中国原子能科学研究院
中核集团 CHINA INSTITUTE OF ATOMIC ENERGY

Study of the optical potential parameters of ^{12}C + nucleus

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Background

- The optical potential is an important tool to study nucleus-nucleus interactions.
- The optical potential is an important quantity to describe not only elastic scattering but also more complicated reactions such as inelastic scattering, breakup, and transfer reactions.

The optical potential

- Phenomenological and Microscopic potentials.

- The parameters of phenomenological potentials can be obtained by analyzing experimental data. Such as Woods-Saxon potential.
- The calculation of microscopic potentials based on the nucleon-nucleon interaction and approximation of nuclear material or nuclear structure. Such as folding potential.

Research status

- The optical potential of reactions induced by light particles have been studied a lot.

- The optical potential parameters always have large ambiguities for reactions between heavy ions because of strong Coulomb interaction, the study is far from satisfied.

Research status

- Microscopic potentials:
  - Sao Paulo Potential (SPP)
  - Phys. Rev. C 66, 014610 (2002)
    - University of Sao Paulo, Spanish.

System	E_{Lab} (MeV)
^{16}O+^{58}Ni	35, 35.5, 36, 36.5, 37, 38
^{16}O+^{60}Ni	35, 35.5, 36, 37, 38
^{16}O+^{62,64}Ni	34, 35, 36
^{16}O+^{88}Sr	43, 44, 45
^{16}O+^{90}Zr	46, 47, 48
^{16}O+^{92}Zr	45, 46, 47, 48
^{16}O+^{92}Mo	48, 48.5, 49
^{16}O+^{120}Sn	53, 54, 55
^{16}O+^{138}Ba	54, 55, 56, 57
^{16}O+^{208}Pb	74, 75, 76, 77, 78
^{18}O+^{58}Ni	35.1, 35.5, 37.1, 38
^{18}O+^{60}Ni	34.5, 35.5, 37.1, 38

System	E_{Lab} (MeV)
p+^{40}Ca, ^{208}Pb	30.3
d+^{40}Ca, ^{208}Pb	52
^{4}He+^{40}Ca, ^{208}Pb	104
^{6}Li+^{12}C, ^{28}Si	210, 318
^{6}Li+^{40}Ca, ^{58}Ni, ^{90}Zr, ^{208}Pb	210
^{7}Li + ^{12}C, ^{28}Si	350
^{12}C+^{12}C	300, 360, 1016, 1440, 2400
^{12}C+^{208}Pb	1440
^{13}C+^{208}Pb	390
^{16}O+^{16}O	250, 350, 480, 704, 1120
^{16}O+^{12}C, ^{28}Si, ^{40}Ca, ^{90}Zr, ^{208}Pb	1504
^{40}Ar + ^{60}Ni, ^{120}Sn, ^{208}Pb	1760

Research status

- Microscopic potentials:
  - Phys. Rev. C 87, 044605 (2013)
    - Beihang University, China
    - Incident particle: ^{6}Li,^{7}Li
    - Target:^{40}Ca~^{208}Pb
    - E_{lab}:30~240 MeV。

$$N_r^{^6\mathrm{Li}}(E_{\mathrm{lab}}) = (0.00424 E_{\mathrm{lab}}/A_P + 0.423) \pm 0.068,$$

$$N_i^{^6\mathrm{Li}} = 1.22 \pm 0.17,$$

$$N_r^{^7\mathrm{Li}} = 0.489 \pm 0.096,$$

$$N_i^{^7\mathrm{Li}} = 1.28 \pm 0.22.$$

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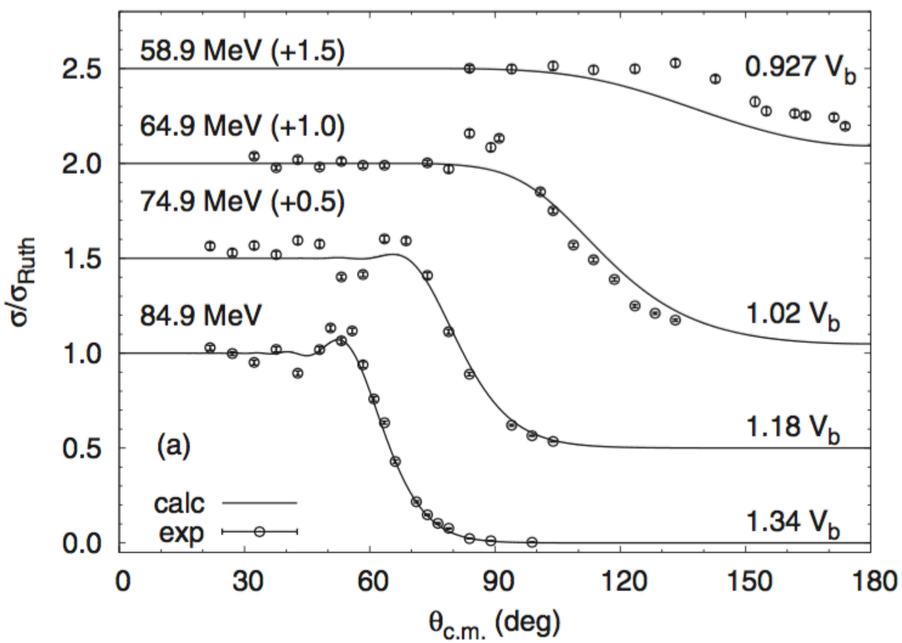
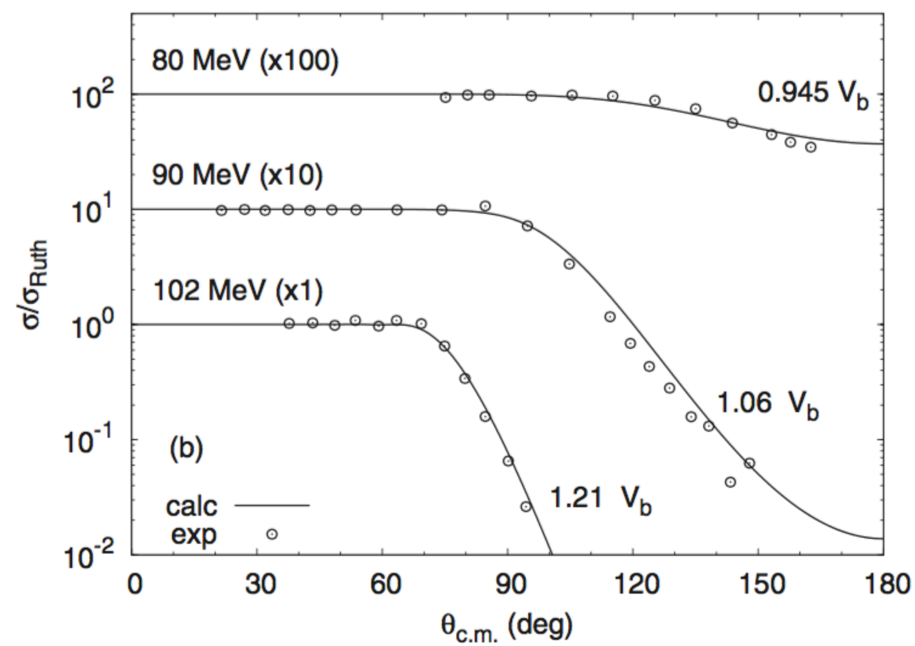
Research status

- Microscopic potentials:
  - Phys. Rev. C 87, 044605 (2013)
    - For other reaction systems



