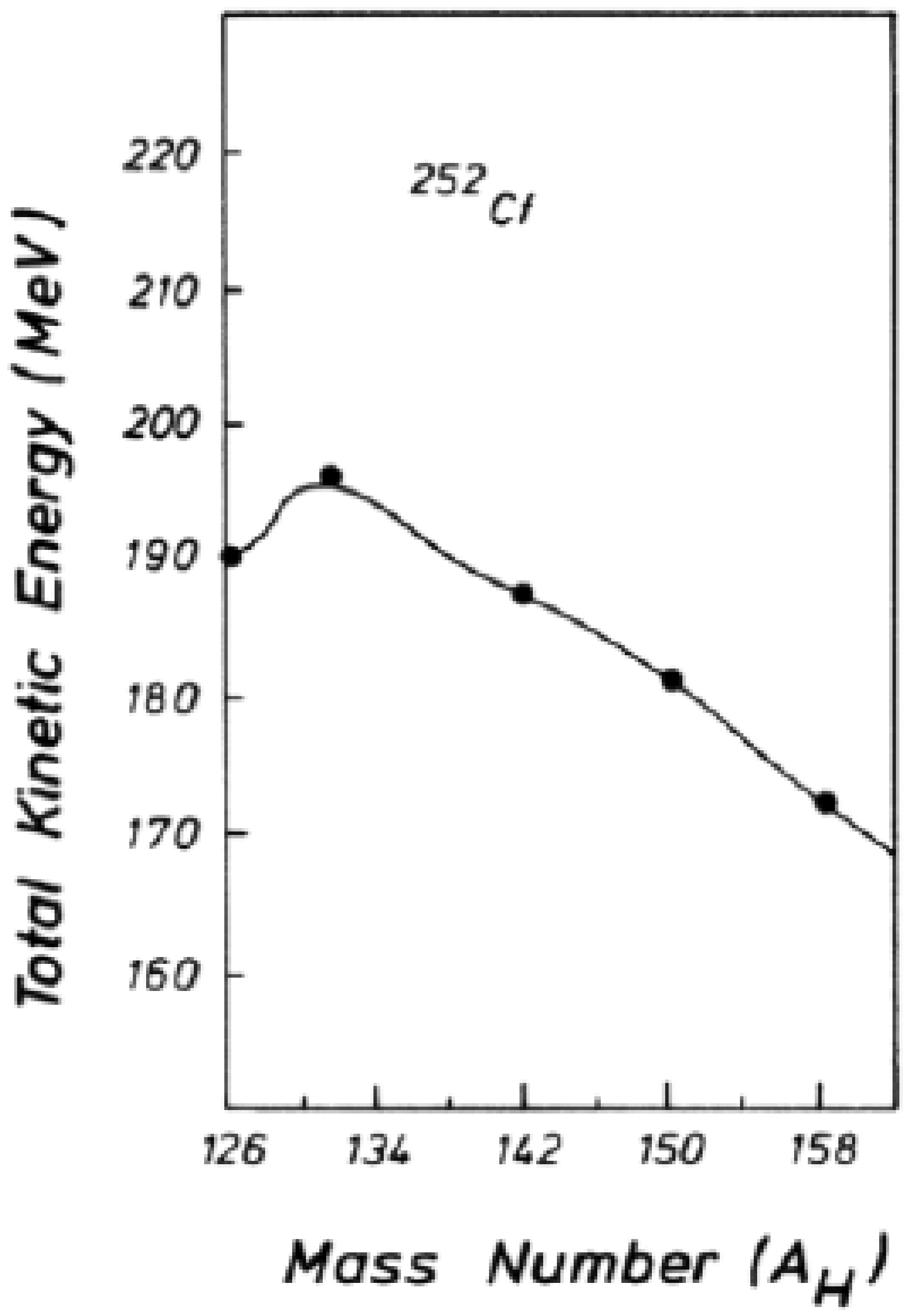
- ^{252}Cf
- fission dynamics from neck model
- dN/dE goes to zero as $E_+ \rightarrow m_T$ because of tunneling probability
- divergence at high E_+ comes from assumption that fragments begin at rest, softened by increasing β
- difference between red and blue curves shows dynamics of fission

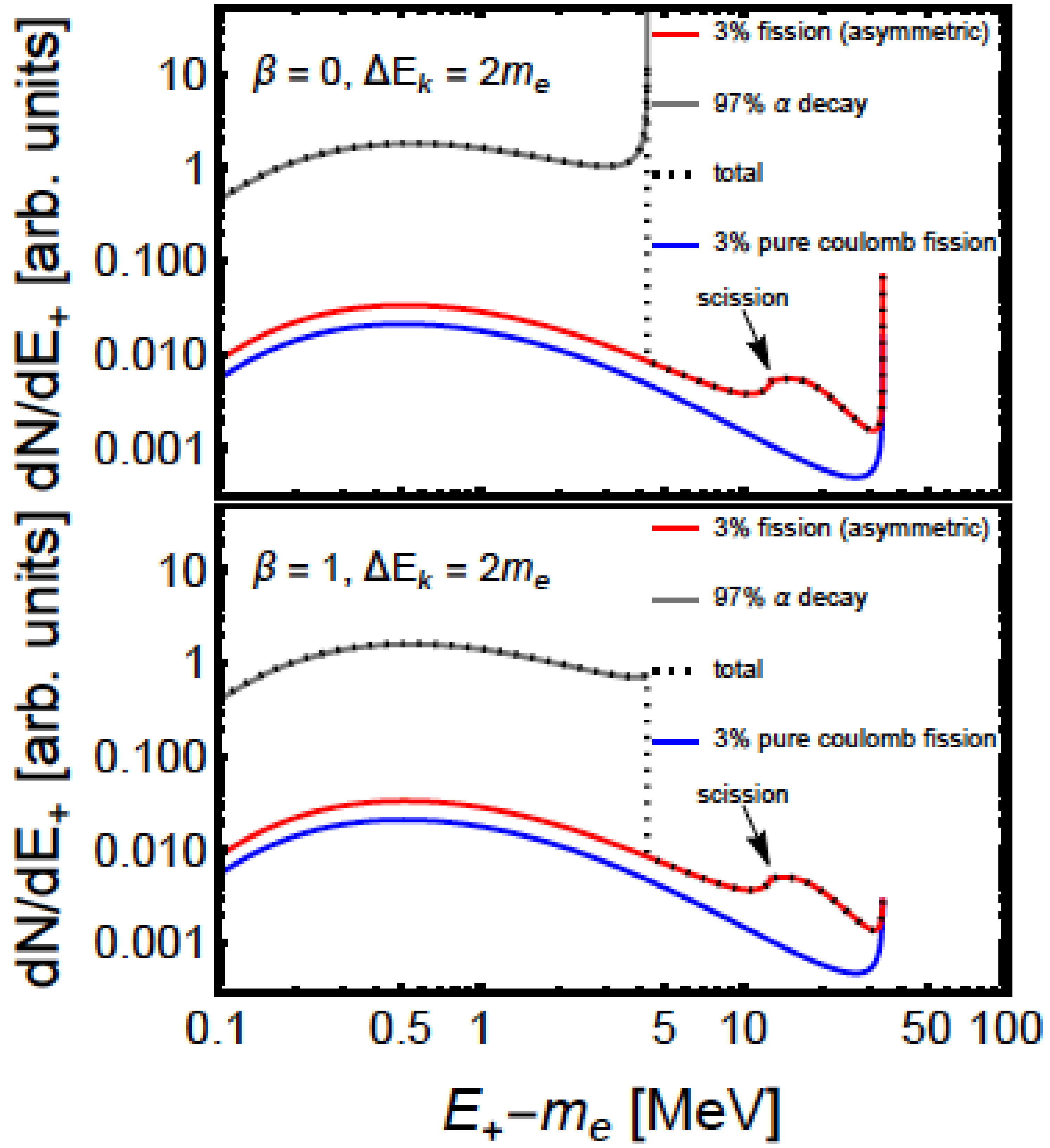


[12] Settlemyre, T., Zheng, H., and Bonasera, A. Pair production as a probe for the dynamics of nuclear fission and α decay. *Phys. Rev. C*, **107**, L031301 (2023).

