Consistent folding model analysis of ^{6}Li and ^{6}He elastic scattering

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QE nucleus-nucleus scattering *a+A->b+B*

Elastic scattering

OM

Optical Pot. *U(a+A)*

Microscopic: Yes
Phenomen. : Yes/No

Inelastic scattering
Charge-exchange

DWBA or CC

Trans. Form Factor

Microscopic: Yes
Phenomen. : Yes/No

Transfer reaction

OM ?

Optical Pot. *U(b+B)*

Microscopic: May be
Phenomen. : No

Optical potential between two composite nuclei is a complicated many-body problem due to the heavy-ion collision dynamics. An approximate microscopic approach can be formulated based on the reaction theory by Feshbach
(H. Feshbach, Theoretical Nuclear Physics, Vol. II, Wiley, NY, 1992)

$$U = U_{00} + \lim_{\epsilon \to 0} \sum_{\alpha\alpha'}{}' U_{0\alpha} \left(\frac{1}{E - H + i\epsilon} \right)_{\alpha\alpha'} U_{\alpha' 0} = U_{00} + \Delta U$$

U_{00} can be evaluated using the double-folding method
=> Hartree-Fock-type potential

$$U_{00} = \sum_{i\in a, j\in A} [< ij|v_{\rm D}|ij > + < ij|v_{\rm EX}|ji >]$$

At low and medium energies, $v_{\rm D(EX)}$ must be based on a Brueckner Hartree Fock G-matrix => *complex, energy- and density dependent*

Complex bare nucleus-nucleus OP

$$U_{00} = V_{\rm F} + iW_{\rm F}$$

CDJLM: New complex density dependent interaction based on BHF results for nuclear matter and the effective M3Y-Paris interaction.

U_{00} is a vital input for any coupled reaction channel calculation !

PHYSICAL REVIEW C VOLUME 16, NUMBER 1 JULY 1977

Optical-model potential in finite nuclei from Reid's hard core interaction

J.-P. Jeukenne, A. Lejeune, and C. Mahaux

Brueckner G-matrix

$$g_\rho[w] = v + v \sum_{a,b>k_F} \frac{|\vec{a},\vec{b}\rangle\langle\vec{a},\vec{b}|}{w - e_\rho(a) - e_\rho(b) + i\delta}\, g_\rho[w] \;,$$

Mass operator in the BHF approximation

$$M_\rho(k,\mathcal{E}) = \sum_{j<k_F} \langle\vec{j},\vec{k}\,|g_\rho[\mathcal{E}+e_\rho(j)]\,|\,\vec{j},\vec{k}\rangle_a$$

Isoscalar OP of a nucleon incident on nuclear matter at the energy E

$$V_0(\rho,E) = \mathrm{Re}M_\rho(k_\rho(E),E)\,,$$

$$W_0(\rho,E) = m[\overline{m}(\rho,E)]^{-1}\,\overline{W}_0(\rho,E)\,,$$

$$\overline{W}_0(\rho,E) = \mathrm{Im}M_\rho(k_\rho(E),E)\,,$$

$$\overline{m}(\rho,E)/m = \left[1 - \frac{\partial}{\partial\mathcal{E}}\mathrm{Re}M_\rho(k_\rho(E),\mathcal{E})\right]_{\mathcal{E}=E}$$

Mean-field absorption

(finite nucleon mean free path in nuclear medium)

Using **CDM3Y** functional form for the density dependence

$$F_u(E,\rho) = C_u(E)[1+\alpha_u(E)\exp(-\beta_u(E)\rho)-\gamma_u(E)\rho]$$

D.T. Khoa, G.R. Satchler, W. von Oertzen, *Phys. Rev.* C **56**, 954 (1997)

to construct separately the real (*u=V*) and imaginary (*u=W*) parts of the CDJLM interaction

$$\begin{aligned} \mathrm{Re}\ v_{\mathrm{D(EX)}}(E,\rho,s) &= F_{\mathrm{V}}(E,\rho)v_{\mathrm{D(EX)}}(s), \\ \mathrm{Im}\ v_{\mathrm{D(EX)}}(E,\rho,s) &= F_{\mathrm{W}}(E,\rho)v_{\mathrm{D(EX)}}(s) \end{aligned}$$

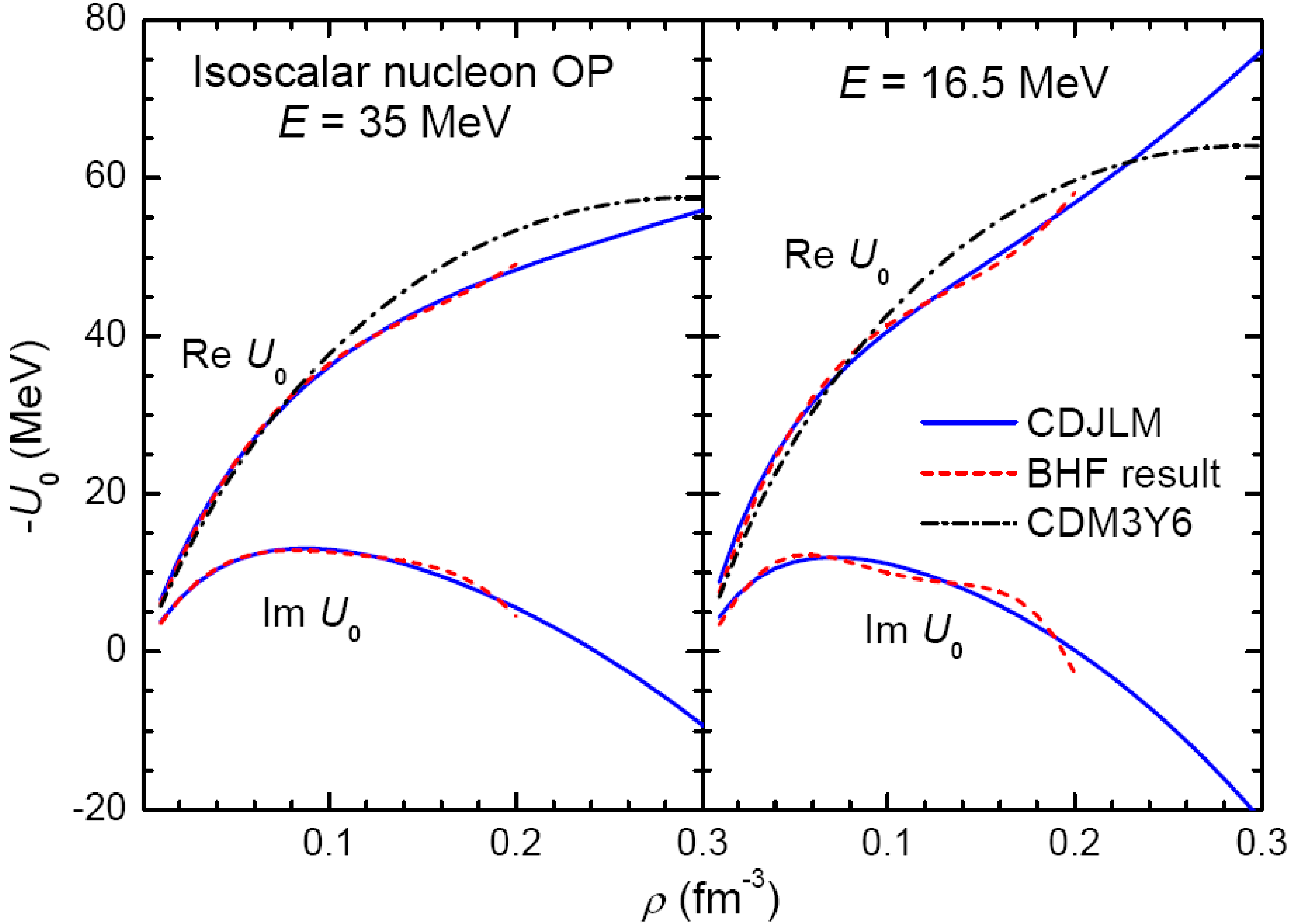
$v_{\mathrm{D(EX)}}$ ⟸ M3Y-Paris interaction by N. Anantaraman, H. Toki, G.F. Bertsch, *Nucl. Phys*. A **398**, 269 (1983).