$^{12}C+^{208}Pb$



$^{16}O+^{208}Pb$

Research status

- Phenomenological potentials:
  - Phys. Rev. C 78, 014607 (2008)
    - Guangxi Normal University, China
    - modified Woods-Saxon

$$V_N(R) = \frac{V_0}{1+\exp[(R-R_0)/a]},$$

r_0 (fm)	c (fm)	u_0 (MeV)	κ	a (fm)
1.27	−1.37	−44.16	−0.40	0.75

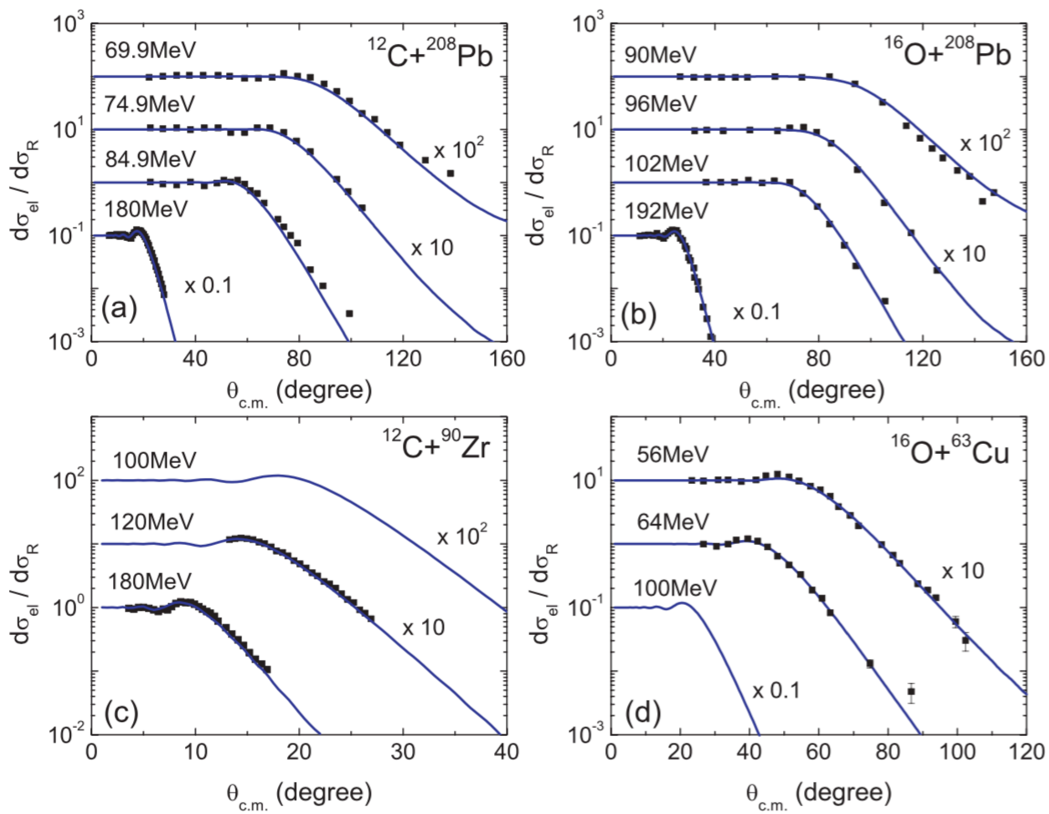
$$V_0 = u_0[1+\kappa(I_1+I_2)]\frac{A_1^{1/3}A_2^{1/3}}{A_1^{1/3}+A_2^{1/3}},$$

$$I_1 = (N_1 - Z_1)/A_1 \text{ and } I_2 = (N_2 - Z_2)/A_2$$

$$R_0 = r_0\left(A_1^{1/3}+A_2^{1/3}\right)+c.$$

Research status

- Phenomenological potentials:
  - Phys. Rev. C 78, 014607 (2008)



Motivation and method

- The study for optical potential for reactions between heavy ions should be carried on.
- In this work, Woods-Saxon (WS) parameters will be extracted through fitting the elastic scattering angular distributions of ^{12}C + heavy ions.
- The ambiguities will be overcome with volume integral.
- Formulas to infer global heavy-ion potential parameters will be summarized.

data sources

NNDC and RNB team of CIAE

Incident particle : ^{12}C

Target: ^{39}K, ^{40}Ca, ^{56}Fe, $^{90,91,92,94,96}Zr$, ^{115}In, ^{169}Tm, ^{209}Bi

E_{lab}: 54 ~420 MeV

• WS parameters setting:

Woods-Saxon form:

$$V_n(r) = \frac{-V}{1 + exp[(r - R_v)/a_v]} + i\frac{-W}{1 + exp[(r - R_w)/a_w]}$$

$$R_i = r_i \times (A_P^{1/3} + A_T^{1/3})$$

Fixed:

W=35 MeV， r_W=1.15 fm， a_W=0.56 fm， r_C=1.0 fm

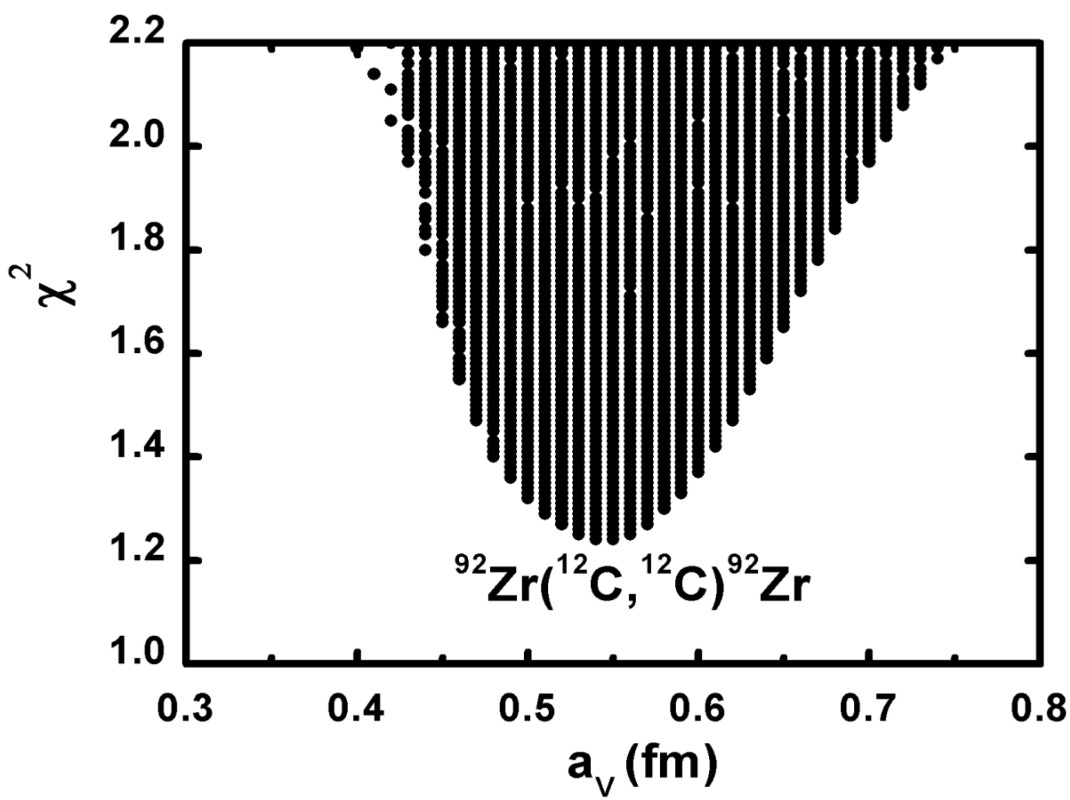
Variables :

