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FACULTY OF **SCIENCES**

Imbalanced Fermi Systems: Nuclear properties as a function of the Z/A ratio

Modeling Quasi-Free (p,pN) Reactions with Unstable Nuclei

BriX

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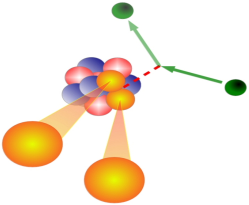
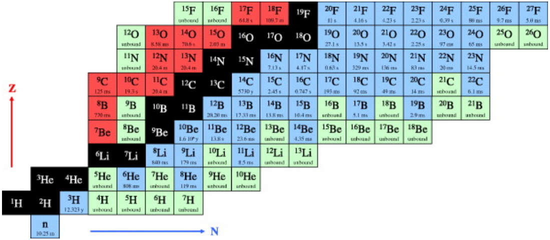


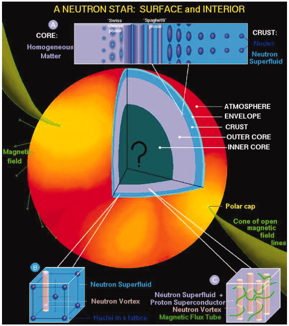
Introduction

Why Study Asymmetric Nuclei?



Asymmetric nuclei have some unusual properties

- halo nuclei
- new magic numbers in neutron-rich nuclei
- special dynamical properties due to short-range correlations (SRC)
- ...



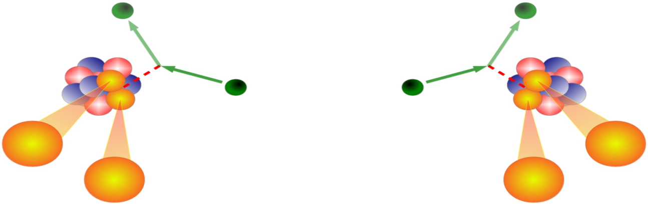
Neutron stars:

- extremely imbalanced Fermi systems ($x_p = Z/A \ll 0.5$)
- look for clues of their properties in the study of neutron-rich nuclei ($\mathbf{x_p < 0.5}$)

Understanding the properties of exotic nuclei is important for nuclear astrophysics

How to Probe Asymmetric Nuclei?

Quasi-Free (p,pN) Reactions in Inverse Kinematics



Experimentally

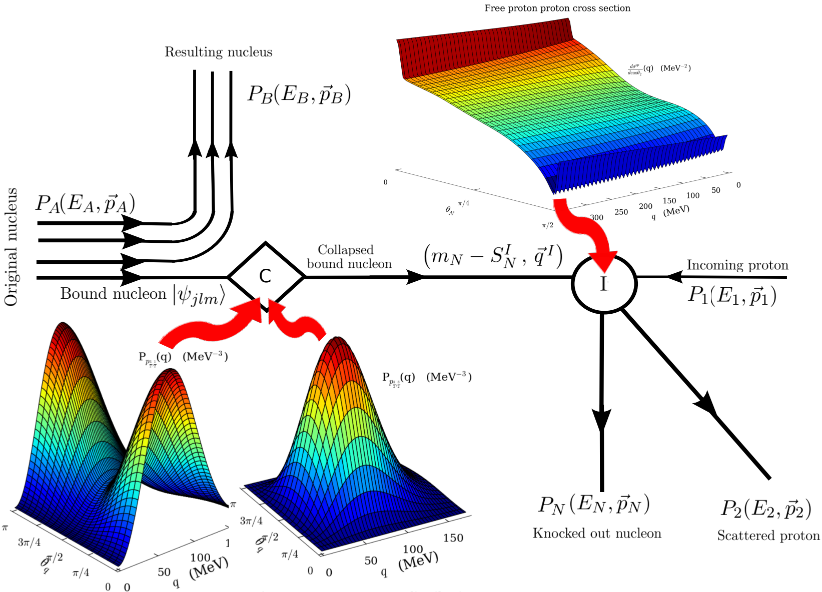
Quasi-Free A(p,pN)B Reactions in Inverse Kinematics

- highly asymmetric nuclei are unstable
  $\Rightarrow$ need experiments with accelerated nuclei
- in inverse kinematics we can also study deeply bound nucleons

Sufficiently High Beam Momenta

- reveal SRC effects
  $\Rightarrow$ need to probe high momentum tails
- lower the contribution of other possible reactions to the cross section

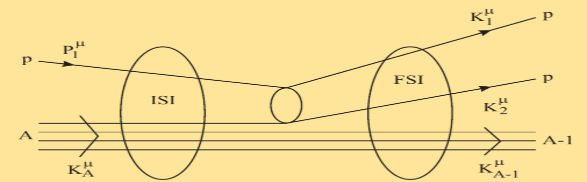
Theoretically



$1p_{\frac{3}{2},\frac{1}{2}}$ proton momentum distribution

$1p_{\frac{3}{2},\frac{3}{2}}$ proton momentum distribution

Theoretically



Distorted Wave Impulse Approximation

- $(A-1)$ degrees are frozen in the interaction Hamiltonian (can be kinematically controlled)
- one “hard” pN interaction process
- three nucleons subject to intranuclear attenuation
  - “soft” initial-state interaction of the impinging proton
  - “soft” final-state interactions of the two ejected nucleons
  - modeled by using distorted plane waves in Eikonal approximation

(T. Aumann, C. A. Bertulani, and J. Ryckebusch, Phys. Rev. C 88, 064610 (2013))

