Scattering of exotic nuclei around the coulomb barrier:

Experiments and theory

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- What we already know about the scattering of stable nuclei
- What we would like to know about the scattering of exotic nuclei
- Recent experiments on 6He scattering
- Some answers ... and a wish list

Collaboration

Birmingham - Catania - Edinburgh - Huelva - Leuven - Lisboa - Louvain la Neuve - Madrid - Sevilla - Surrey - Teheran - Warsaw

What we know about the scattering of stable nuclei

Elastic scattering

- **The scattering wavefunction in the elastic channel can be described as the solution of a one-body Schrödinger equation using a complex optical potential which depends on the relative co-ordinate.**

$$U(E) = P\mathcal{V}P + P\mathcal{V}Q\frac{1}{E^{+} - QHQ}Q\mathcal{V}P$$

- **The optical potential can be described as a local, L-independent function which is the sum of a real and an imaginary potentials.**

$$U(E) \simeq V(r, E) + iW(r, E)$$

- **The real optical potential can be obtained by a double folding of some effective nucleon-nucleon interaction.**

$$V(r, E) = \int d^3\vec{r_p} d^3\vec{r_t} \rho_p(r_p)\rho_t(r_t) v_{NN}(|\vec{r} - \vec{r_p} + \vec{r_t}|)$$

- **The imaginary optical potential can be parameterized in terms of some analytic form (Woods-Saxon), which vanishes at distances in which there is not a significant overlap of the nuclear densities.**
- **The sensitivity to the values of the real and imaginary potentials is maximum at the strong absorption radius.**
- **The energy dependences of the real and imaginary potentials are linked by dispersion relations.**

Reactions

- **Inelastic scattering to collective states can be calculated deforming the real and imaginary potentials (or the densities in a folding model), in DWBA or CC calculations.**
- **Transfer reactions can be calculated in DWBA or CRC calculations, using the elastic optical potentials to distort the waves in the incident and outgoing channels.**

$$(A+C)+B \rightarrow A+(B+C)$$

$$U(E) \simeq U_{AC}+U_{AB}+U_{BC}$$

- **Break-up reactions can be calculated in DWBA or CDCC calculations, discretizing the continuum and folding effective interactions.**

$$(A+C)+B \rightarrow A+C+B$$

$$U(E) \simeq V_{AC}+U_{AB}+U_{BC}$$

- **Fusion reactions can be calculated from barrier penetration through the barriers determined by the optical potentials, or by absorption by imaginary potentials**

Successes

- **Elastic cross sections are reproduced with optical potentials which depend smoothly on the energy and the target mass.**
- **Deformation parameters are obtained from the fits to inelastic scattering.**
- **Spectroscopic factors are obtained from the fits to transfer reactions.**
- **Sub-barrier fusion enhancement is explained through coupled channels effects in the entrance channels.**
- **The sharp energy dependence in the elastic optical potential, where present (Threshold anomaly), is explained as the effect of coupling to collective states or transfer channels.**