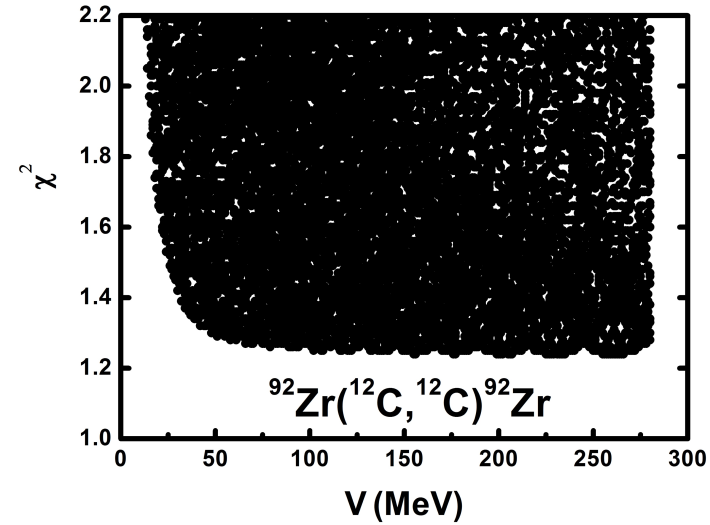
V=20-280 MeV， step: 1 MeV

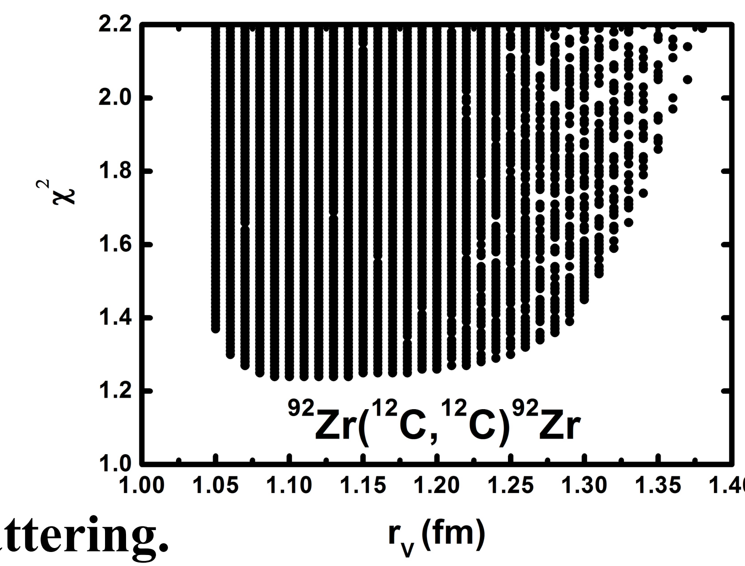
r_V=0.70-1.40 fm， step: 0.01 fm

a_V=0.30-0.80 fm， step: 0.01 fm

- **Result for a_V**

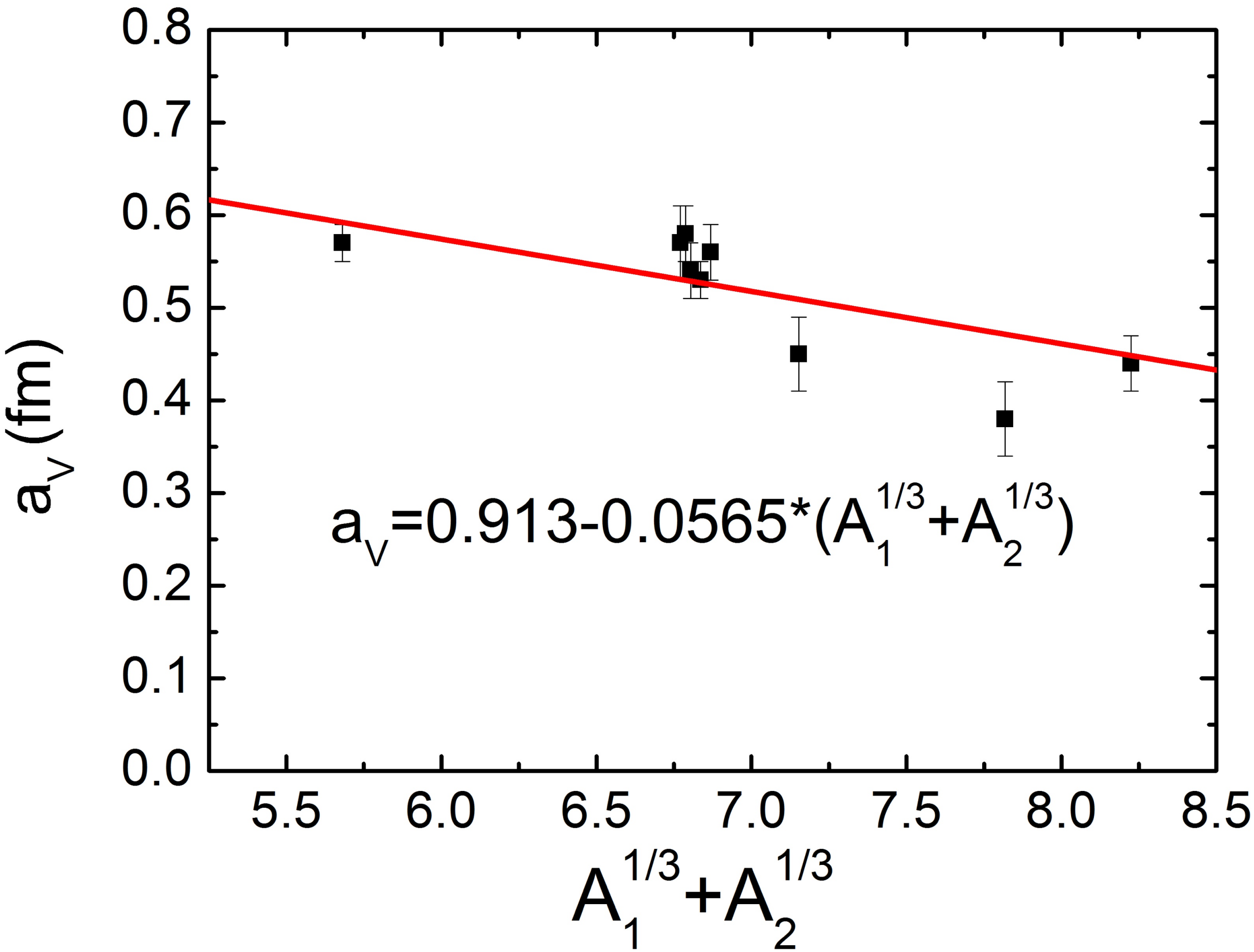






χ^2 versus V, r_V, a_V for $^{12}C + ^{92}Zr$ elastic scattering.