Isoscalar nucleon OP in the HF approximation

$$U_0(E,\rho) = \sum_{j\le k_F}[<\boldsymbol{kj}|v_{\mathrm{D}}(E,\rho)|\boldsymbol{kj}> + <\boldsymbol{kj}|v_{\mathrm{EX}}(E,\rho)|\boldsymbol{jk}>]$$

$$k_F = [1.5\pi^2\rho]^{1/3},\ k = \sqrt{\frac{2m}{\hbar^2}\{E - \mathrm{Re}\ U_0(E,\rho)\}}$$

Parameters of $F(E,\rho)$ adjusted iteratively at each energy E until $U_0(E,\rho)$ agrees with that calculated at energy E in the BHF approximation by J.P. Jeukenne, A. Lejeune and C. Mahaux, *Phys. Rev*. C 16, 80 (1977).



BHF result: Nuclear matter calculation by J.P. Jeukenne, A. Lejeune, C. Mahaux, *Phys. Rev*. C **16**, 80 (1977)

CDM3Y6: D.T. Khoa, G.R. Satchler, W. von Oertzen, *Phys. Rev.* C **56**, 954 (1997)

99 MeV data: P. Schwandt *et al*., *Phys. Rev*. C **24**, 1522 (1981)

MSU Cyclotron

156 MeV data: J. Cook *et al*., *Nucl. Phys*. A **388**, 173 (1982)

Karlsruhe Cyclotron

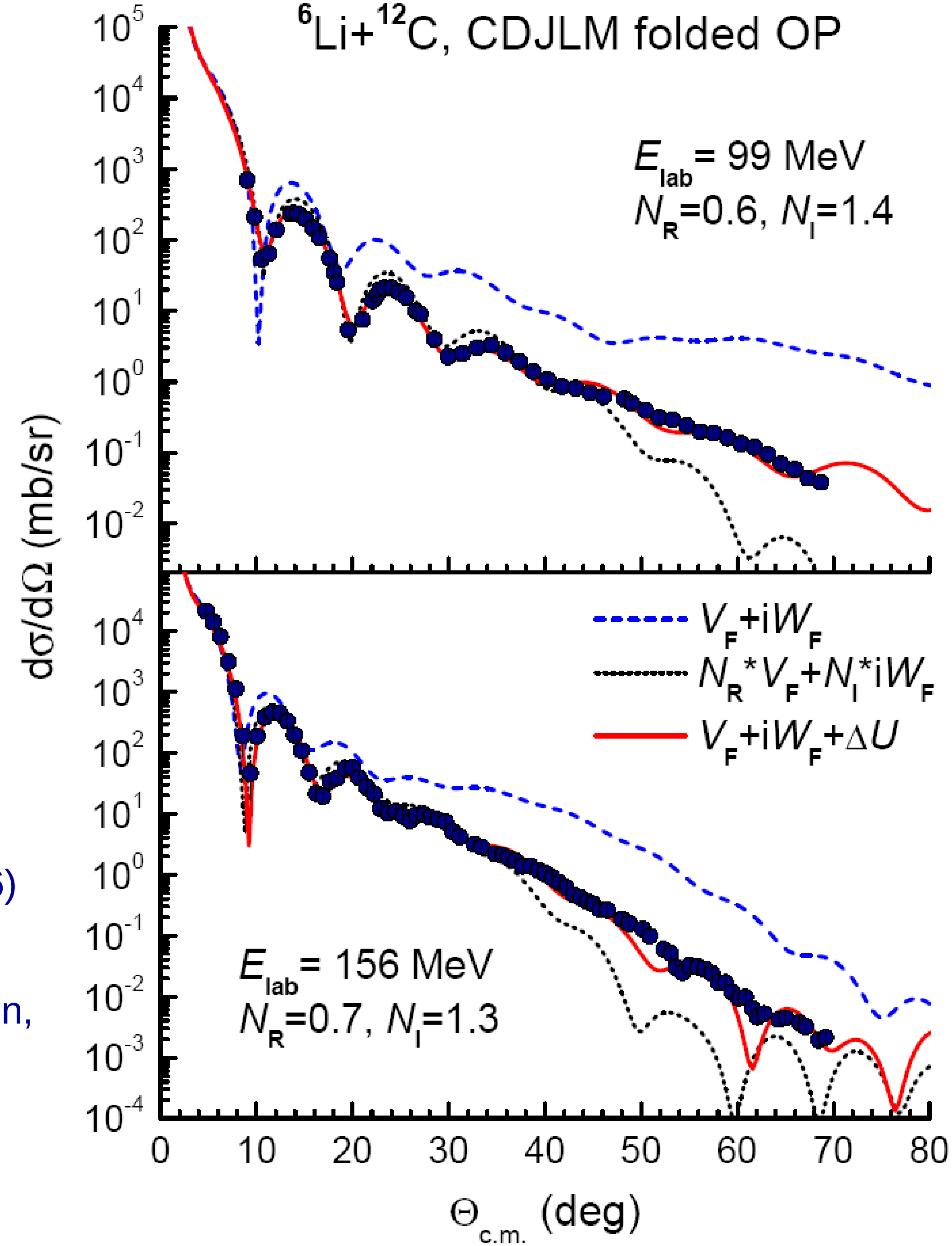
Very strong dynamic polarization of the OP by breakup !

