Nuclear transparencies: two-nucleon knockout & fast neutrons

Wim Cosyn

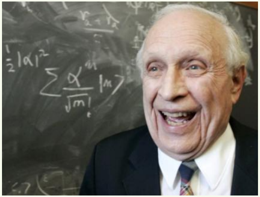
Ghent University, Belgium

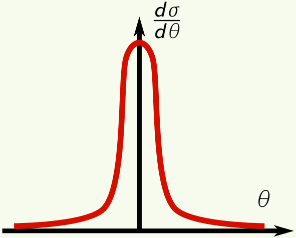
2nd Workshop on Quantitative Challenges in SRC and EMC Research
21$^{\text{th}}$ March, 2019

Outline

- Relativistic Multiple Scattering Glauber Approximation to account for final-state interactions (FSI) with nuclear medium
- Applicable in exclusive reactions with beams of a few GeV
  - quasi-elastic knockout of one or more particles
  - $A-1$ or $A-2$ residual system with very little excitation energy (either detected or through missing mass cuts)
- Can also be applied in inclusive reactions through application of optical theorem to forward scattering amplitude [**unitarity**]
  - done for inclusive DIS in the subasymptotic [high x, low Q^2 regime]
    `WC, W. Melnitchouk, M. Sargsian, PRC89 '14`
- Some results focussing on $2N$ knockout (fast neutrons)
- FSI affect effective nuclear densities that are probed: comparison between reactions

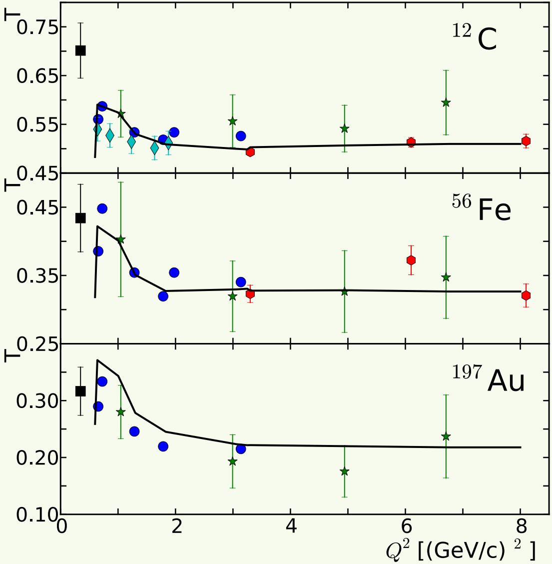
Hadron-nucleon FSI with Glauber scattering theory





- Glauber theory has origins in optics
- High-energy diffractive scattering: small angles
- Applicable when wavelength of scattering particle is significantly smaller than interaction range → momenta of a few 100 MeV
- Eikonal method: outgoing wave gets complex phase $\phi_{scat}(\boldsymbol{r}) = e^{i\chi(\boldsymbol{r})}\phi_{in}(\boldsymbol{r})$
- Scattering parameters taken from data (NN scattering)
- Multiple scattering: phase-shift additivity $e^{i\chi_{tot}} = \prod_i \left(1 - \Gamma_i(\vec{b}_i)\right)$

A(e,e'p)



W.C., J. Ryckebusch, PRC87 ('13)

- No free parameters
- RMSGA: excellent agreement with A(e,e'p) world data (JLab, SLAC, MIT Bates)
- No signs of CT yet