- a_V versus $R_0=(A_1^{1/3}+A_2^{1/3})$



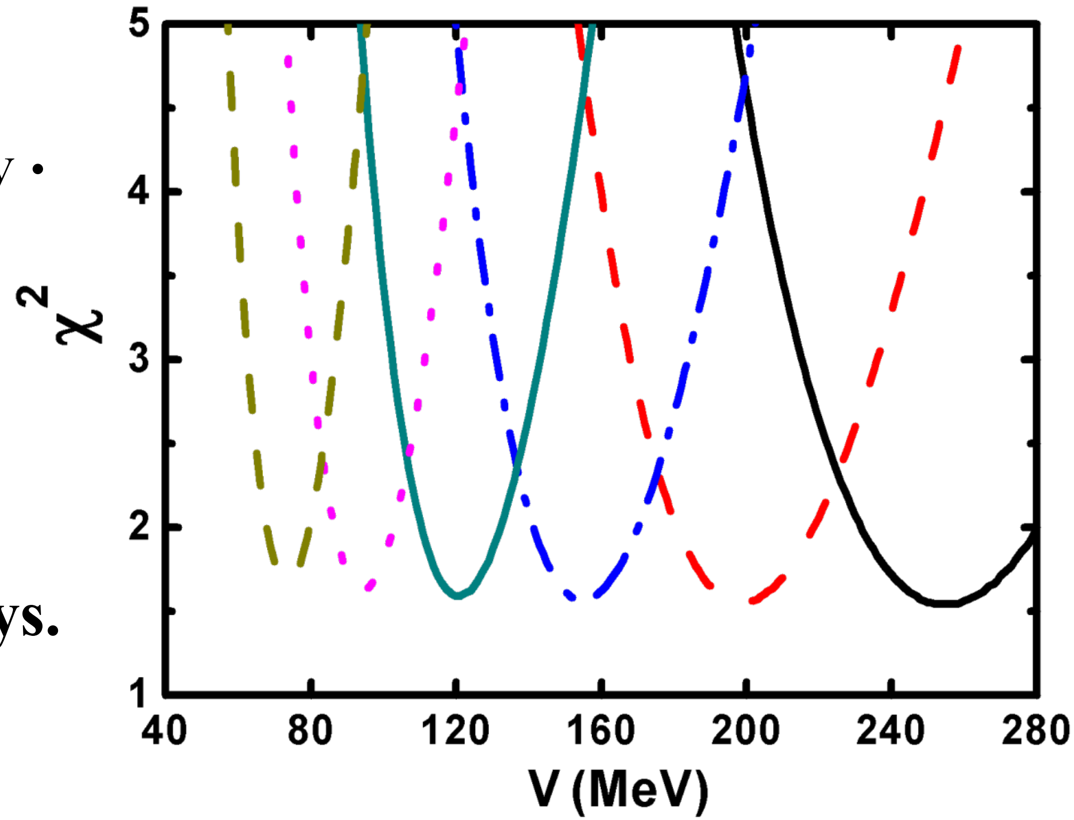
• Optical potential ambiguities

Each curve in picture corresponding to different r_V .

$V \times \exp(R_V/a_V) = const$

$R_V = r_V(A_1^{1/3} + A_2^{1/3})$

The const can be obtained with the parameters of valleys.

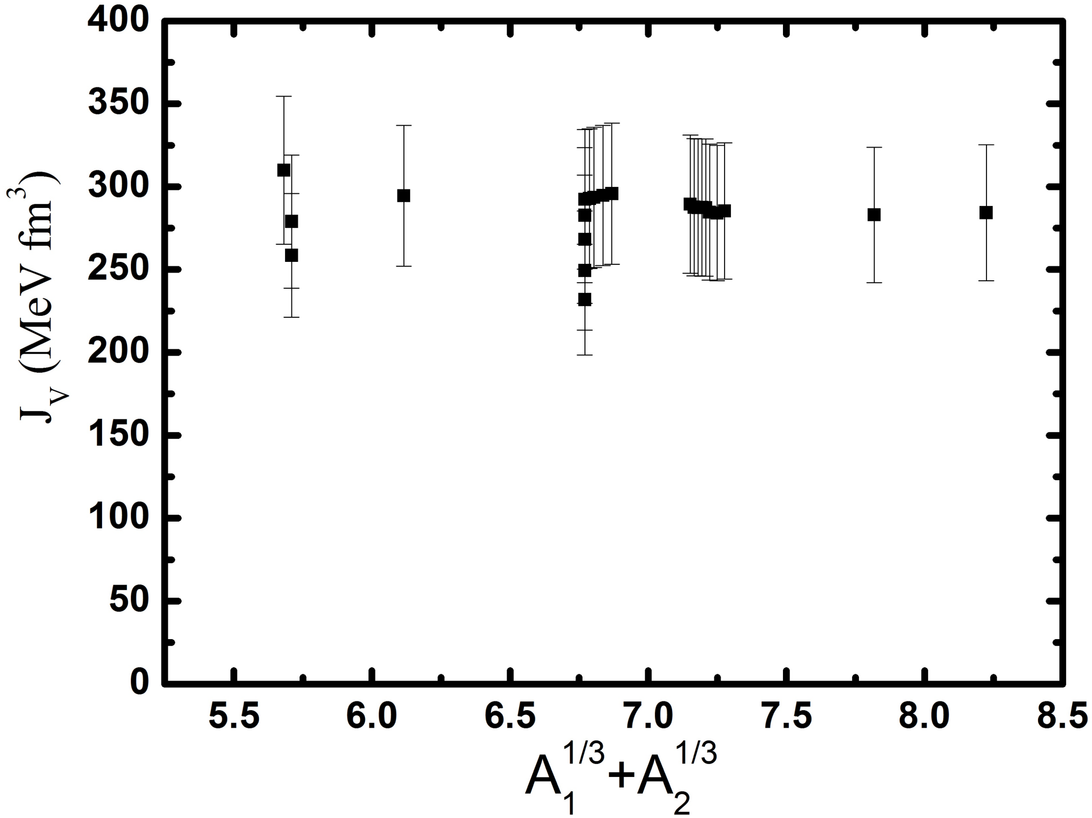


$^{12}C + ^{94}Zr$ elastic scattering

• Volume integral

$$J_V = -\frac{4\pi}{A_P A_T}\int V(r) r^2 dr$$

V(r) employed the double folding form.



• Calculation

$$J_V = -\frac{4\pi}{A_P A_T}\int V(r) r^2 dr$$

$V \times \exp(R_V/a_V) = \text{const}$ ＋

$$V_n(r) = \frac{-V}{1 + exp[(r - R_v)/a_v]}$$

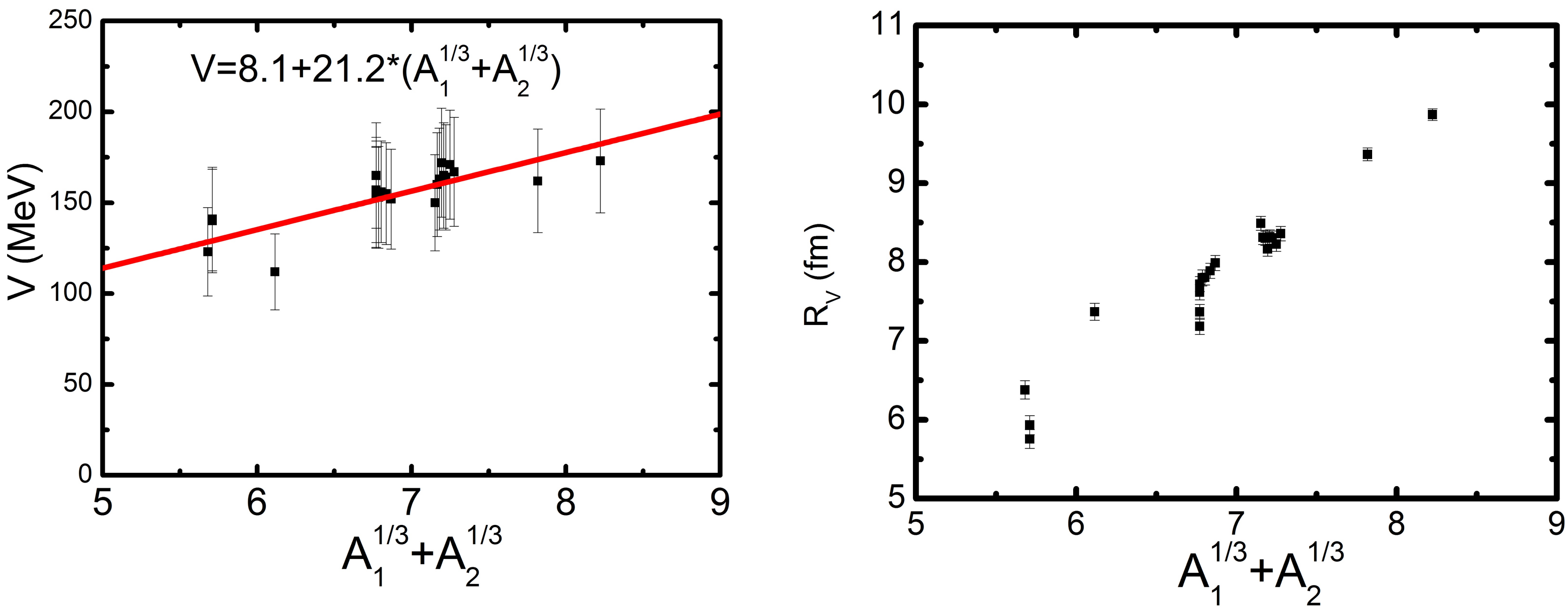
⬇

V and R_V

- **Result --V, R_V**

$$V = 8.1 + 21.2\times({A_1}^{1/3} + {A_2}^{1/3})(\text{MeV})$$

$$R_V = 1.345\times^{({A_1}^{1/3} + {A_2}^{1/3})} - 0.002\times(\text{E} - \text{E}_\text{C}) - 1.318\ (\text{fm})$$