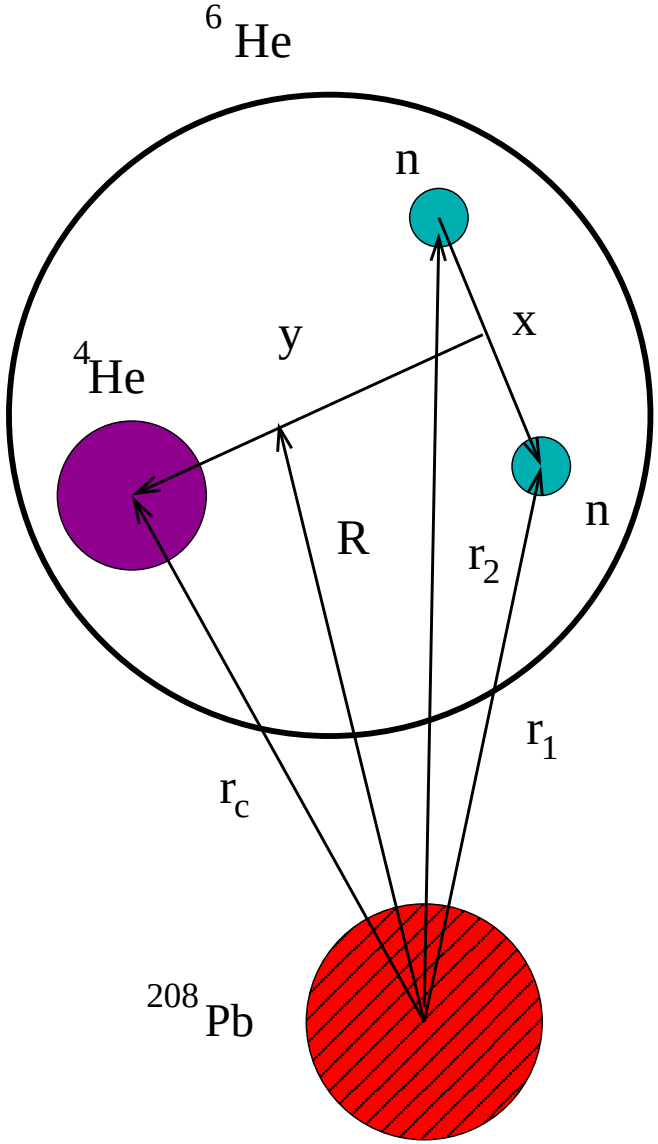
Open questions:

- **Are optical potentials (diagonal and coupling) local?**
- **Should coupling potentials and transfer kernels be real or complex?**
- **Can imaginary potentials for a composite system be derived from those of its components?**

The presence of strong absorption makes these problems not too important

What we would like to know about the scattering of exotic nuclei

- **Can the scattering wavefunction in the elastic channel be described as the solution of a one-body Schrödinger equation using a complex optical potential which depends on the relative co-ordinate? Yes**
- **Can the optical potential be described as a local, L-independent function which is the sum of a real and an imaginary potentials?**
- **Can the real optical potential be obtained by a double folding of some effective nucleon-nucleon interaction?**
- **Can the imaginary optical potential be parameterized in terms of some analytic form (Woods-Saxon), which vanishes at distances in which there is not a significant overlap of the nuclear densities?**
- **Is the sensitivity to the values if the real and imaginary potentials maximum at the strong absorption radius?**
- **Is the energy dependence of the real and imaginary potentials related by dispersion relations? Yes**
- **Can elastic and break-up cross sections be described consistently ?**


^{6}He
n
x
y
^{4}He
n
R
r_2
r_1
r_c
^{208}Pb

Recent experiments on 6He scattering

^{6}He + ^{208}Pb (Louvain la Neuve)