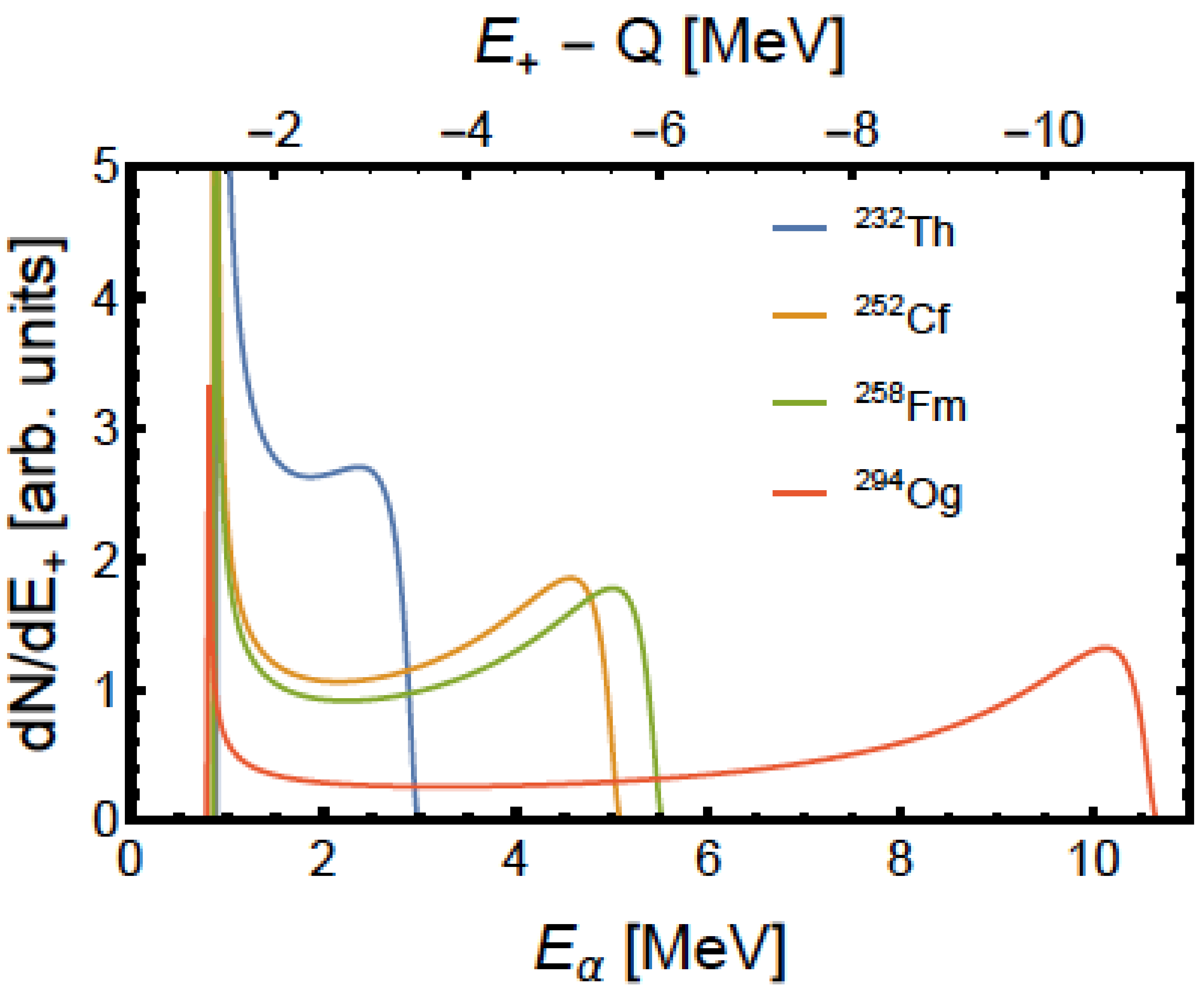


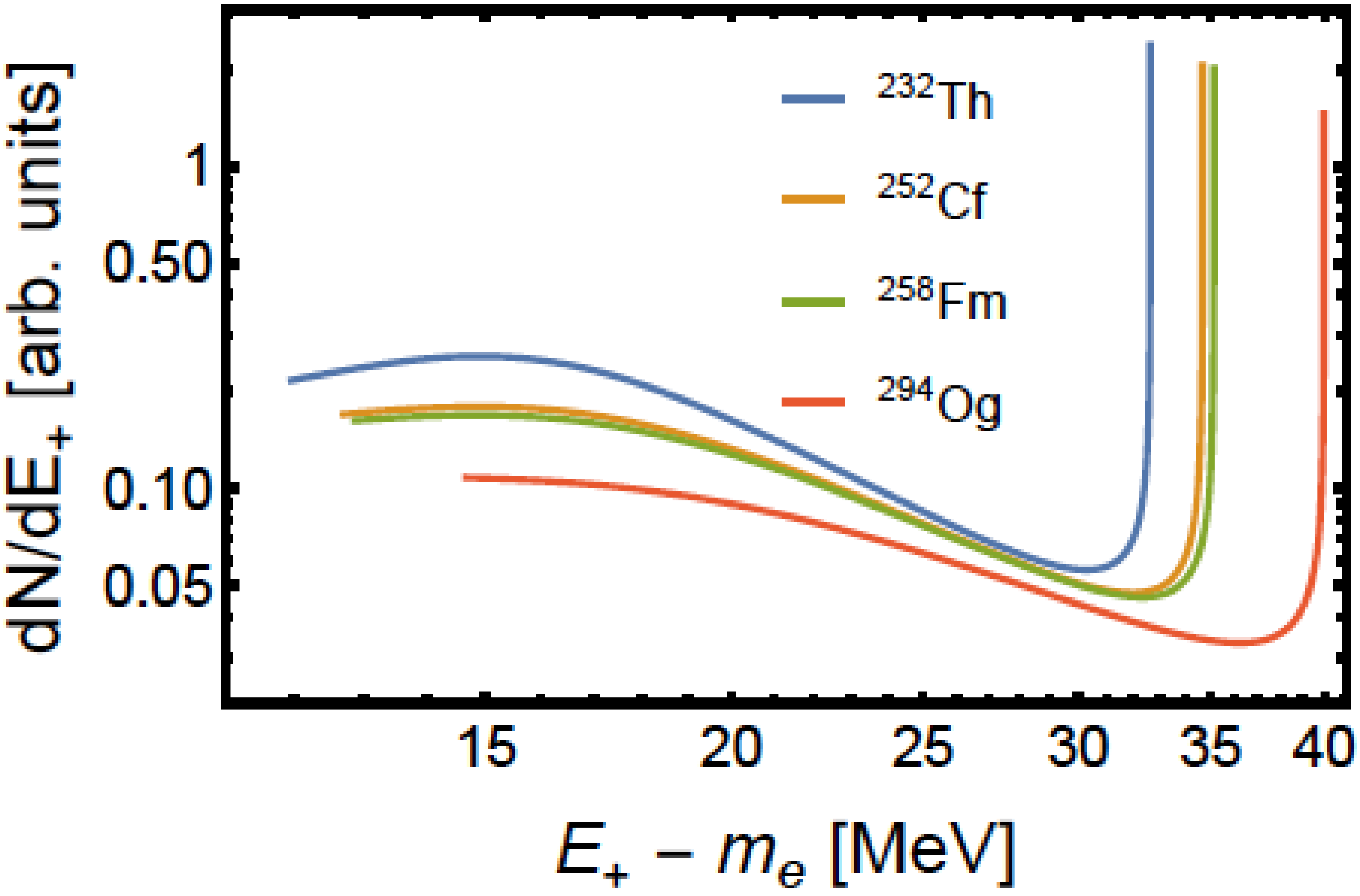
neck model applied to fission [13]