- **Formulas**

$$V = 8.1 + 21.2\times(A_1^{1/3} + A_2^{1/3})(\mathrm{MeV})$$

$$R_V = 1.345\times(A_1^{1/3} + A_2^{1/3}) - 0.002\times(\mathrm{E} - \mathrm{E_C}) - 1.318\ (\mathrm{fm})$$

$$a_V = 0.913 - 0.0565\times(A_1^{1/3} + A_2^{1/3})\quad(\mathrm{fm})$$

$$W = 35\ (\mathrm{MeV})$$

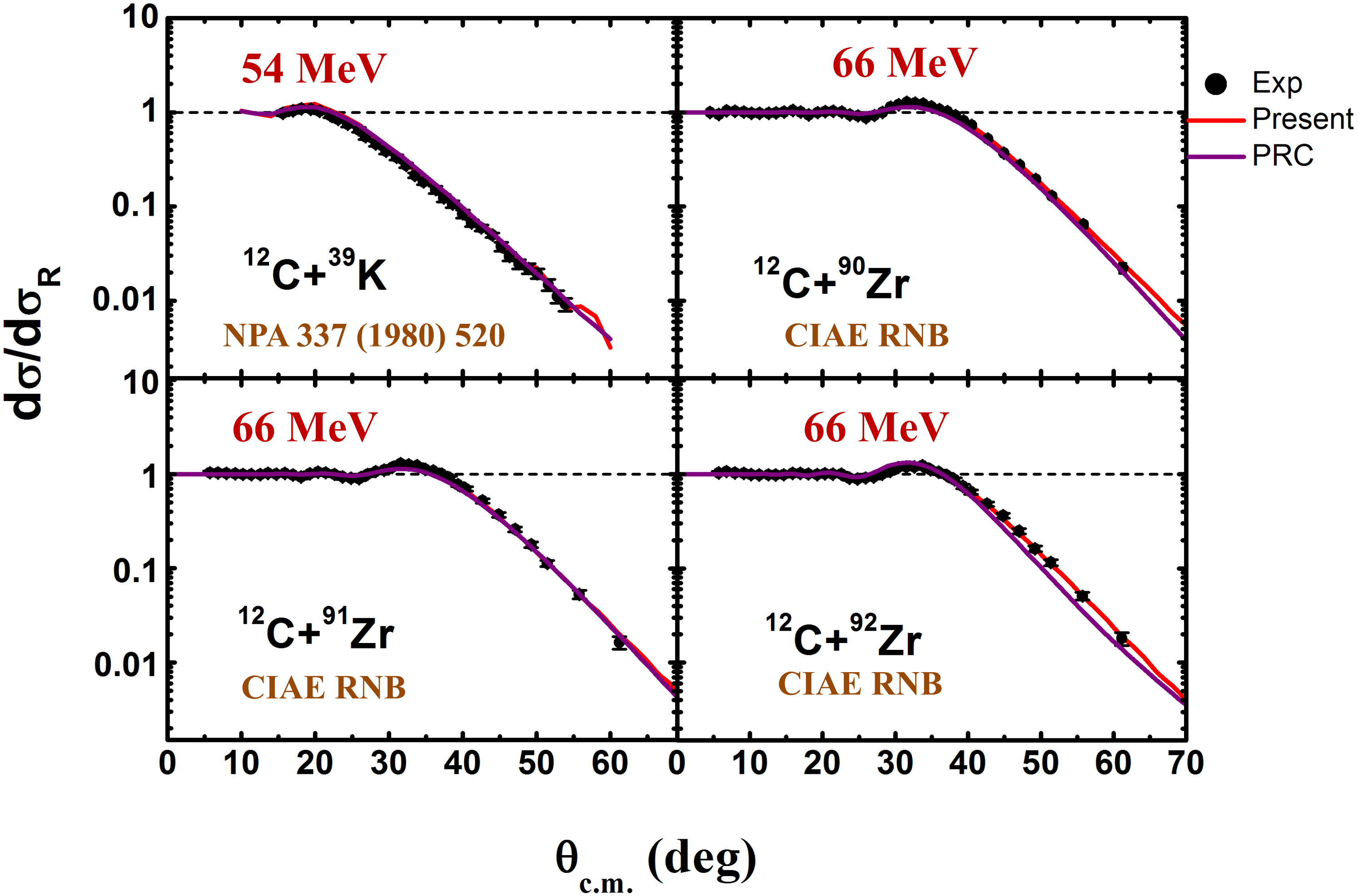
$$R_W = 1.15\times R_0\ (\mathrm{fm})$$