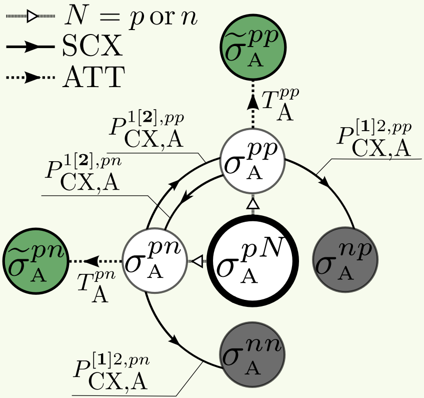
2N knockout

- 2N knockout cross section can be factorized under certain assumptions
  `C. Colle, WC, J. Ryckebusch, M. Vanhalst PRC89 ('14)`
  "Decay Function" (Frankfurt, Strikman)

$$\mathrm{d}\sigma^{A}_{N_1 N_2} = K \, \mathrm{d}\sigma_{N_1 N_2} F^{D}_{A}(\boldsymbol{P}_{\mathrm{cm}})$$

- $\mathrm{d}\sigma_{N_1 N_2}$ interaction of the probe with correlated nucleon pair
  - includes FSI between the correlated nucleons
  - in ratios assumed to drop out given the local and universal character of nuclear SRCs
- $F^{D}_{A}(\boldsymbol{P}_{\mathrm{cm}})$: 2$N$ pair center-of-mass momentum distribution
  - Contains all the FSI of the 2N pair with the residual $A-2$ (MF)
  - Normalized to # of SRC 2N pairs (isospin dependent) times a transparency factor
  - A-dependent, survives in cross section ratios

$F_A^D(\boldsymbol{P}_{\mathrm{cm}})$ calculations with leading proton

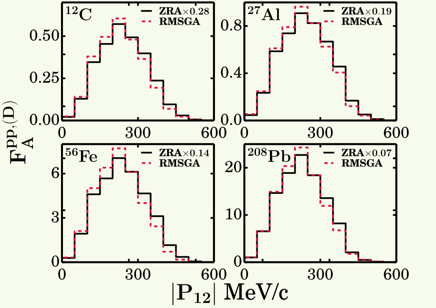


C. Colle, WC, J. Ryckebusch, PRC93 ('16)

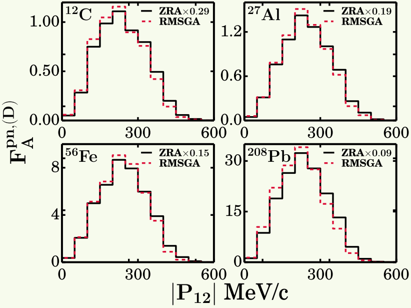
- Different possible FSI mechanisms (attenuation and rescattering, single charge exchange) and channels contribute to measured signal, proportional to $F_A^D(\boldsymbol{P}_{\mathrm{cm}})$
- Feed through the complete phase space of the CLAS detector
- Slow recoil nucleons: optical potential ($N - A$ scattering) instead of eikonal multiple scattering

Calculations for CLAS kinematics

pp



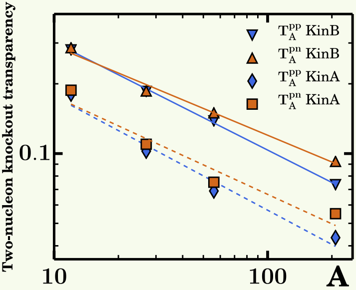
pn



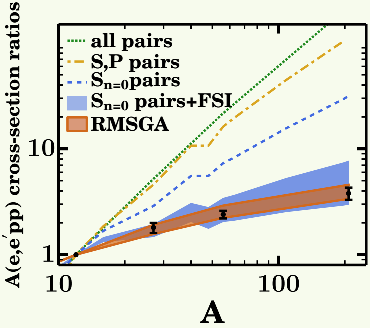
C. Colle, WC, J. Ryckebusch, PRC93 ('16)

- ZRA: plane-wave calculation with zero-range approx. for the $2N$ pair
- FSI cause no shape distortion, attenuation factor [=transparency]

A-dependence in $2N$-knockout



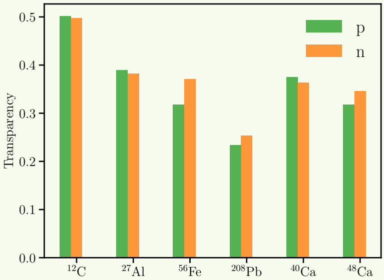
C. Colle, WC, J. Ryckebusch, PRC93 ('16)