[13] A. Bonasera, Dynamical model of nuclear fission with shell effects, Phys. Rev. C 34 (1986) 740-742.





alpha decay

$\beta = 0$

symmetric fission

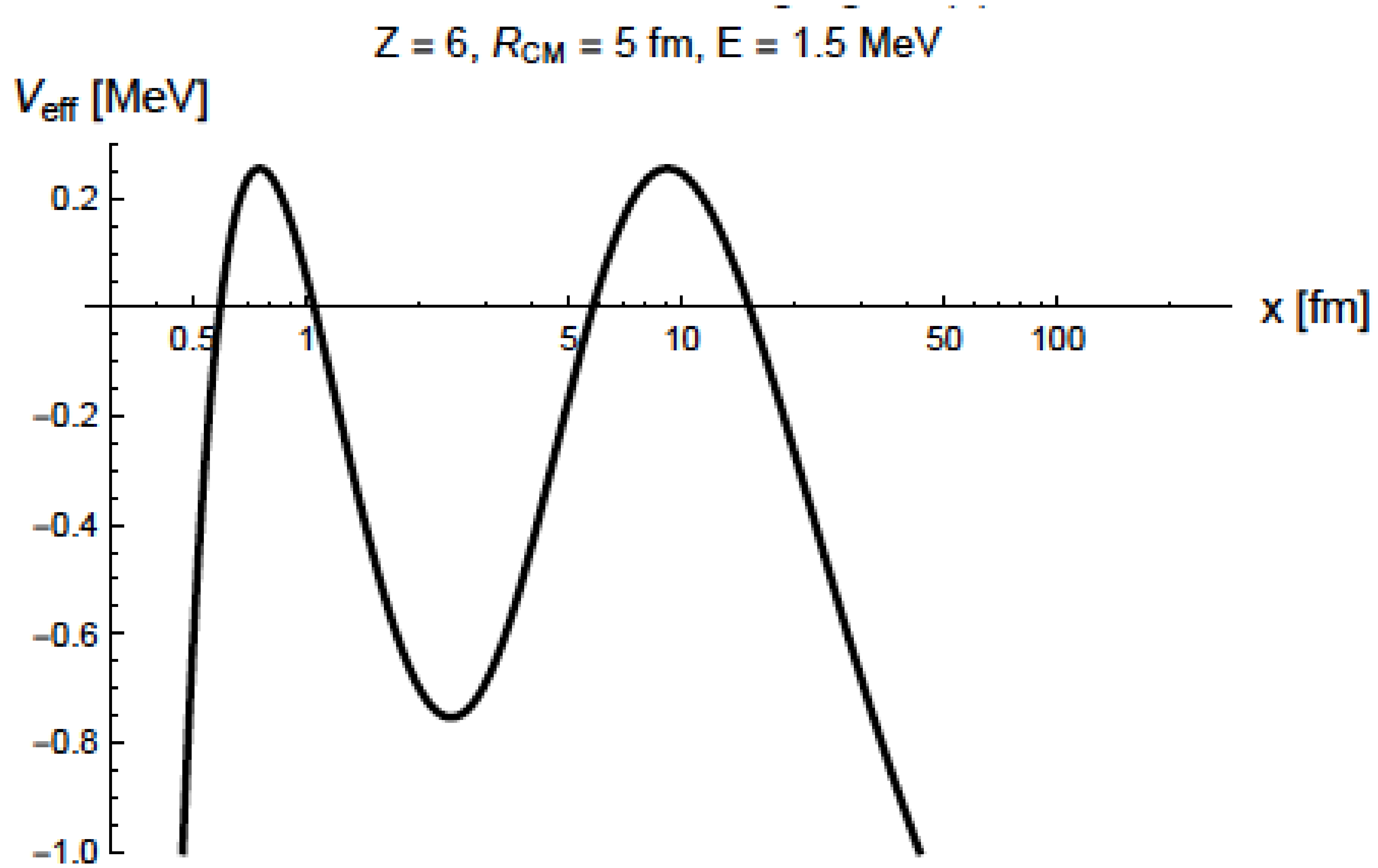
Limit of no screening

- double hump potential

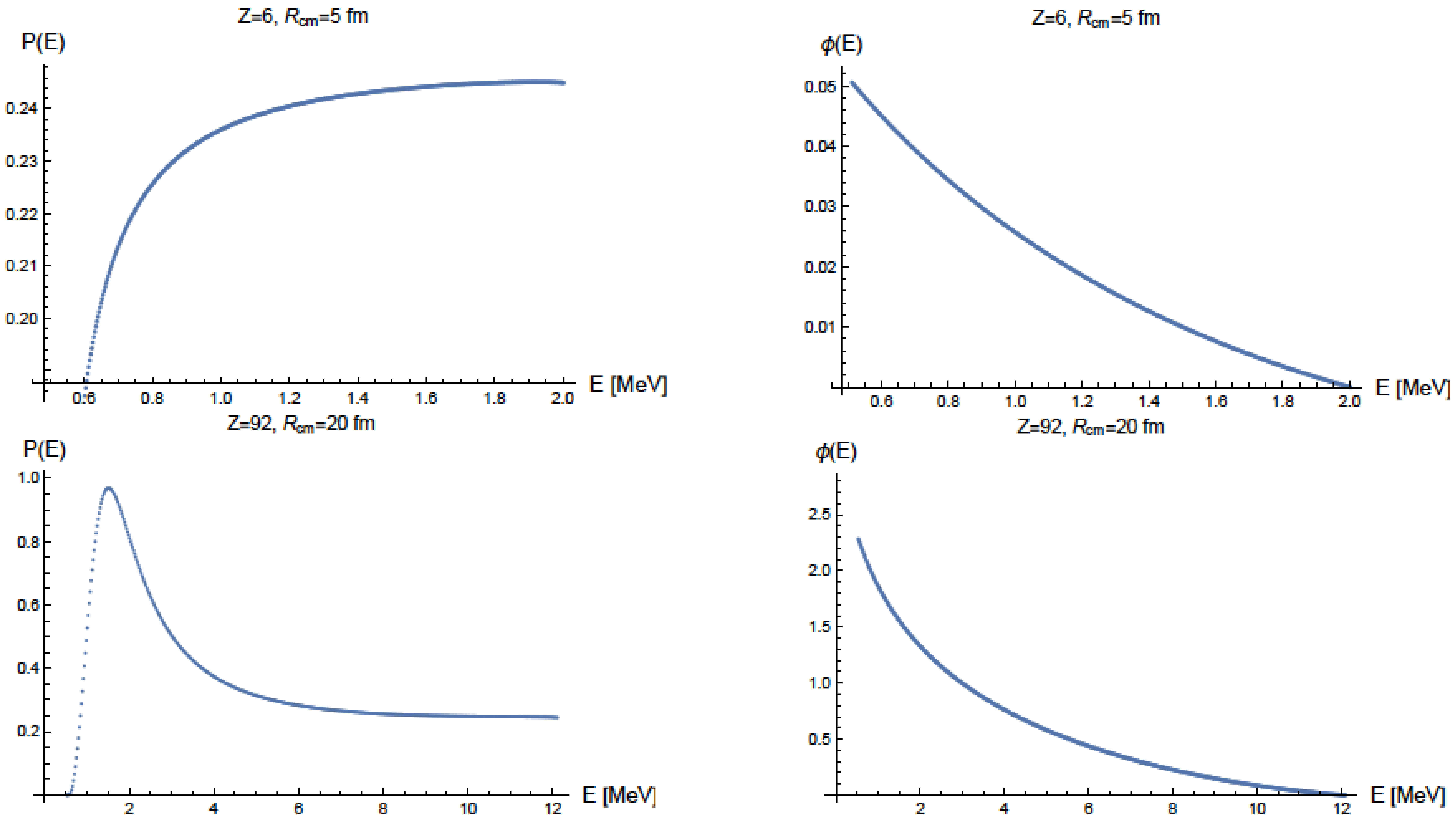
$$P_A = \left(1 + \exp \frac{2}{\hbar}\int_{x_1}^{x_2} \sqrt{2\mu(V_{eff}(x) - E_{eff})}\, dx\right)^{-1}$$