$$a_W = 0.56\ (\mathrm{fm})$$

$$R_C = 1.00\times(A_1^{1/3} + A_2^{1/3})(\mathrm{fm})$$

- $E_C = \dfrac{6Z_P Z_T e^2}{5R_C}$
- $R_V = r_V\times(A_1^{1/3} + A_2^{1/3})$

• Verification



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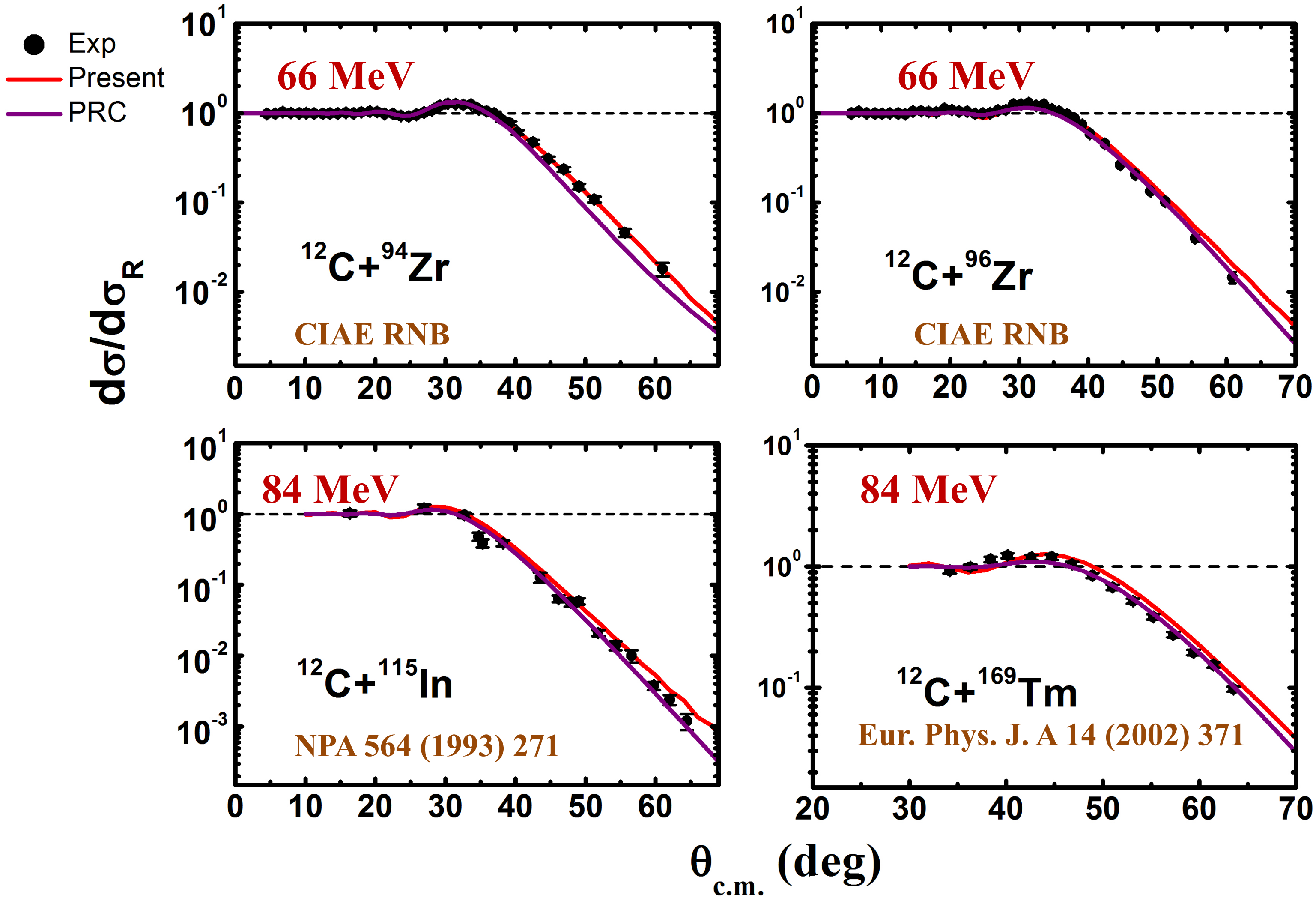
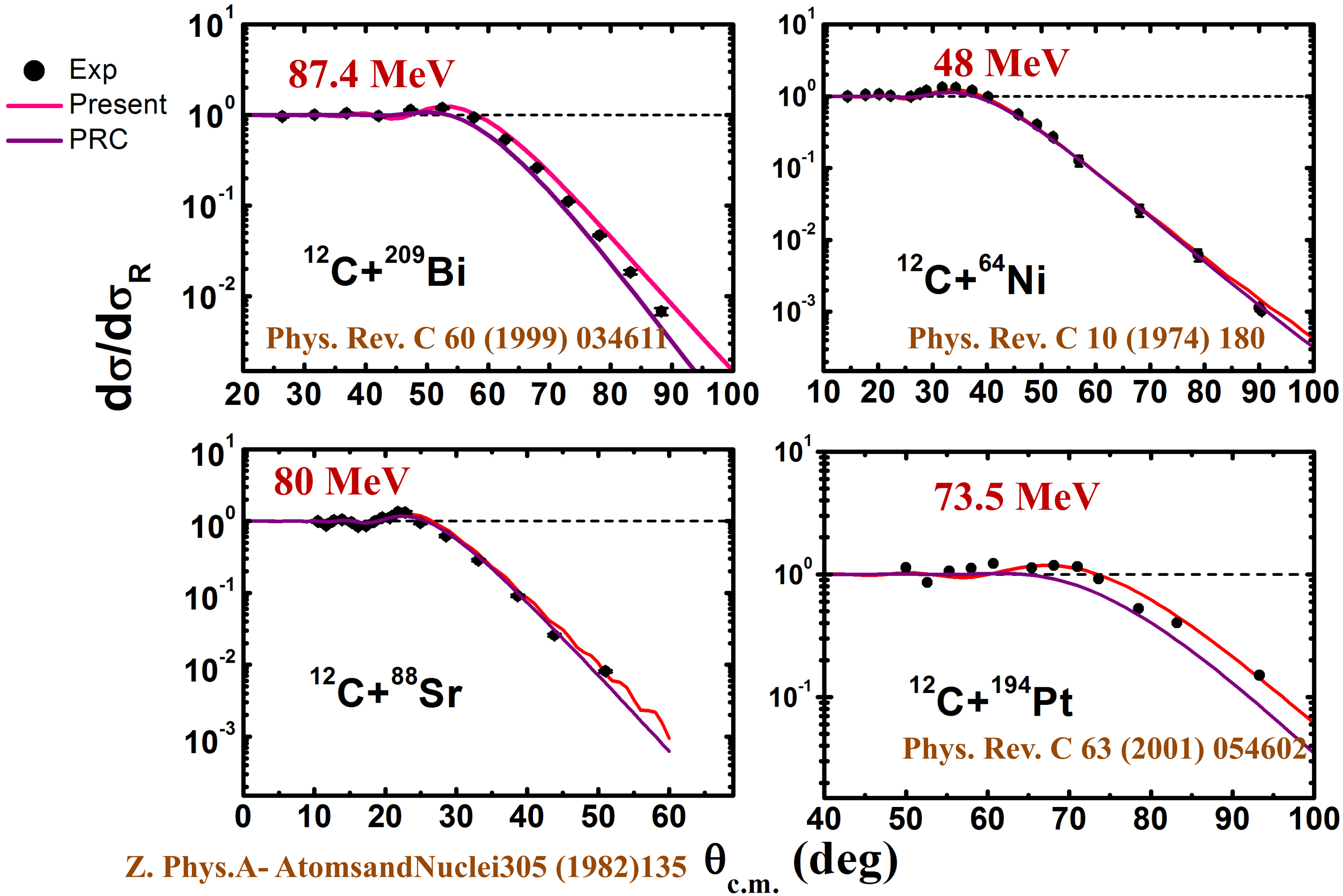
• Verification