Y. Sakuragi, M. Yahiro, M. Kamimura, *Prog. Theor. Phys. Suppl*. **89**, 136 (1986)

CDCC study

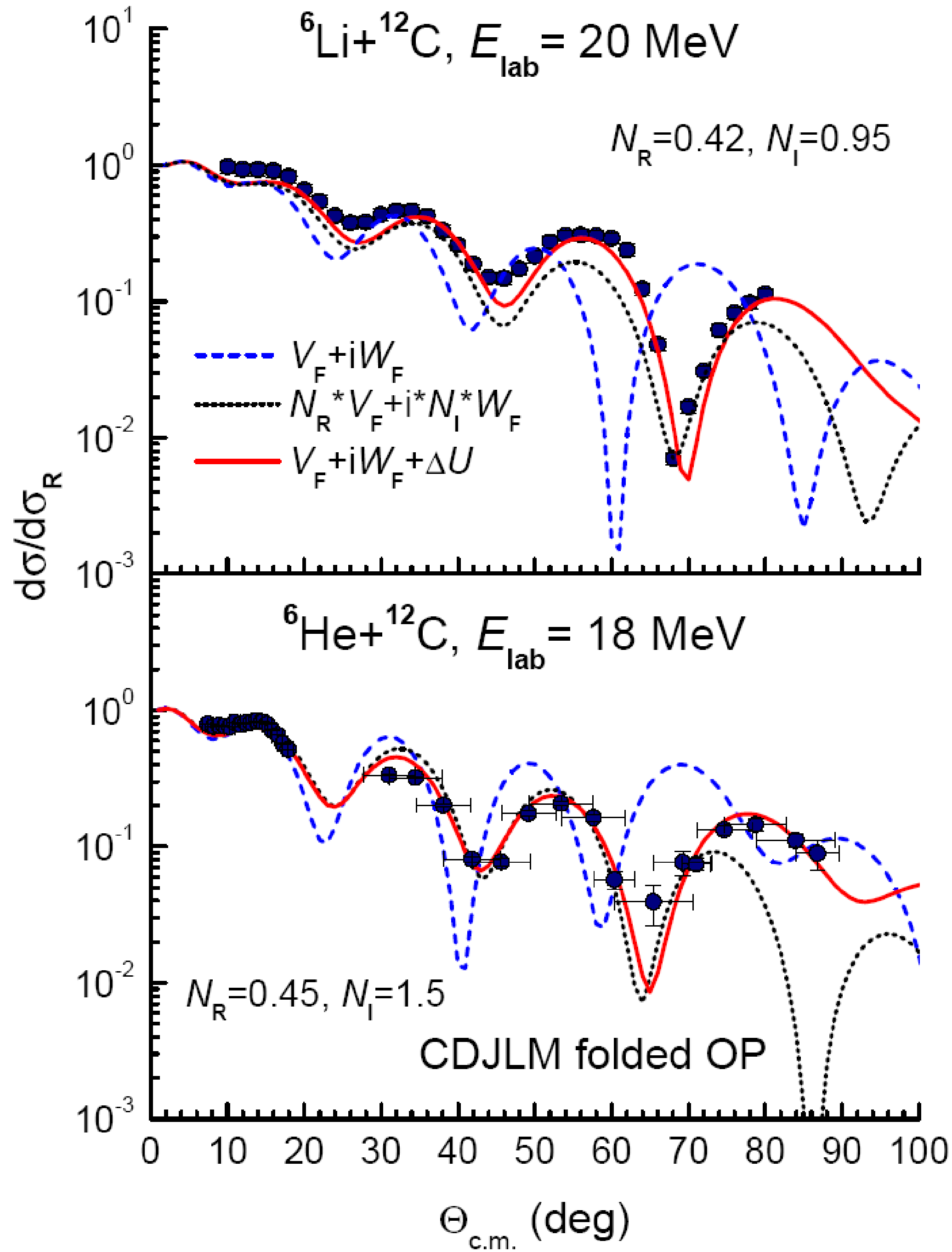
D.T. Khoa, G.R. Satchler, W. von Oertzen, *Phys. Rev*. C **51**, 2069 (1995)

OM study (Folding + Spline)



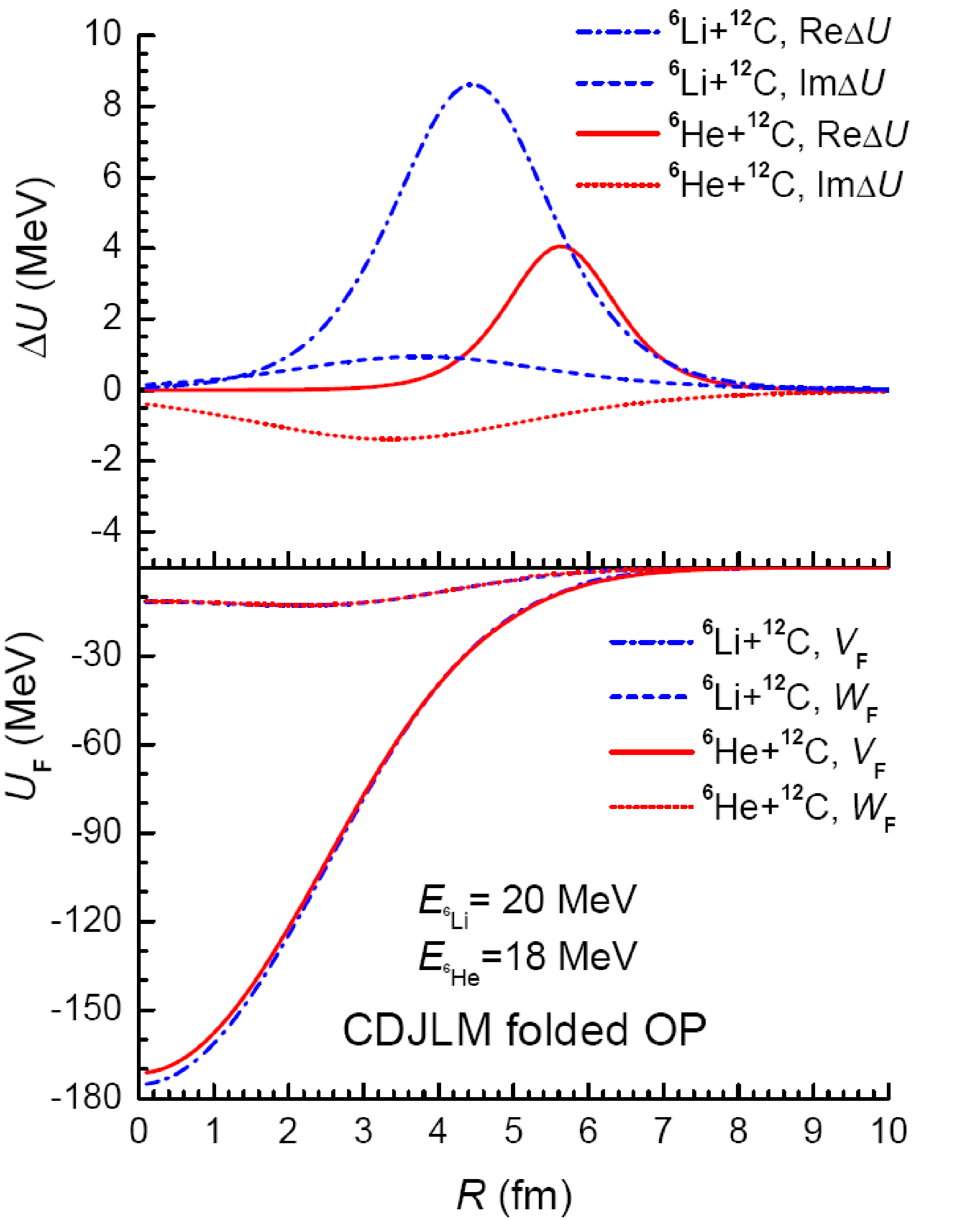
^{6}Li data: D.E. Trcka *et al*.,
Phys. Rev. C **41**, 2134 (1990).
FSU Linac