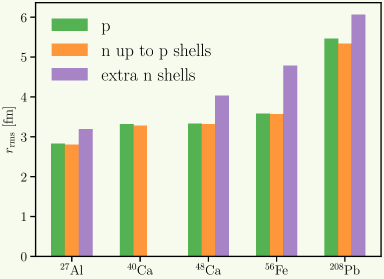


C. Colle, O. Hen et al., PRC92 ('15)

- Kin A: small acceptance spectrometers; Kin B: 4π detector (CLAS)
- Transparencies have robust power law behavior
  $T = A^{-\lambda} \quad \lambda = 0.38 - 0.49$
- Excellent agreement with CLAS data, **no free** parameters!
- Agreement with relative S-state pair counting + transparency factor
  → see Jan's talk

Fast neutron transparencies





- Recent data with fast leading neutrons
- Routinely assumed that $T_p = T_n$ since σ_{tot} is similar in size for pp and pn scattering (and constant in the few GeV regime)
- Careful with $N \neq Z$ nuclei: extra neutron shells are more on the periphery, so have lower transparency
- Correlated with the difference in rms radius between those extra shells and the other ones

Density Dependence

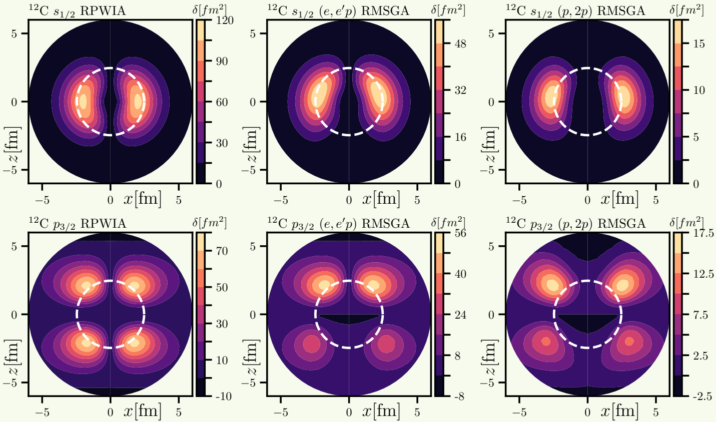
The RMSGA model provides an excellent basis to study the density dependence of removal reactions

- Accommodates variety of reactions
- Scattering parameters are relatively smooth above 1 GeV $\rightarrow$ universal statements
- Density dependence of the attenuation will determine the effective nuclear regions which can be probed

J.R., W.C. & M. Vanhalst, PRC83 054601 ('11)
W.C., J.R., PRC80 011602(R) ('09)

Density Dependence: ^{12}C(e,e'p) and ^{12}C(p,2p)

δ is a measure for the contribution to the cross section at (r,θ) [phase space incl.]