$$P_B = \left(1 + \exp \frac{2}{\hbar}\int_{x_3}^{x_4} \sqrt{2\mu(V_{eff}(x) - E_{eff})}\, dx\right)^{-1}$$

$$\phi(E) = \frac{1}{\hbar}\int_{x_2}^{x_3} \sqrt{2\mu(E_{eff} - V_{eff}(x))}\, dx$$



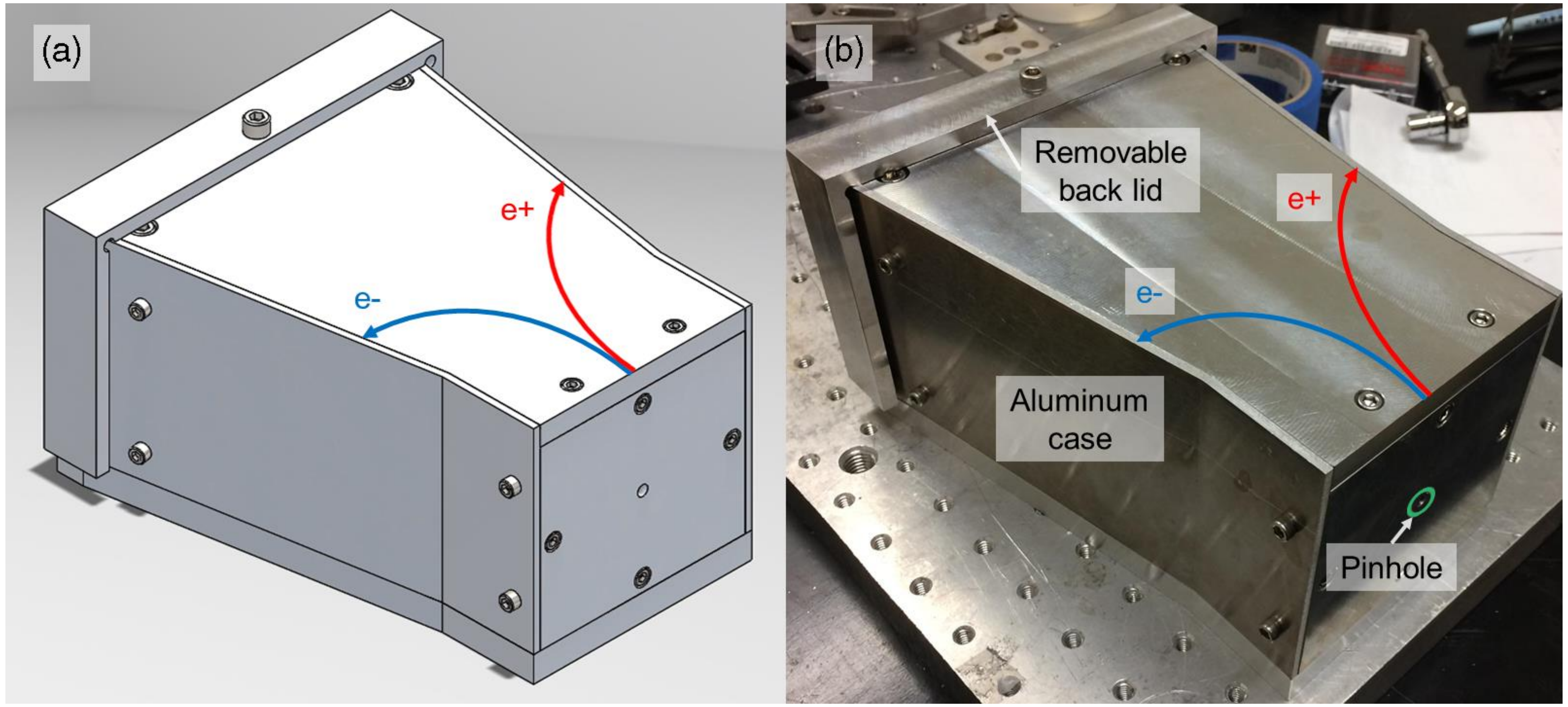
$$P(E_+) = \frac{1}{4} P_A P_B \left(\frac{(P_A + P_B)^2}{16}\sin^2\phi + \cos^2\phi\right)^{-1}$$