^{6}He data: M. Milin *et al*.,
Nucl. Phys. A **730**, 285 (2004)
Louvain-la-Neuve



$$\frac{\mathrm{Re}\Delta U(^6\mathrm{He})}{\mathrm{Re}\Delta U(^6\mathrm{Li})} < 50\%$$

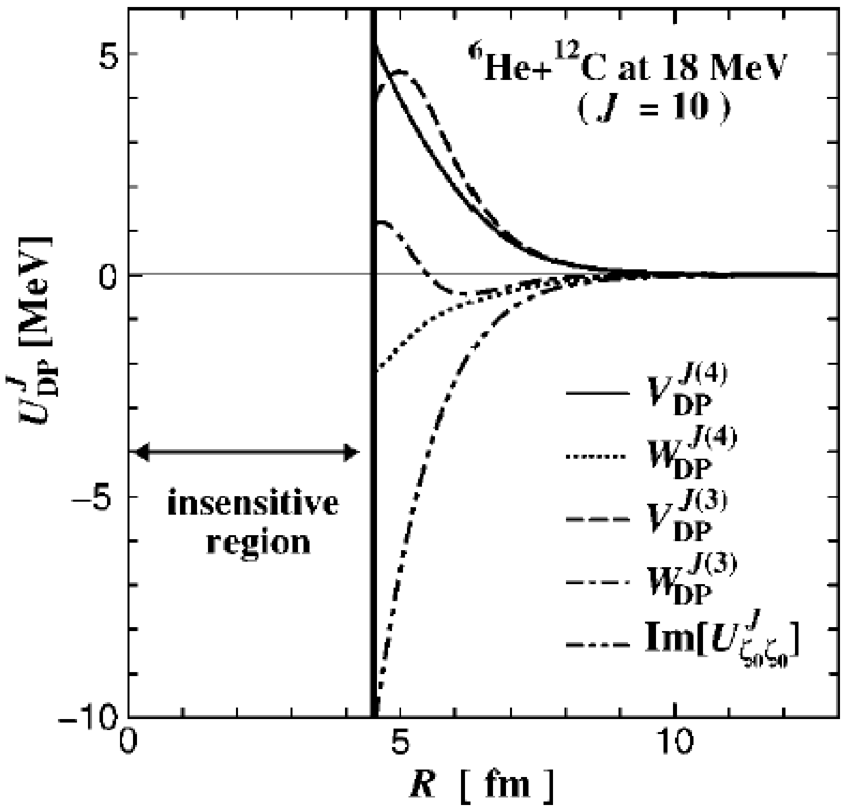
Coupling caused by ^{6}He breakup is weaker than that by ^{6}Li breakup?

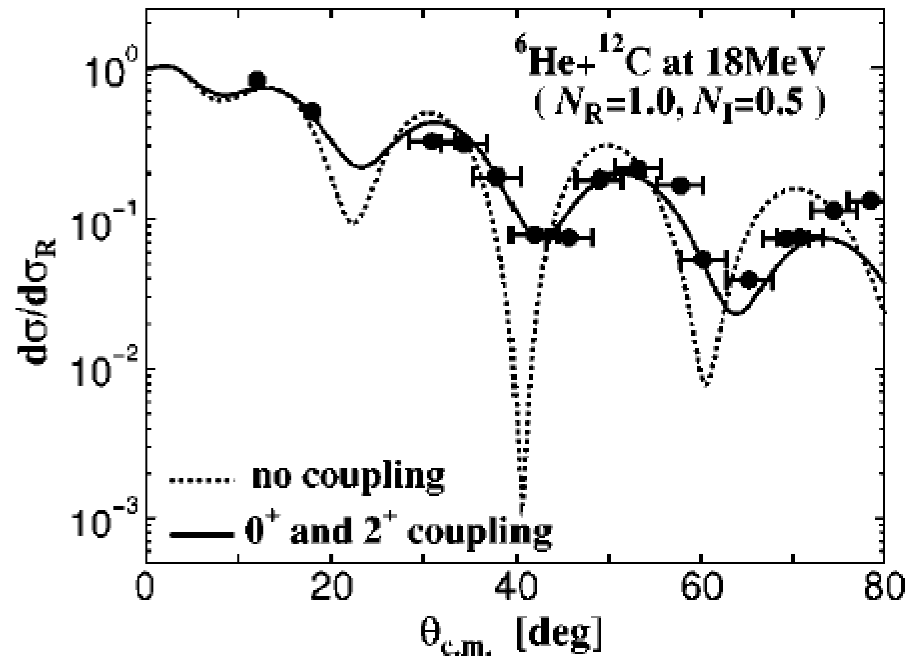


4-body CDCC: T. Matsumoto *et al*., *Phys. Rev*. C **70**, 061601(R) (2004)

$^6He+^{12}C=\alpha+n+n+^{12}C$
Coupling to 25 channels with J^π=0+ and 32 channels with $J^\pi=2^+$.