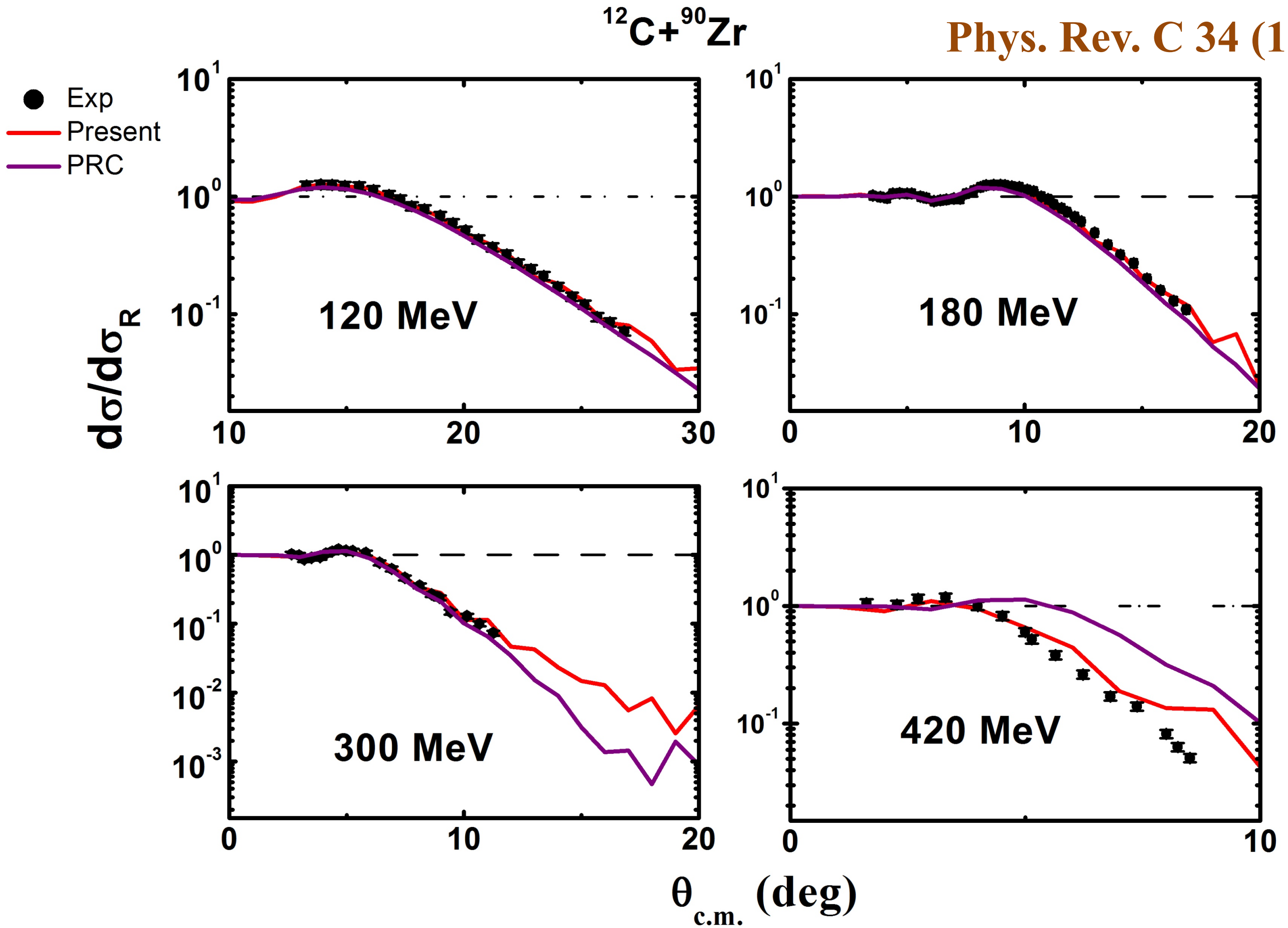


- # Verification



• Verification

Phys. Rev. C 34 (1986) 2165



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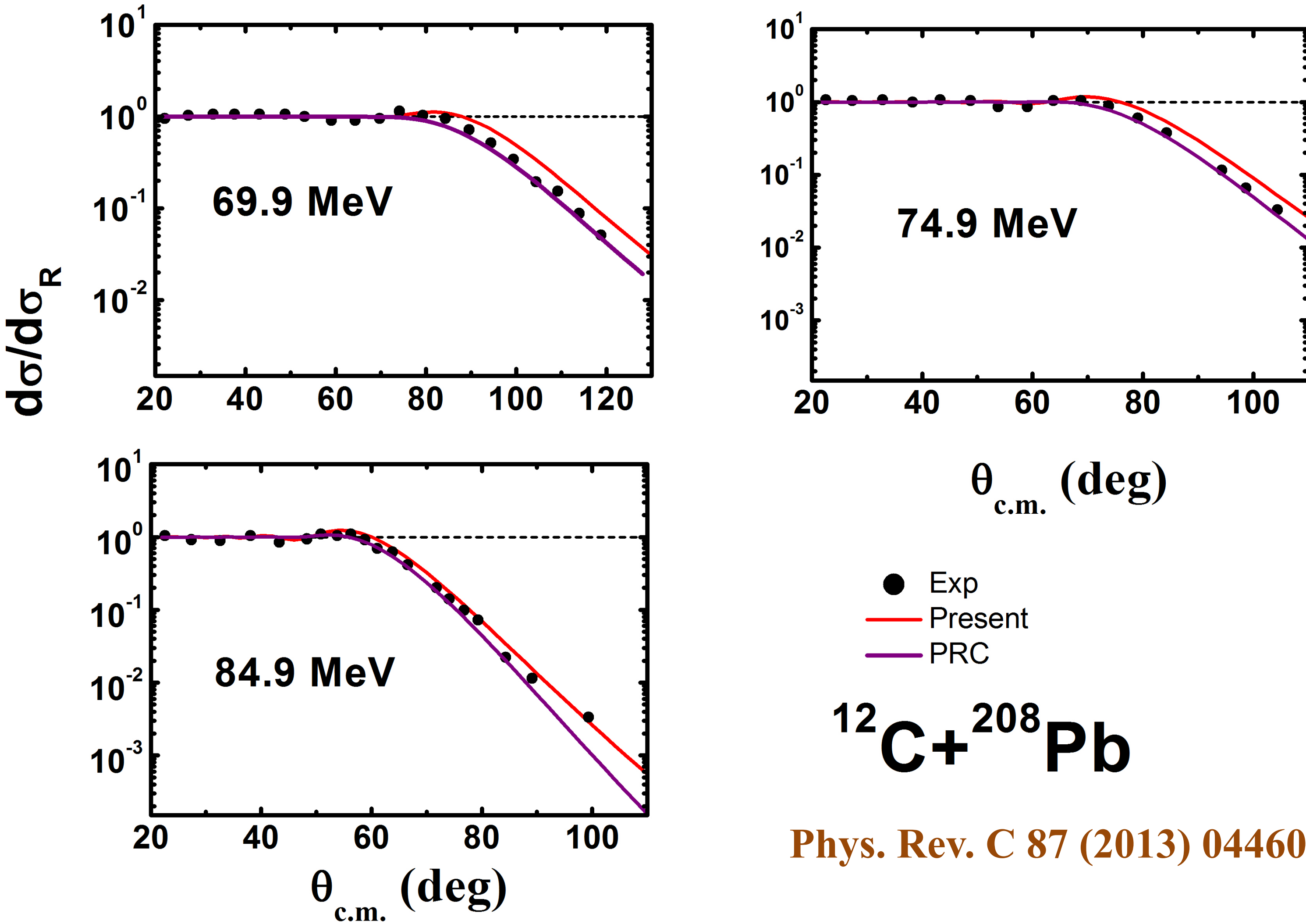
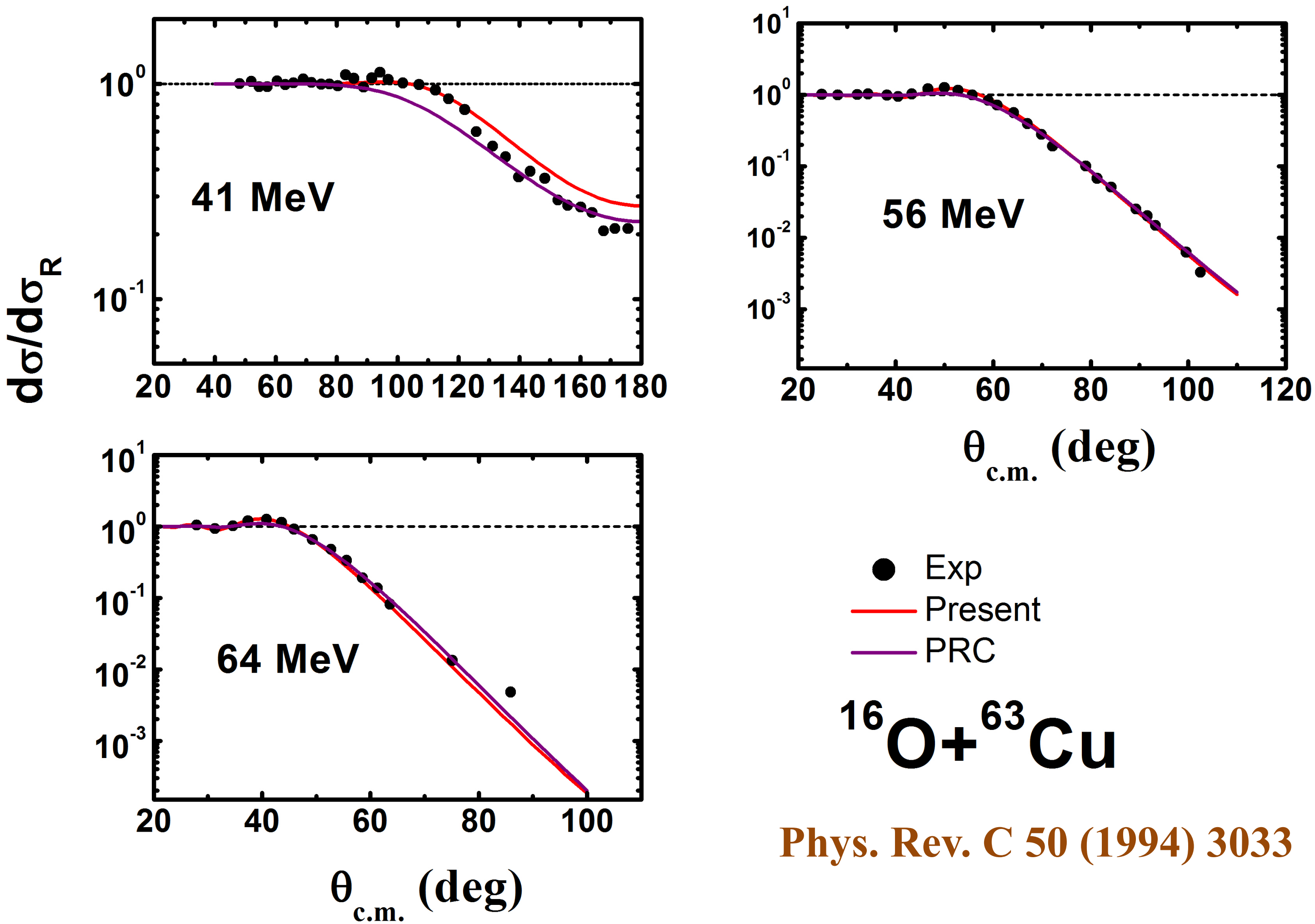