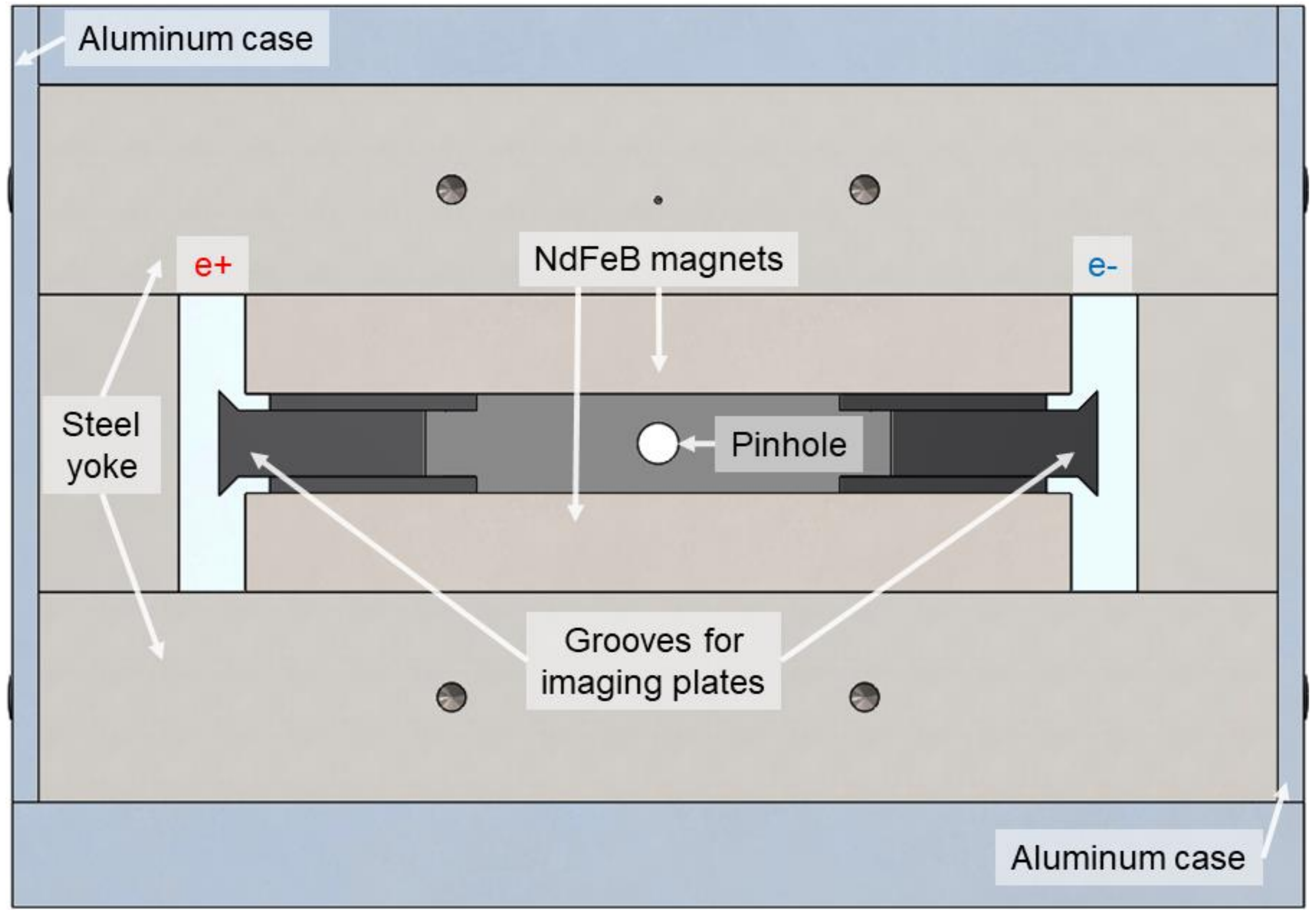


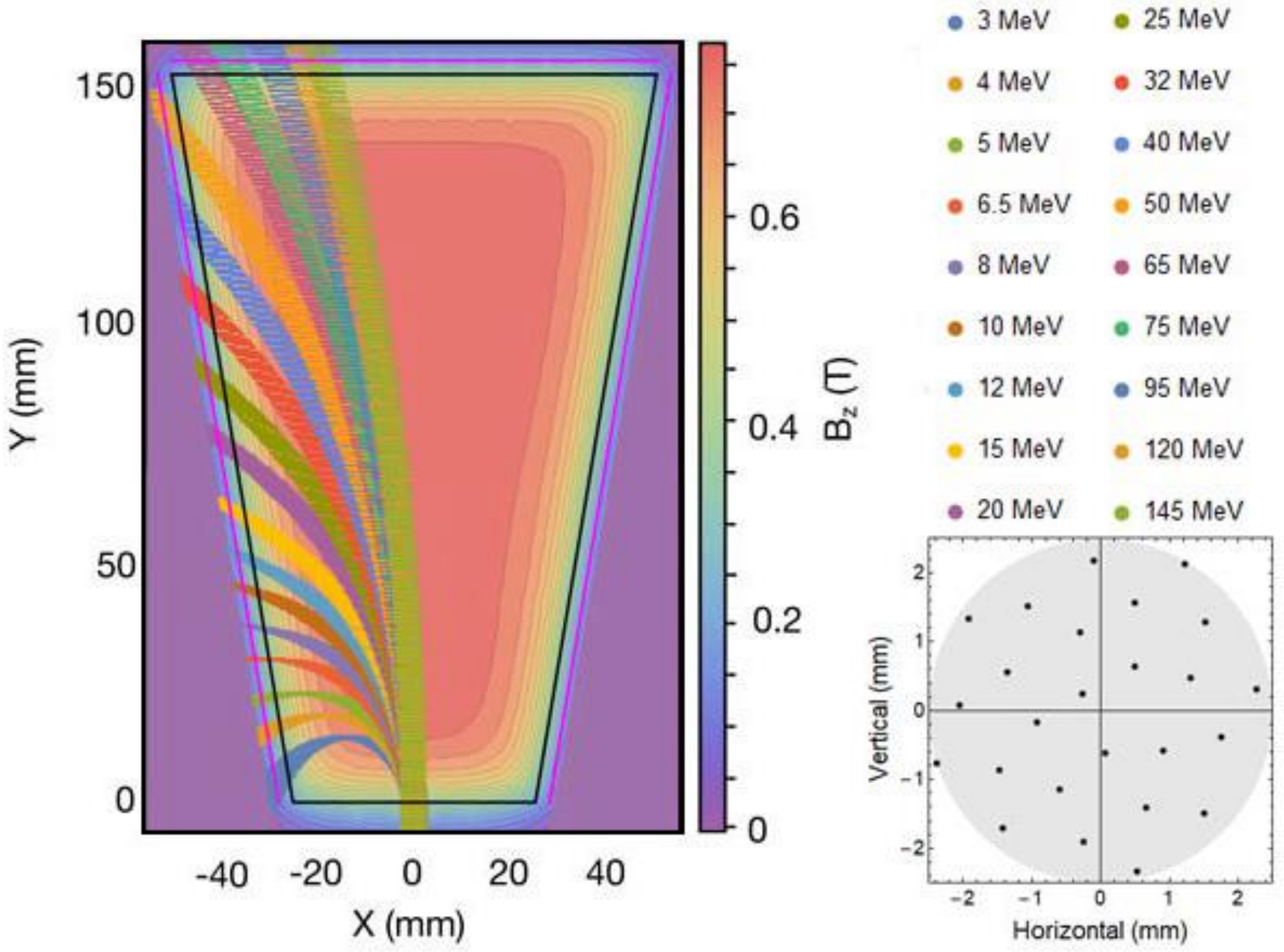
Z=6, R_{cm}=5 fm
P(E)
0.24
0.23
0.22
0.21
0.20
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
E [MeV]
Z=6, R_{cm}=5 fm
ϕ(E)
0.05
0.04
0.03
0.02
0.01
E [MeV]
Z=92, R_{cm}=20 fm
P(E)
1.0
0.8
0.6
0.4
0.2
2
4
6
8
10
12
E [MeV]
Z=92, R_{cm}=20 fm
ϕ(E)
2.5
2.0
1.5
1.0
0.5
E [MeV]