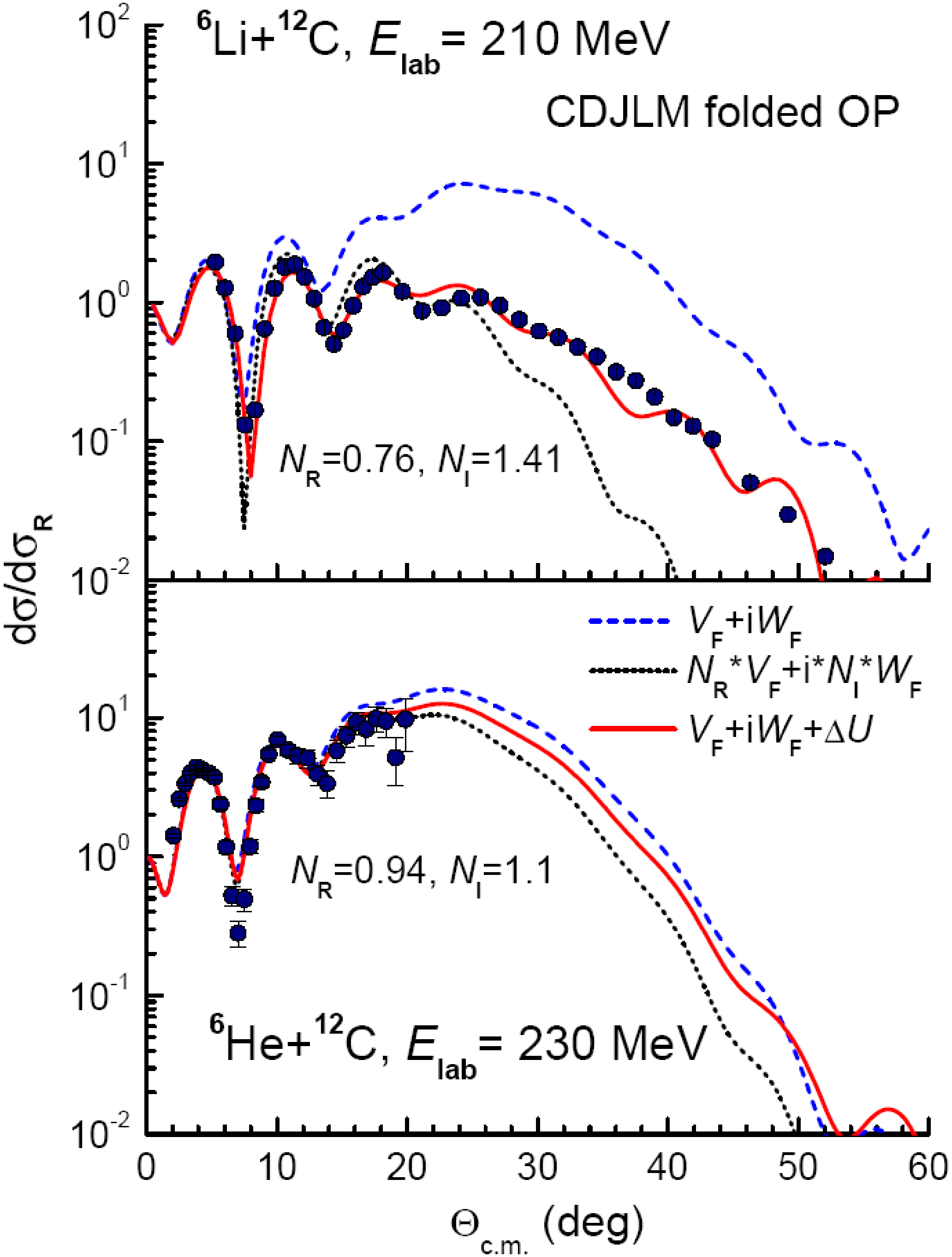
Diagonal $^6He+^{12}C$ optical potential: $U=V_F(1+i*0.5)$, V_F obtained with DDM3Y interaction





^{6}Li data: A. Nadasen *et al*., *Phys. Rev*. C **37**,132 (1988)
MSU Cyclotron

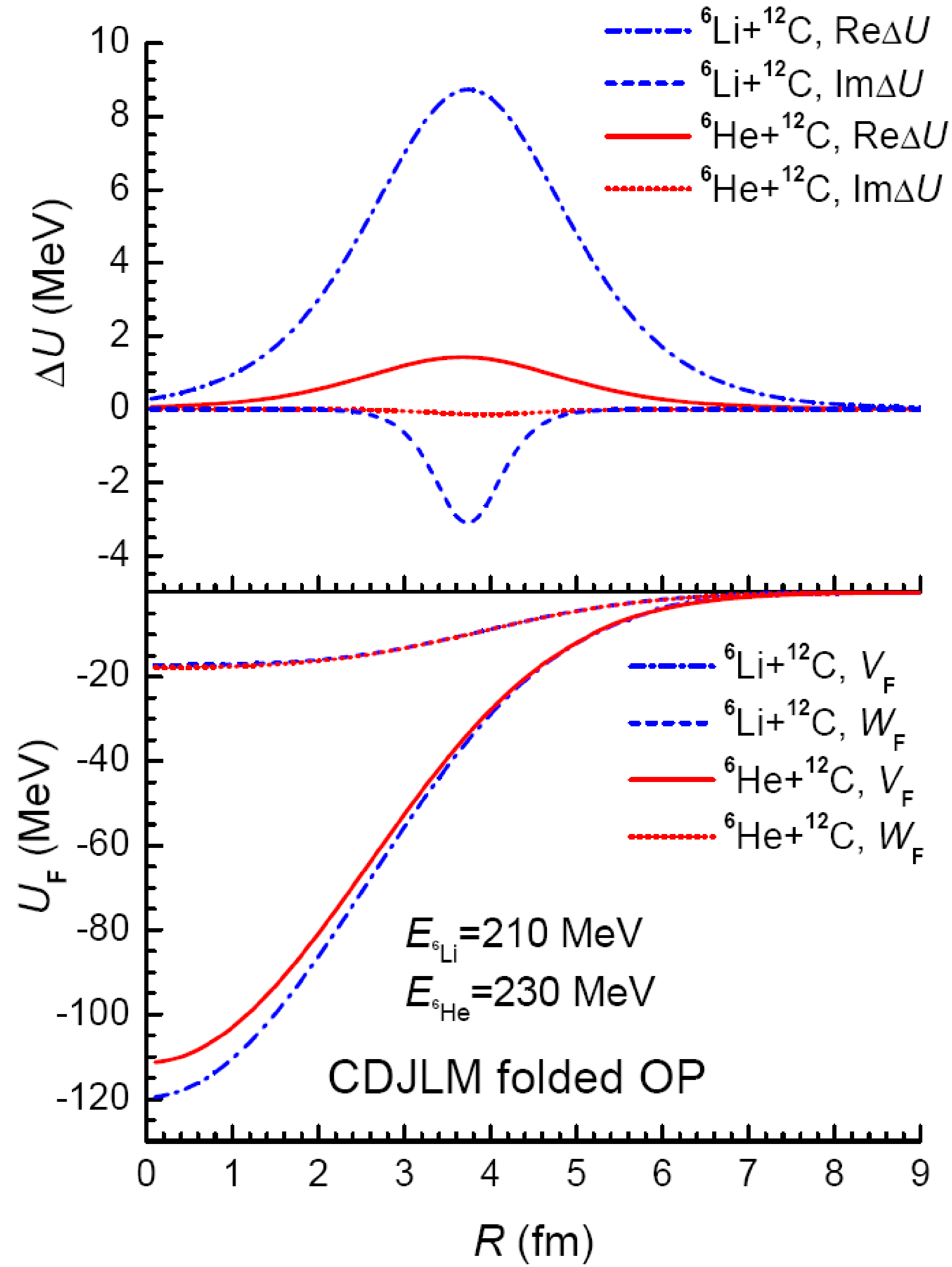
^{6}He data: V. Lapoux *et al*., *Phys. Rev*. C **66**, 034608 (2002)
GANIL Spiral