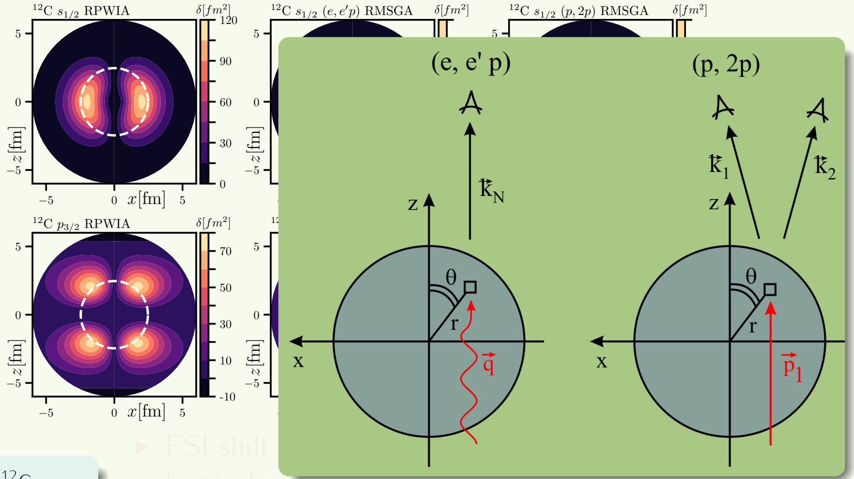


r$_{\text{rms}}$ ^{12}C
2.464 $\pm$ 0.012 fm

- FSI shift contributions to larger r and forward hemisphere ($z > 0$)
- Larger effect for A(p,2p) $\rightarrow$ surface is probed

Density Dependence: ^{12}C(e,e'p) and ^{12}C(p,2p)

δ is a measure for the contribution to the cross section at (r,θ) [phase space incl.]

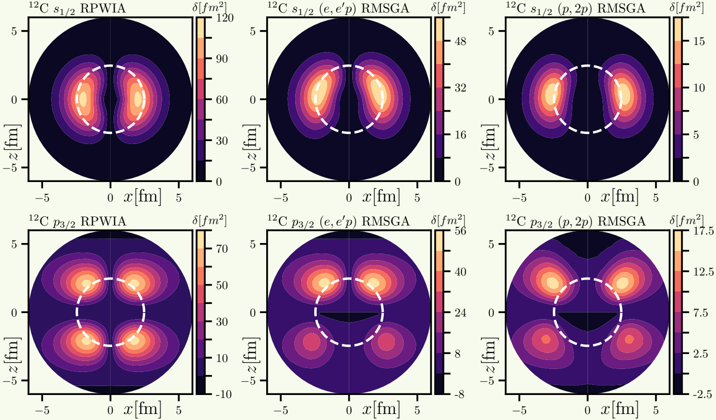


- FSI shift ... hemisphere ($z > 0$)
- Larger effect for A(p,2p) → surface is probed

r_{rms} ^{12}C
2.464 ± 0.012 fm

Density Dependence: ^{12}C(e,e'p) and ^{12}C(p,2p)

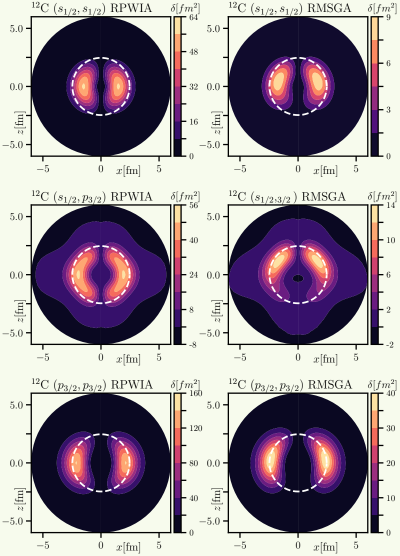
δ is a measure for the contribution to the cross section at (r,θ) [phase space incl.]



r_{rms} ^{12}C
2.464 ± 0.012 fm

- FSI shift contributions to larger r and forward hemisphere ($z > 0$)
- Larger effect for A(p,2p) → **surface** is probed

Density Dependence: ^{12}C(γ, pp)



- Knockout of a correlated pair, originating in certain MF shell combination
- Shift in r much smaller than in one nucleon knockout
- Strength remains in the high density regions of the nucleus
- Transparency factor of course a lot smaller than $A(e, e'p)$

Outstanding issues / projects

- For transparencies in $2N$ knockout, difference between CLAS measurements [recoil nucleon has **low** attenuation] and theory [2 nucleons have **large** attenuation, originating from central regions in nucleus]
  `O. Hen et al. (CLAS), PLB722 ('13)`
- FSI between two correlated nucleons: assumed to factor out in cross section ratios given its local/universal character
- FSI in inclusive scattering through AGK cutting of forward scattering amplitude
- Cross sections more useful than ratios to constrain models!