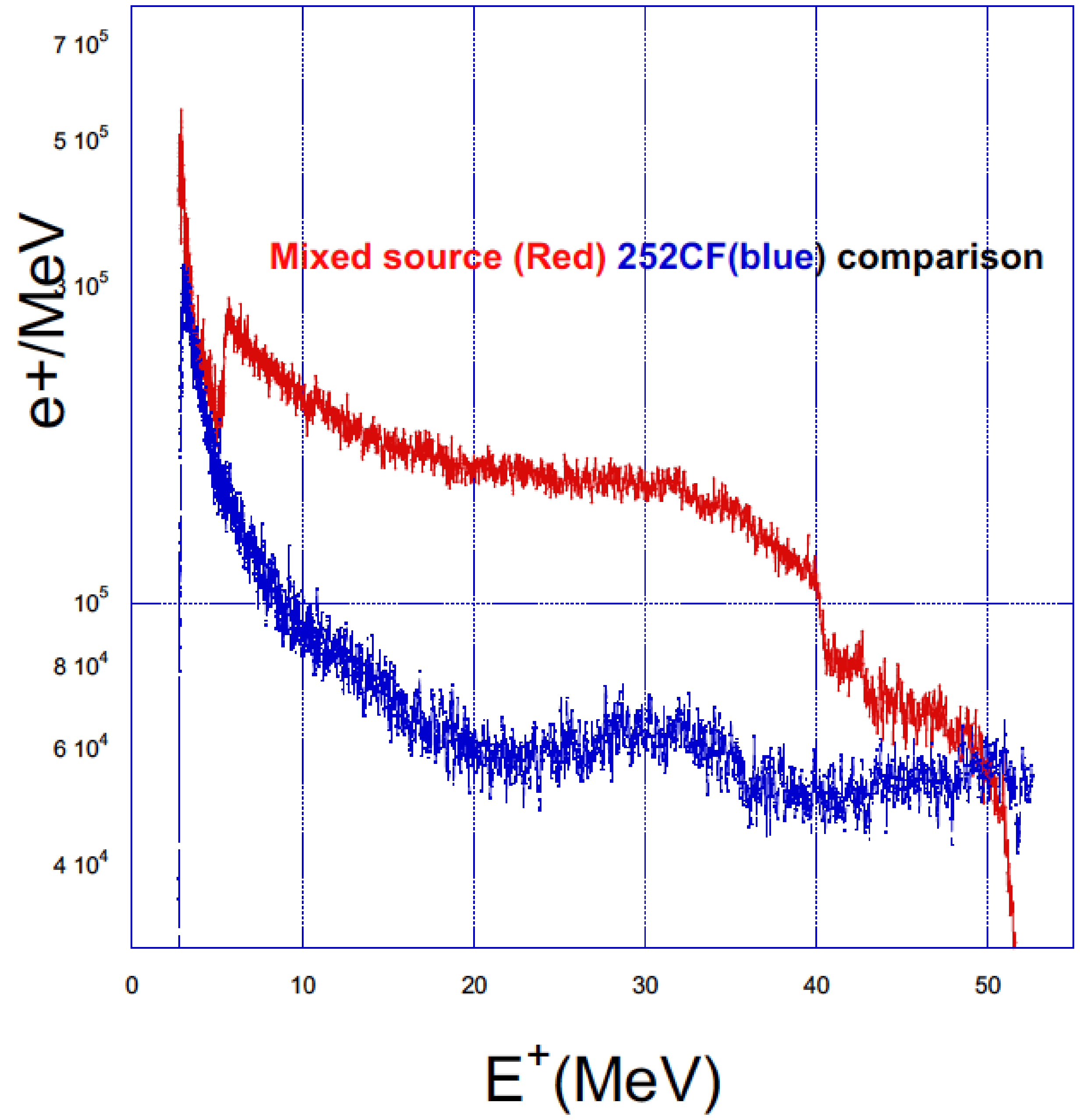
Improved large-energy-range magnetic electron positron spectrometer for experiments with the Texas Petawatt Laser