$$\frac{\mathrm{Re}\Delta U(^6\mathrm{He})}{\mathrm{Re}\Delta U(^6\mathrm{Li})} \sim 15\%$$

$$\frac{\mathrm{Im}\Delta U(^6\mathrm{He})}{\mathrm{Im}\Delta U(^6\mathrm{Li})} \sim 5\%$$

Coupling to elastic channel from ^{6}He breakup channel is weaker than that from ^{6}Li breakup or breakdown of mean-field description in ^{6}He case ?



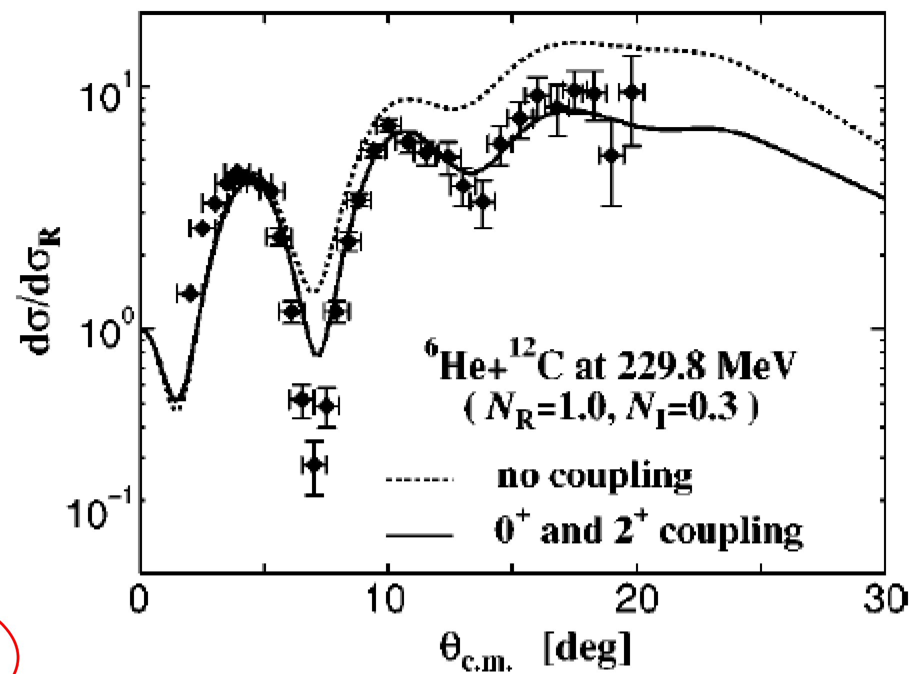
PHYSICAL REVIEW C 70, 061601(R) (2004)

Continuum-discretized coupled-channels method for four-body nuclear breakup in $^{6}He+^{12}C$ scattering

T. Matsumoto,[1] E. Hiyama,[2] K. Ogata,[1] Y. Iseri,[3] M. Kamimura,[1] S. Chiba,[4] and M. Yahiro[1]

4-body CDCC: **$^{6}He+^{12}C=\alpha+n+n+^{12}C$**
Coupling to 44 channels with $J^{\pi}=0+$ and 64 channels with $J^{\pi}=2^{+}$.

Diagonal $^{6}He+^{12}C$ optical potential: $U=V_F(1+i*0.3)$, V_F obtained with DDM3Y interaction



CCDC scenario using the new complex folded CDJLM pot. ?

Eur. Phys. J. A **7**, 367–375 (2000)

Reaction mechanism of ^{6}Li scattering at 600 MeV

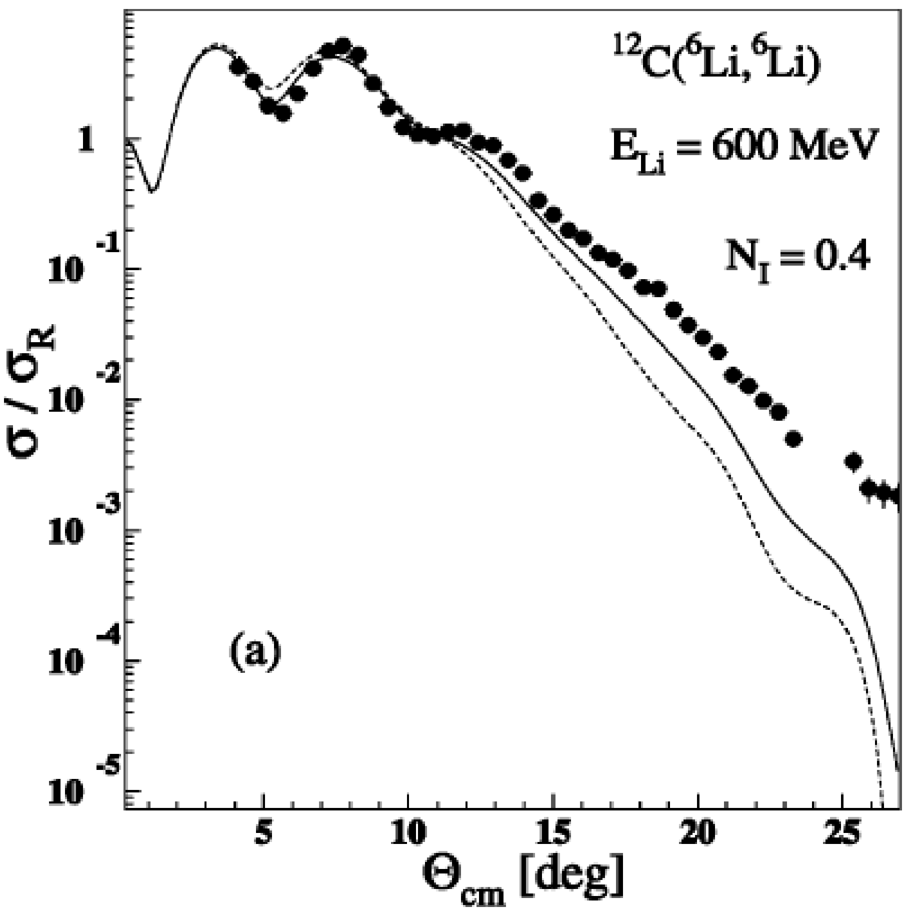
K. Schwarz[1,2], C. Samanta[1,3], M. Fujiwara[1,6], H. Rebel[2], R. De Leo[4], N. Matsuoka[1], H. Utsunomiya[5], H. Akimune[6], I. Daito[1], H. Fujimura[1], F. Ihara[1], K. Ishibashi[1], Y. Maeda[1], T. Yamanaka[1], H. Yoshida[1], A. Okihana[7], T. Yoshimura[7], P.K.J. van Aarle[1,8], W.A.T. Uijen[1,8], M. Ito[9], Y. Sakuragi[9]