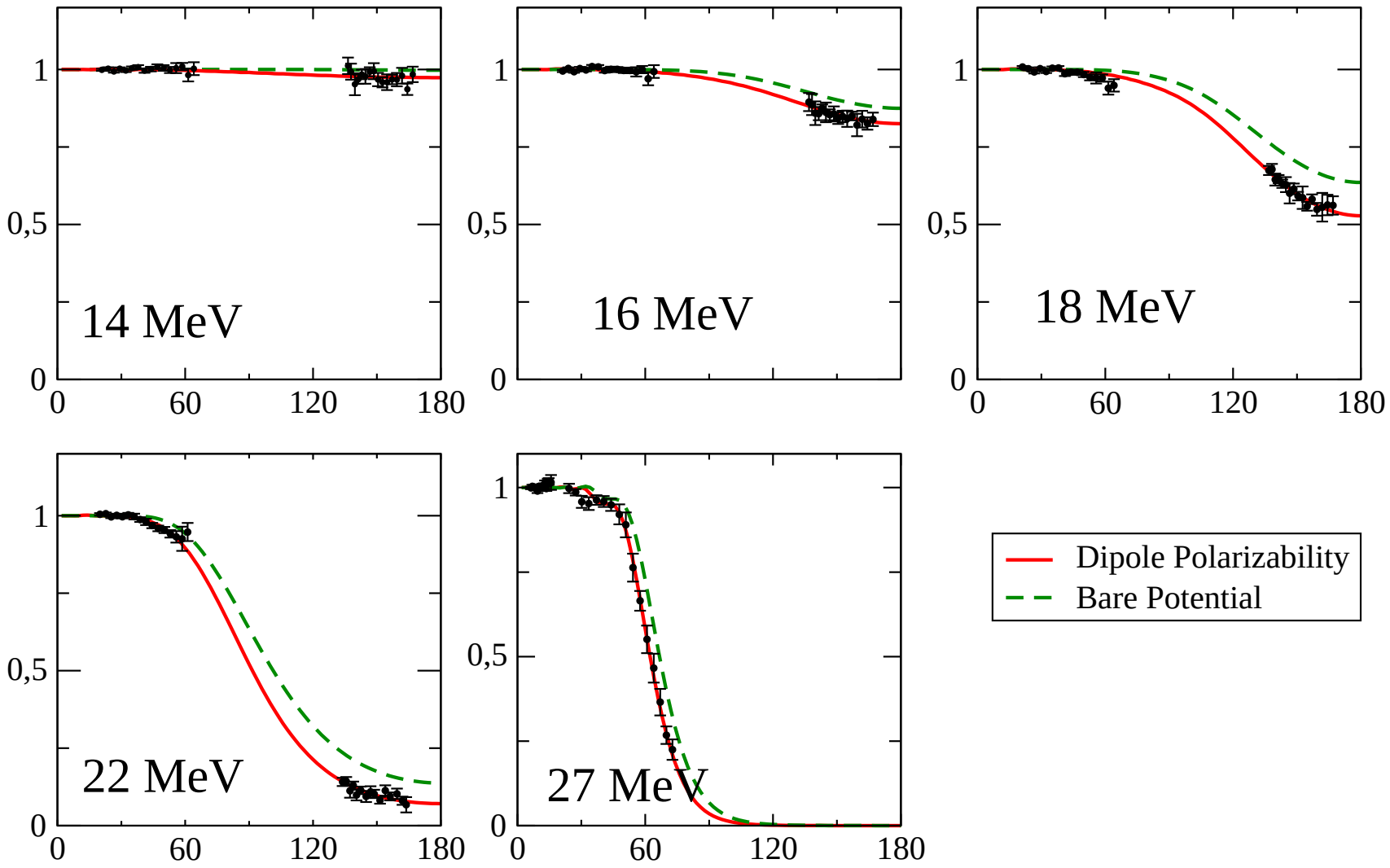
Measurements

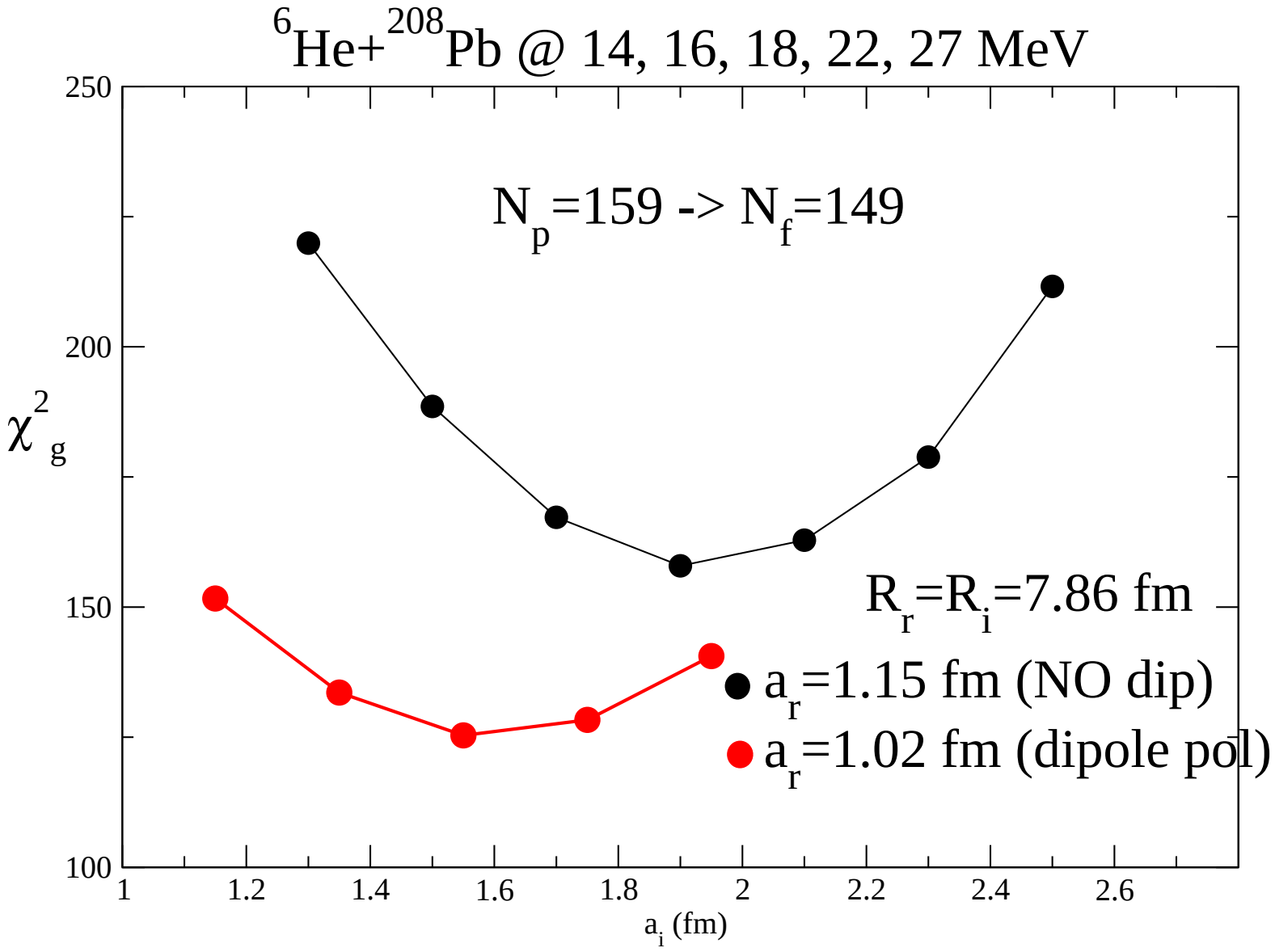
- **Measure elastic scattering (6He).**
- **Measure charged break-up fragments (4He).**
- **Determine energy dependence of cross sections around the Coulomb barrier (14-27 MeV).**