$^{12}C+^{208}Pb$

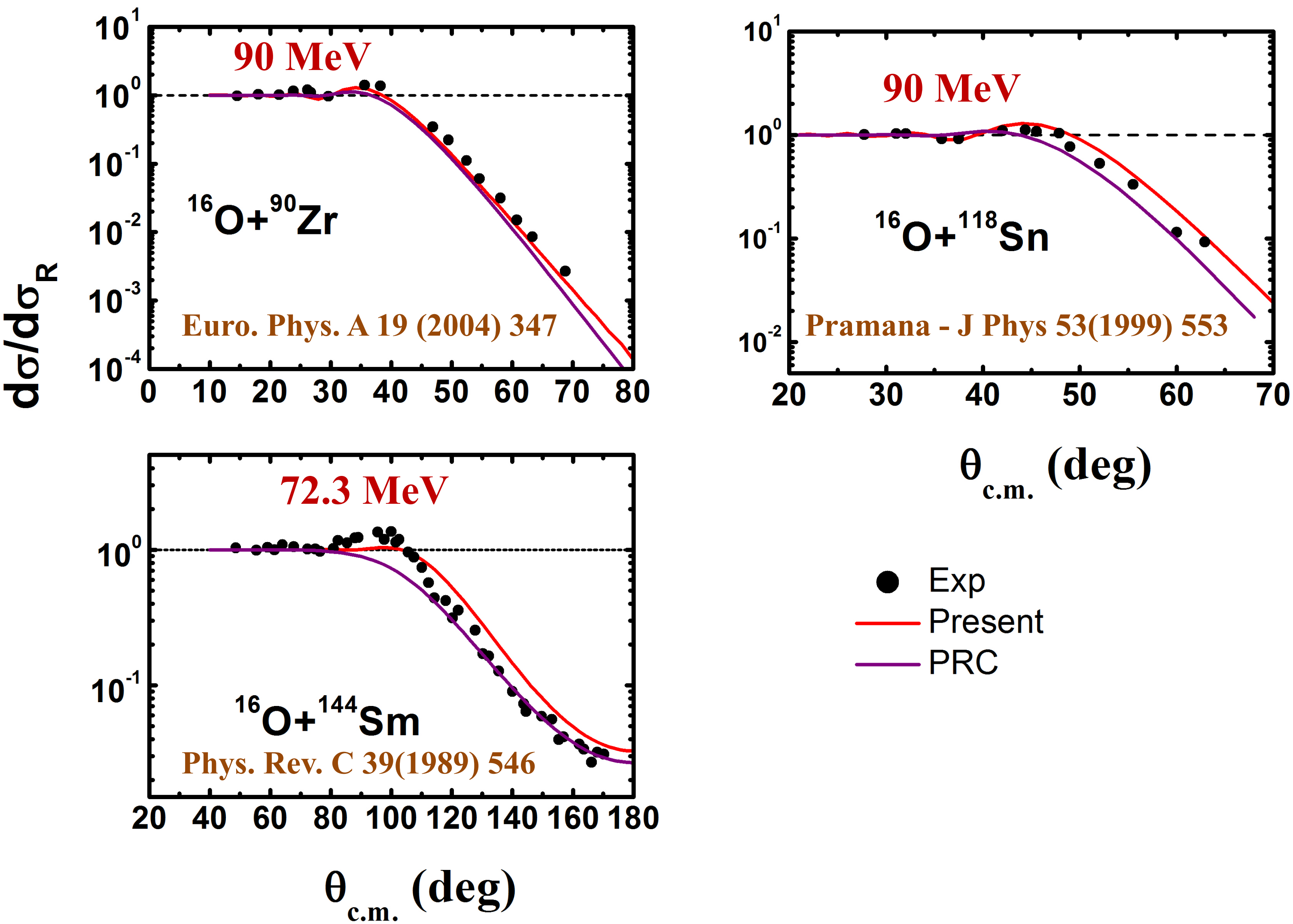
Phys. Rev. C 87 (2013) 044605

• Verification



Phys. Rev. C 50 (1994) 3033

- **Verification**



Summary

- Woods-Saxon parameters for reactions induced by ^{12}C were obtained, and the formulas were summarized.
- The formulas can reproduce a lot of ^{12}C and ^{16}O+ heavy ions' experimental data.
- More data will be introduced to test the applicability of the formulas in the future.

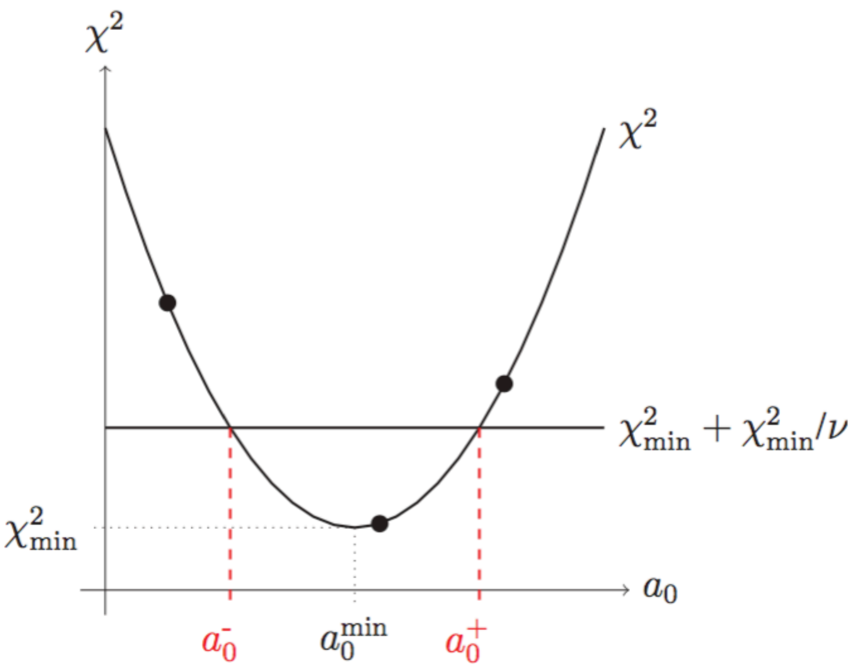
THANKS

• Uncertainty of a_V

$$\hat{\chi}^2 = \chi^2_{\min} + \frac{\chi^2_{\min}}{\nu}, \tag{6}$$

was calculated, where ν denotes the number of degrees of freedom. The intersection of $\hat{\chi}^2$ with the χ^2 envelope gives the two values a_0^-, a_0^+, as shown in Fig. 5, resulting in an error

$$\Delta a_0 = \frac{a_0^+ - a_0^-}{2}.$$



Phys. Rev. C 78, 034614 (2008)

ν denotes the number of degrees of freedom.

- **E_C : Columb correction**

PHYSICAL REVIEW C 79, 024615 (2009)
PHYSICAL REVIEW C 94, 014619 (2016)

where E_C is the Coulomb correction to the incident energy [5,8,15]:

$$E_C = \frac{6Z_P Z_T e^2}{5R_C}, \tag{4}$$