CDCC results: coupling to the **^{6}Li->α+*d*** continuum (3^+, 2^+ and 1^+ resonances)

Diagonal ^{6}Li+^{12}C optical potential: $U=V_F(1+i*0.4)$, V_F obtained with DDM3Y interaction

↓

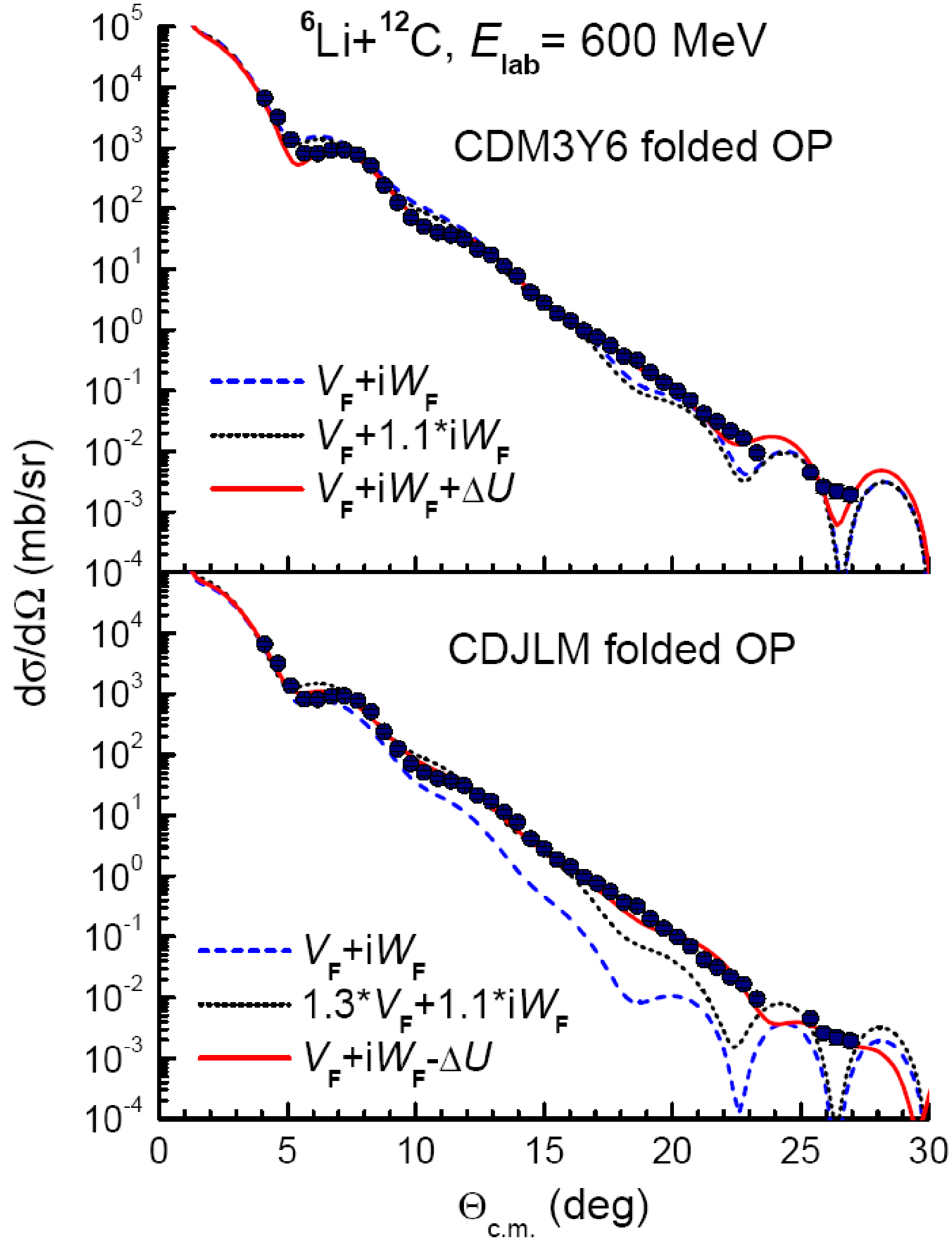
Local equivalent *Re* ΔU
Repulsive or attractive?