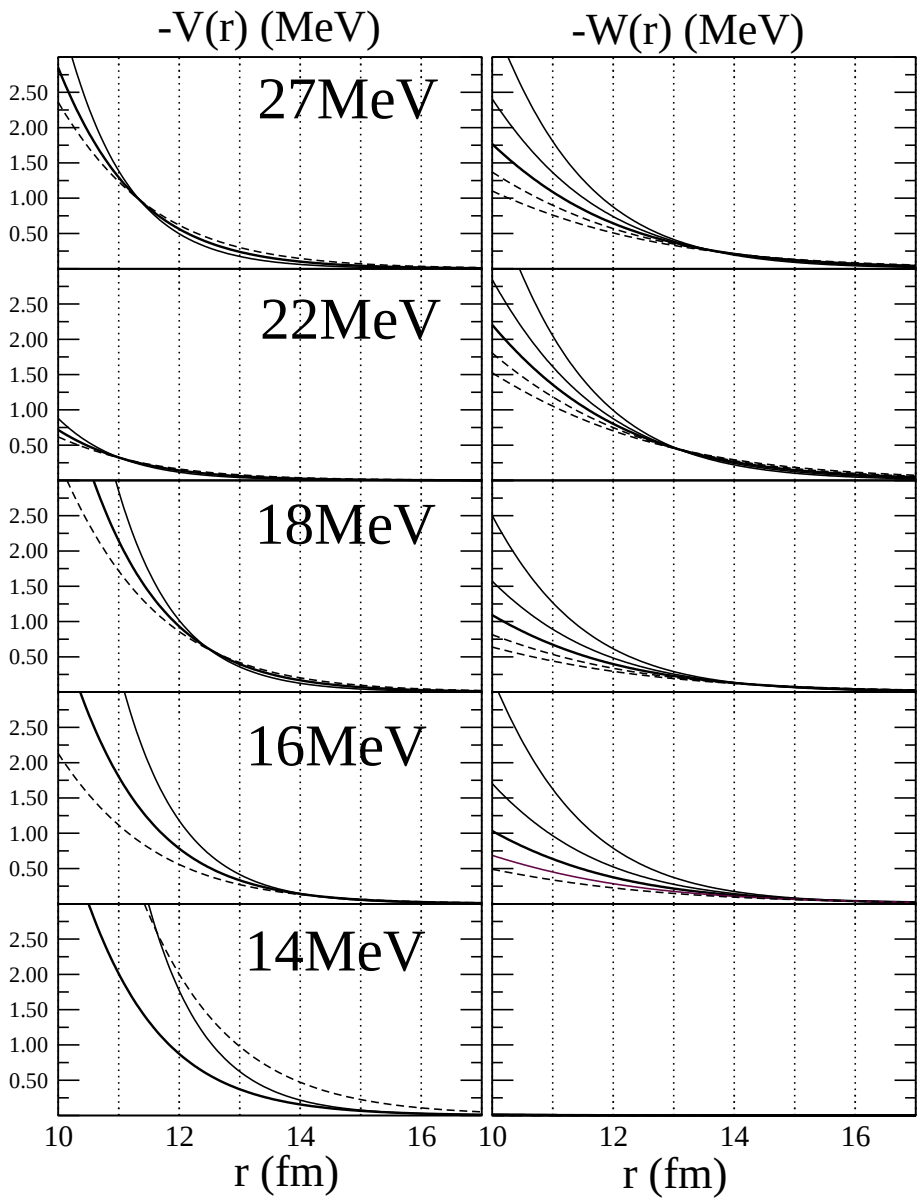
Experimental Requirements

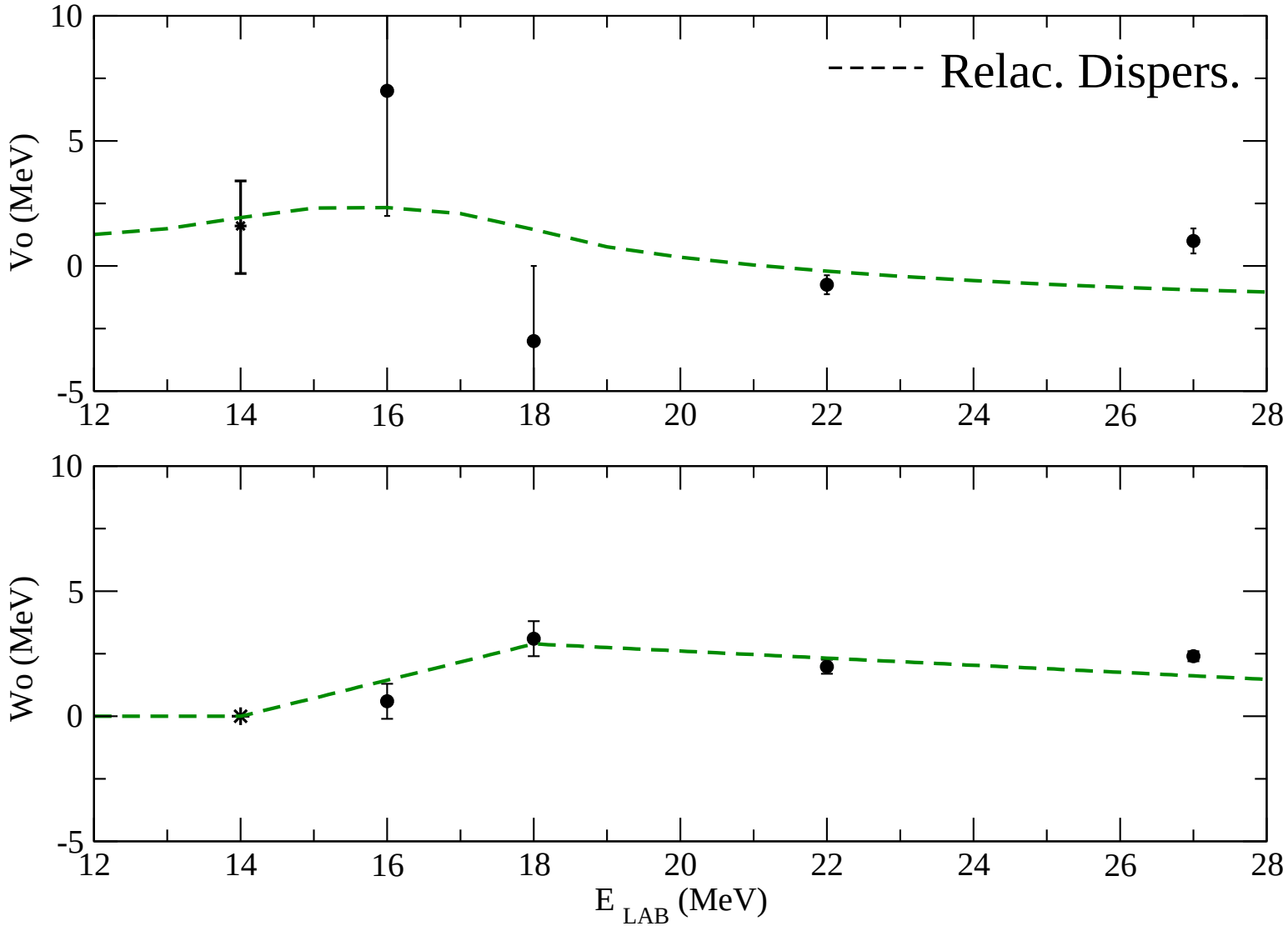
- **Sufficient 6He beam intensity ($10^5 - 10^6$ pps).**
- **Similar stable beam for calibration (4He).**
- **Detectors covering a wide range of angles (specially at backward angles).**
- **Particle identification (telescopes).**