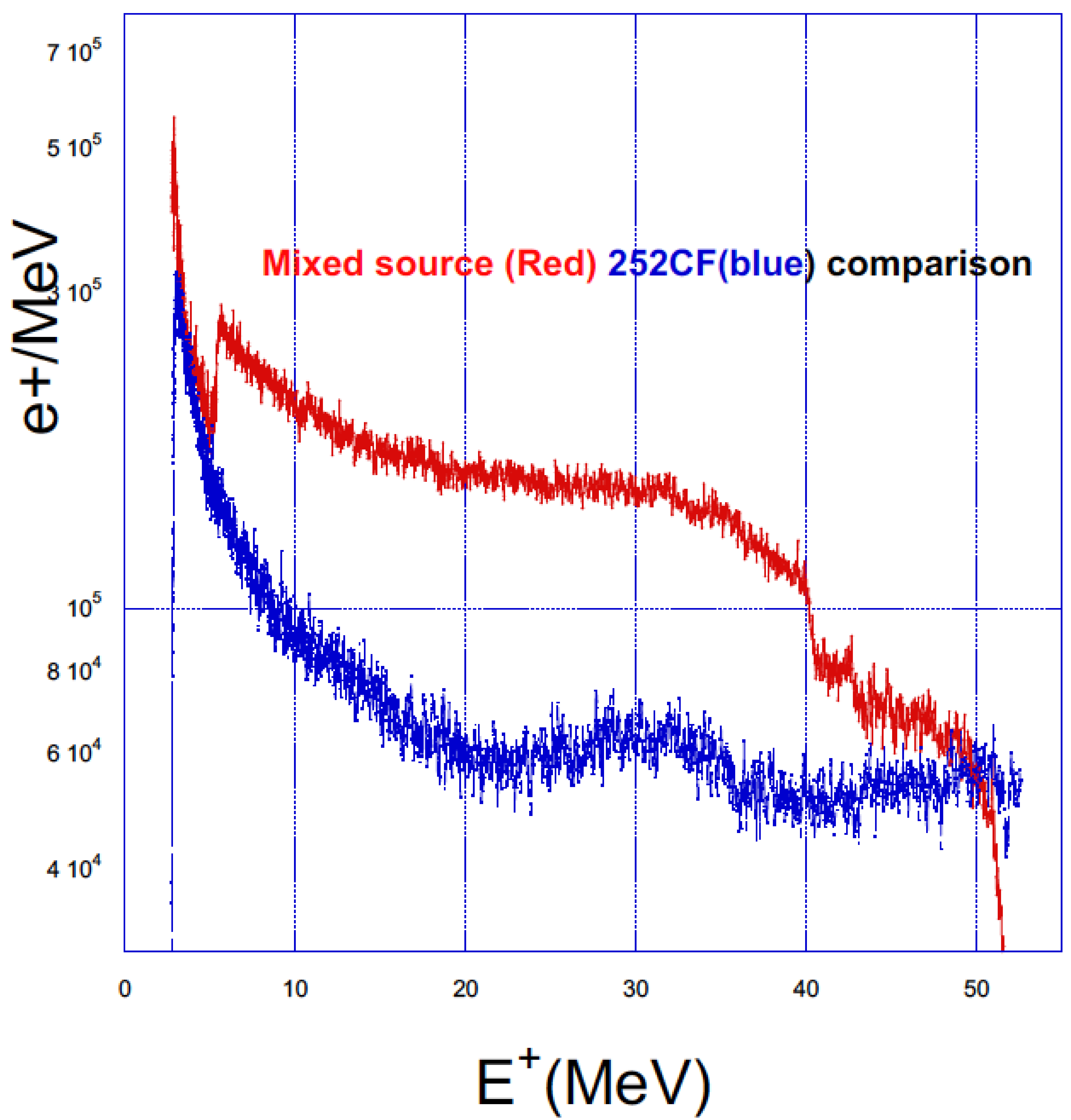
G.D. Glenn et al 2019 JINST 14 P03012

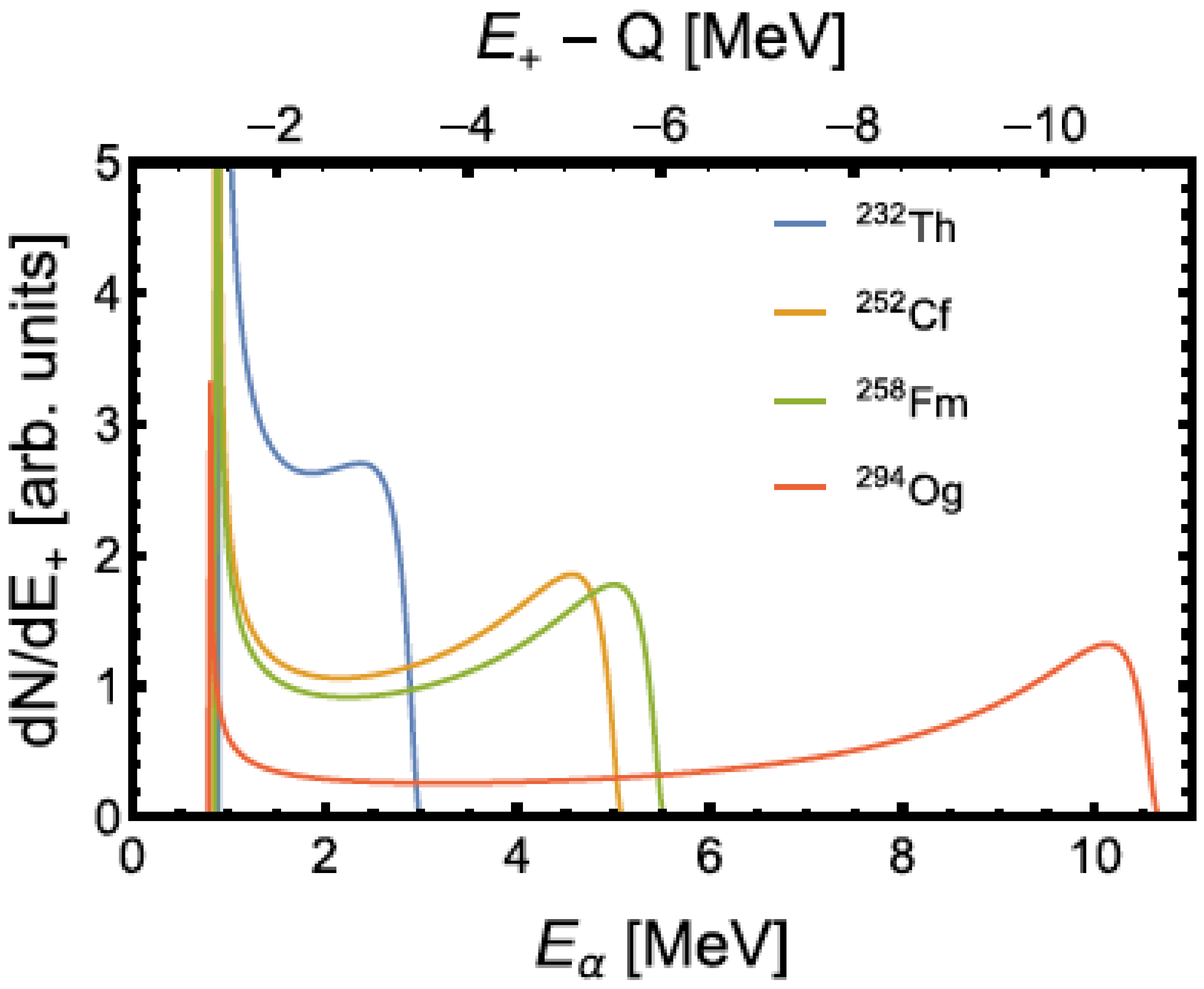


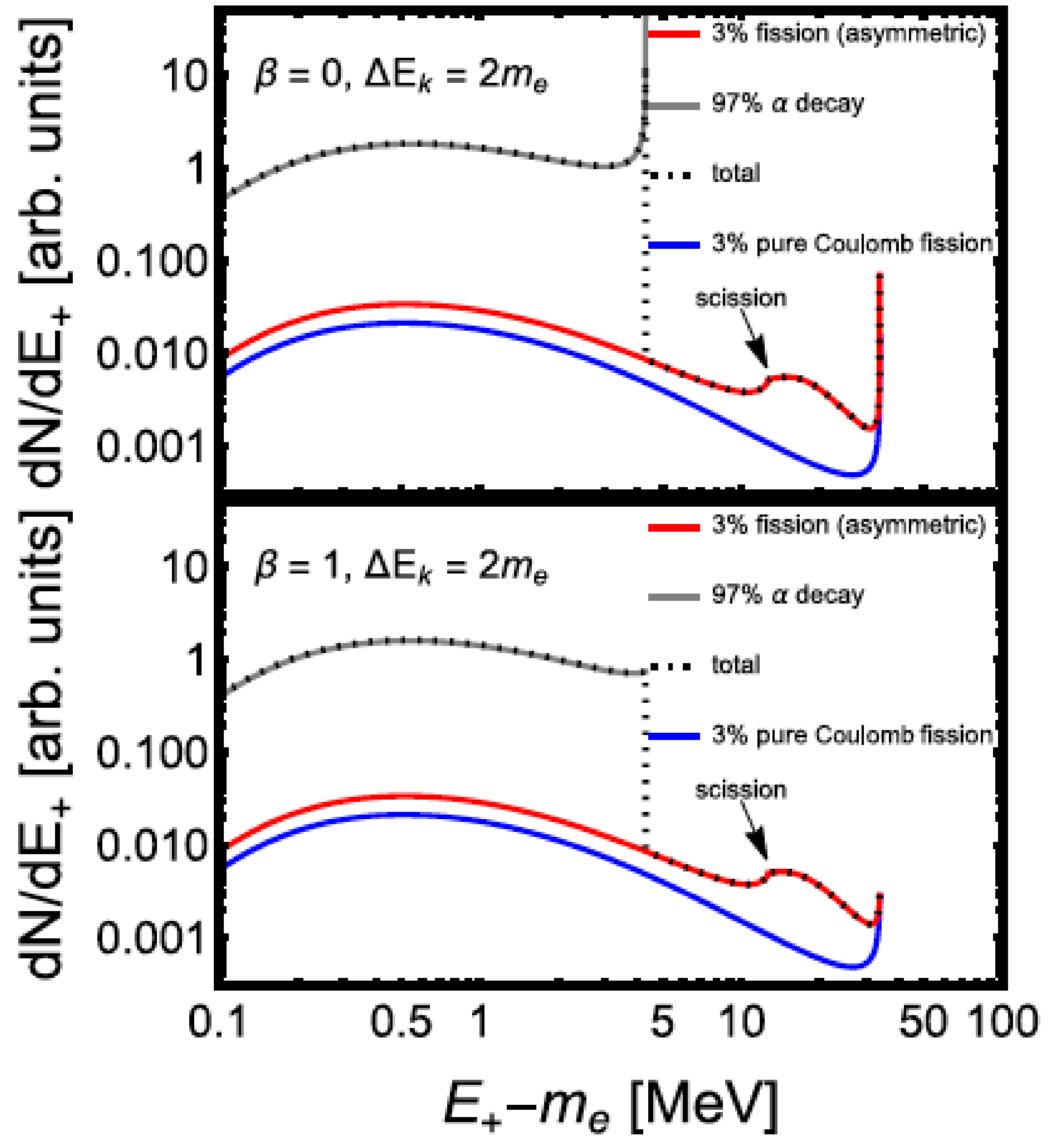







Mixed source (Red) 252CF(blue) comparison
e+/MeV
E+(MeV)
7 10^5
5 10^5
3 10^5
10^5
8 10^4
6 10^4
4 10^4
0
10
20
30
40
50

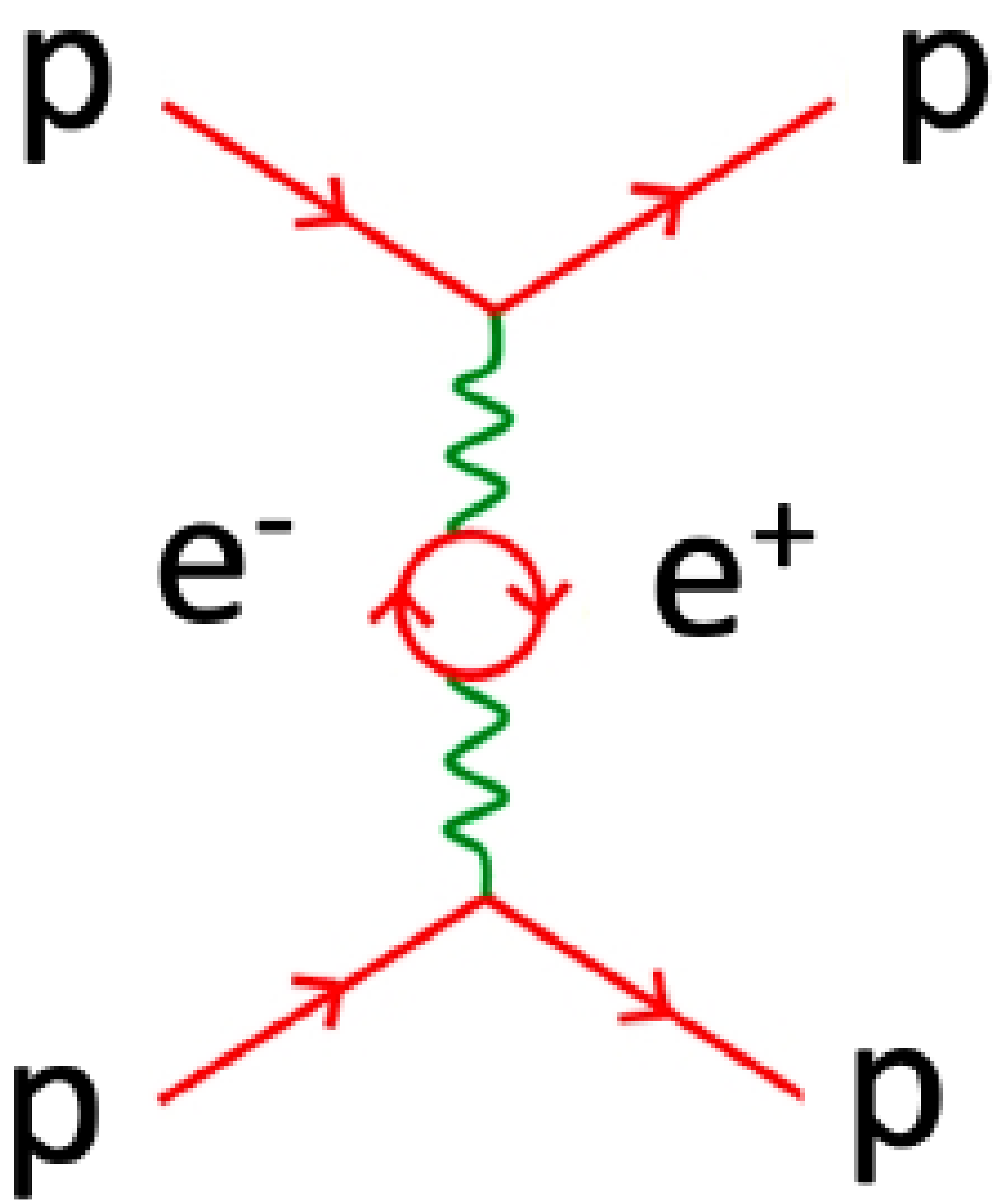

E+ − Q [MeV]
dN/dE+ [arb. units]
Eα [MeV]
232Th
252Cf
258Fm
294Og


β = 0, ΔEk = 2me
β = 1, ΔEk = 2me
3% fission (asymmetric)
97% α decay
total
3% pure Coulomb fission
scission
dN/dE+ [arb. units]
E+−me [MeV]

Conclusions

- electric fields in nuclear systems are strong enough to create real pairs
- energy of pairs can be used to probe dynamics of fission, alpha decay, scattering, fusion, …
- pairs give information about nature of quantum tunneling
- screening length parameter x_s helps understand the structure of the vacuum

Virtual Pair Production



$$V_{e^+e^-}(r) = -\frac{2\alpha}{3\pi}\frac{Z_1 Z_2 e^2}{r}\left(\ln\frac{r}{\lambda_0} + \gamma + \frac{5}{6}\right)$$

Instrumentation Details

- 0.77 T NdFeB magnets
- 5 mm hole
- Texas Petawatt Laser (TPW)
- 140 J, 130 fs pulse of s-polarized laser 1057 nm light
- Phosphor Imaging Plates