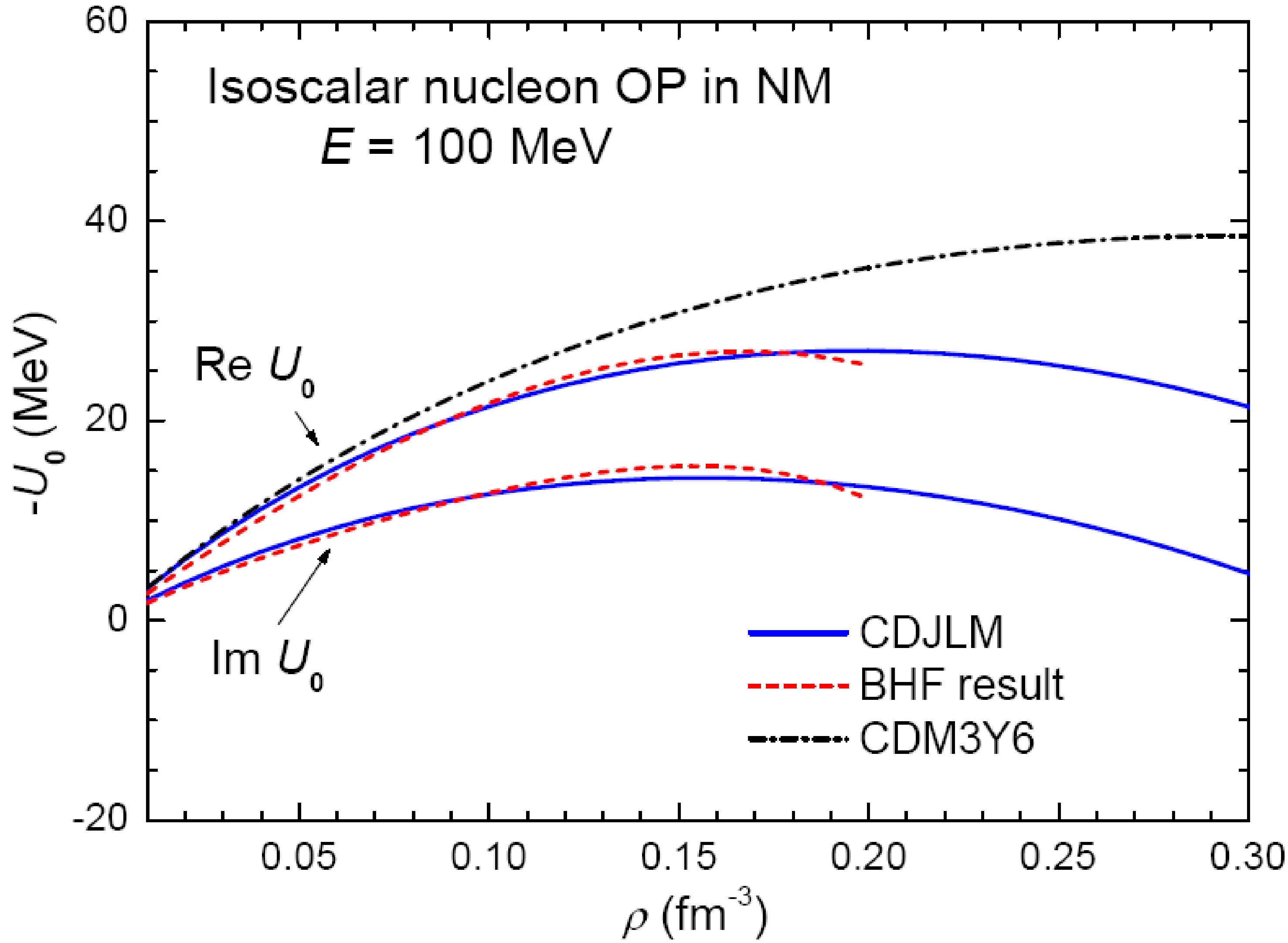
Data: K. Schwarz et al.,
Eur. Phys. J. A **7**, 367 (2000)
measured with "Grand Raiden"

Repulsive *Re* Δ*U*

Attractive *Re* Δ*U*



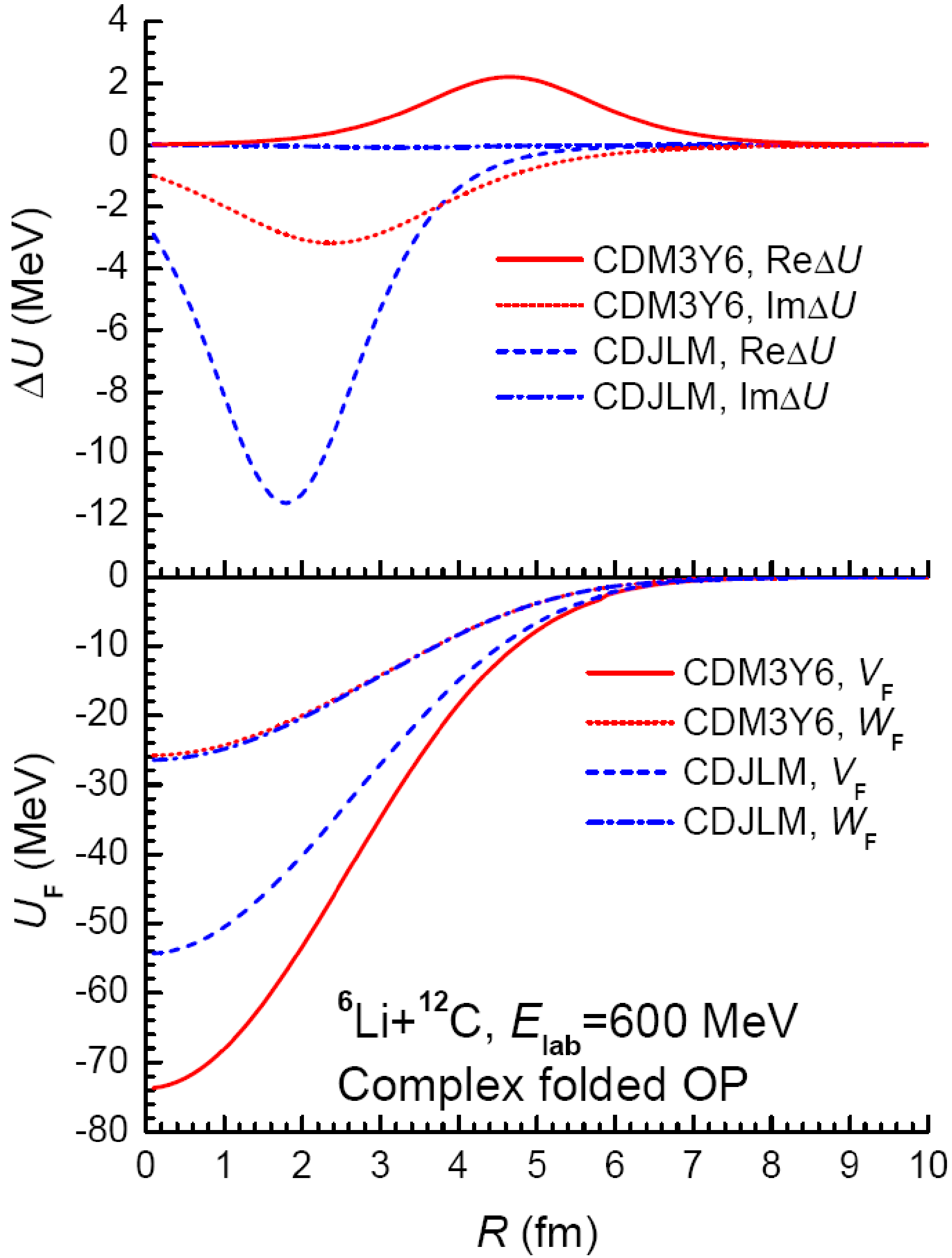
CRC check if the coupling strengths come with opposite signs depending on the choice of OP at *E* ~ 100 MeV/nucleon !



BHF result: Nuclear matter calculation by J.P. Jeukenne, A. Lejeune, C. Mahaux, *Phys. Rev*. C **16**, 80 (1977)

CDM3Y6: D.T. Khoa, G.R. Satchler, W. von Oertzen, *Phys. Rev.* C **56**, 954 (1997)

- Adequacy of BHF results by JLM at high energies ?
- Where is threshold where Re ΔU changes sign ?



^{6}He+^{12}C measurement at energies up to 100 MeV/u on new RIKEN accelerator ?

CDCC check of the energy dependence of Re ΔU caused by ^{6}Li breakup using the new CDJLM bare ^{6}Li+^{12}C potential !