Elastic cross sections

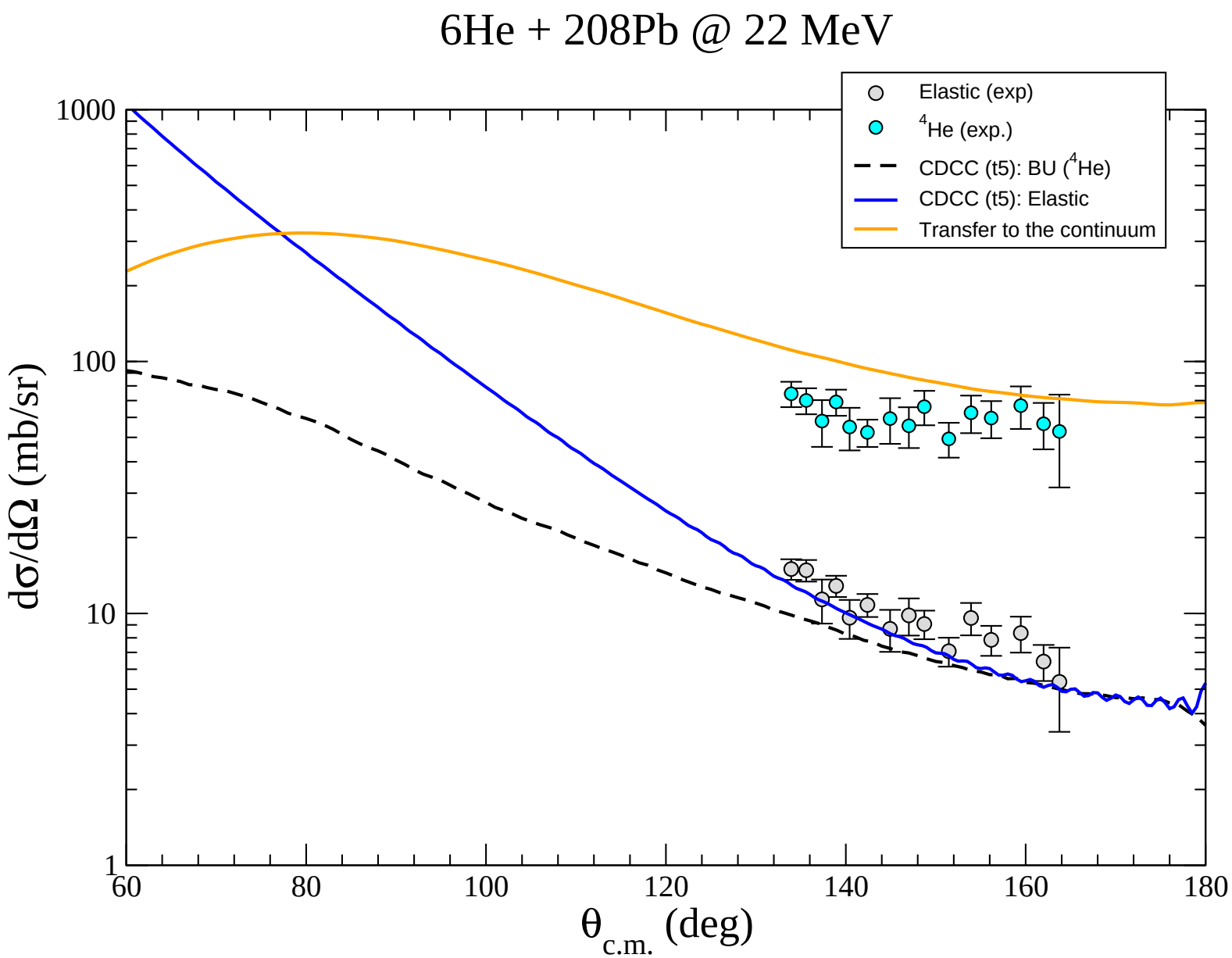

14 MeV
16 MeV
18 MeV
22 MeV
27 MeV
0
0,5
1
0
60
120
180
Dipole Polarizability
Bare Potential


^{6}He+^{208}Pb @ 14, 16, 18, 22, 27 MeV
N_p=159 -> N_f=149
R_r=R_i=7.86 fm
a_r=1.15 fm (NO dip)
a_r=1.02 fm (dipole pol)
χ^2_g
a_i (fm)
250
200
150
100
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6

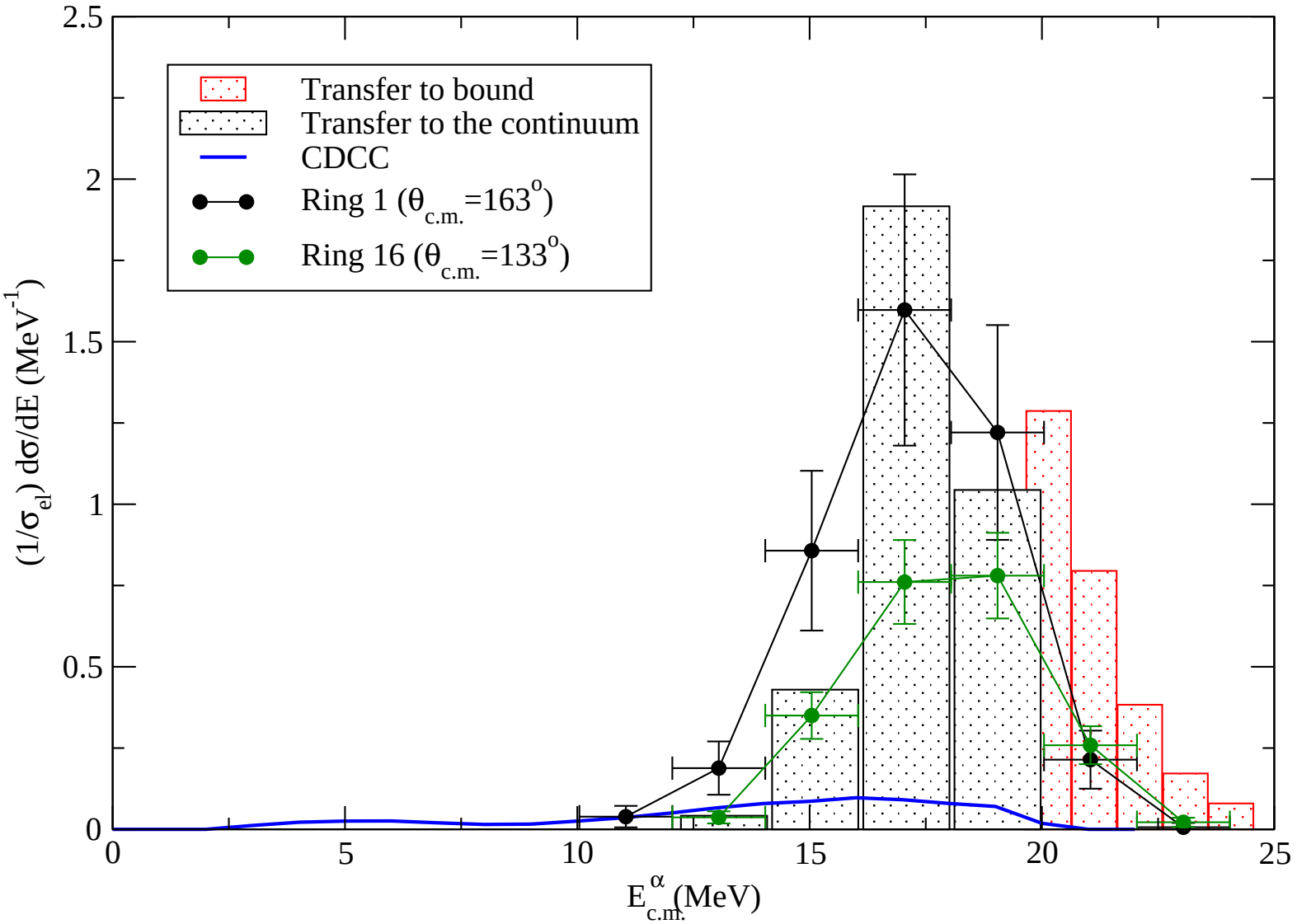

-V(r) (MeV)
-W(r) (MeV)
27MeV
22MeV
18MeV
16MeV
14MeV
2.50
2.00
1.50
1.00
0.50
10
12
14
16
r (fm)


Relac. Dispers.
Vo (MeV)
Wo (MeV)
E LAB (MeV)
10
5
0
-5
12
14
16
18
20
22
24
26
28

Break-up cross sections


6He + 208Pb @ 22 MeV
Elastic (exp)
4He (exp.)
CDCC (t5): BU (4He)
CDCC (t5): Elastic
Transfer to the continuum
1000
100
10
1
60
80
100
120
140
160
180
dσ/dΩ (mb/sr)
θc.m. (deg)

^{6}He + ^{208}Pb @ 22 MeV



Some answers ...

- **Can the optical potential for exotic nuclei be described as a local, L-independent function which is the sum of a real and an imaginary potentials. ?**

  Yes, but the radial dependence is very different from the case of normal nuclei

- **Can the real optical potential be obtained by a double folding of some effective nucleon-nucleon interaction ?**

  Probably not. Dynamic effects are very important.

- **Can the imaginary optical potential be parameterized in terms of some analytic form (Woods-Saxon), which vanishes at distances in which there is not a significant overlap of the nuclear densities ?**

  Probably yes. Imaginary potentials have a very long range, but so do nuclear densities.

- **Is the sensitivity to the values if the real and imaginary potentials maximum at the strong absorption radius ?**

  No. Real potentials are determined at the SAR, but Imaginary potentials are determined well beyond the SAR.

- **Is the energy dependence of the real and imaginary potentials related by dispersion relations ?**

  The validity of DR should be assumed, and the potentials fitted accordingly.

- **Can elastic and break-up cross sections be described consistently ?**

  Hope so. More work is needed

... and a wish list

- **We can have accurate experimental data on elastic and inclusive break-up cross sections from the Coulomb barrier upwards. A reliable theory to describe these observables consistently is needed. Transfer to the continuum?**
- **Continuum discretization treatments rely presently on folding local imaginary potentials over long range diagonal and transition densities. An alternative treatment of the absorption in the scattering of weakly bound systems may be convenient. Supress configurations which strongly overlap with the target?**
- **Coupled channels approach rely on the importance of the projectile-target co-ordinate as the principal degree of freedom. When break-up is dominant, this may not be adequate. Return to Faddeev?**
- **Why not forget about potentials and coordinates, and get the 3 or 4-body S matrix from the S matrices of the 2-body subsystems? Group theory approach?**