Factorized Cross Section in the DWIA

- knockout of a nucleon N with quantum numbers l and j:

$$\frac{\mathrm{d}^5\sigma}{\mathrm{d}\vec{q}\,\mathrm{d}\Omega_N} \propto \frac{S(lj)}{j+1}\sum_{\alpha} \mathcal{K}(\alpha,\sigma,\vec{q},\Omega_N)\,\rho^D_\alpha(\vec{q})\,\left(\frac{\mathrm{d}\sigma^{\mathrm{fs}}_{pN}}{\mathrm{d}\Omega_N}\right)$$

- scaling variable: missing momentum

$$\vec{q} = \vec{p}_1 + \vec{p}_N - \vec{p}_1$$

- scaling function: distorted momentum distribution

$$\rho^D_\alpha(\vec{q}) = \frac{1}{(2\pi)^3}\left|\int d\vec{r}\; e^{-i\vec{q}\cdot\vec{r}}\;\widehat{S}_{IFSI}(\vec{r})\;\psi_\alpha(\vec{r})\right|^2$$

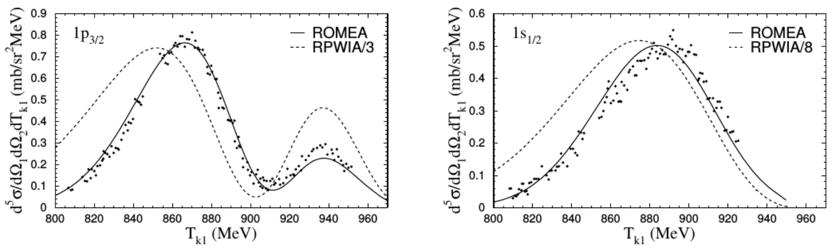
Distorted momentum distribution

$$\rho^{D}_{\alpha}(\vec{q}) = \frac{1}{(2\pi)^3} \left| \int d\vec{r}\; e^{-i\vec{q}\cdot\vec{r}}\; \widehat{S}_{IFSI}(\vec{r})\; \psi_{\alpha}(\vec{r}) \right|^2$$

- α: quantum number of bound nucleon
- $\widehat{S}_{IFSI}(\vec{r})$ encodes the **attenuation** for the 3 nucleons that are subject to **initial and final state interactions**
- two different **eikonal approaches** to calculate $\widehat{S}_{IFSI}(\vec{r})$

(B. Van Overmeire, W. Cosyn, P. Lava, and J. Ryckebusch, Phys. Rev. C 73, 064603 (2006))

Relativistic Optical Model Eikonal Approximation (ROMEA)



Differential cross section for the ${}^{12}C(p,2p)$ reaction in the kinetic energy range $800 MeV < T_1 < 1 GeV$.

For most asymmetric nuclei: no optical potential available
⇒ need to use a **Multiple Scattering Glauber model**

Relativistic Multiple Scattering Glauber Approximation (RMSGA)

- eikonal approximation based on **diffractive scattering**
- more natural at **higher energies**
- **multiple scattering** theory with “frozen” nucleons
- based only on individual **nucleon-nucleon scattering**:
  - data readily available from free *pp* and *pn* scattering

$\Longrightarrow$ can be used for the **whole mass range**!

Single Charge Exchange

- charge exchange in initial and final state interactions
- only **single charge exchange** is taken into account
- modelled in a **semi-classical** way:

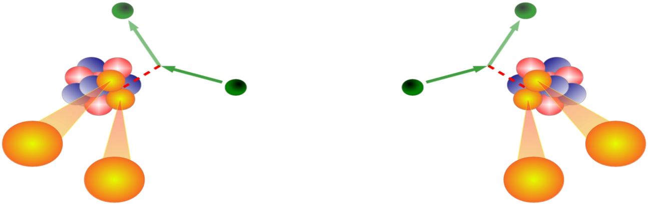
$$P^{\mathrm{CX}}_{N_1\to N_2}(\vec{r},T_k) \;=\; 1-\exp\left[-\sigma_{CX}(T_{N_1})\int_z^{+\infty}\mathrm{d}z'\,\rho_{N_2}(x,y,z')\right]$$

- use average probabilities:

$$\overline{P}^{\mathrm{CX}}_{N_1\to N_2}(T_k) \;=\; \int \mathrm{d}\vec{r}\,\rho_{N_1}(\vec{r})\,P^{\mathrm{CX}}_{N_1\to N_2}(\vec{r},T_k)$$

Available $(p, 2p)$ Data

And Future Prospects

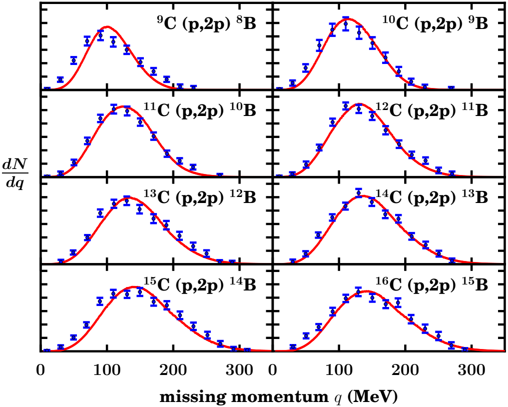


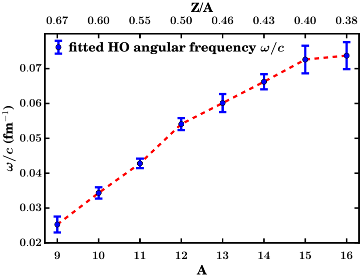
T. Kobayashi et al.: C$(p, 2p)$B reactions on $^{9-16}$C

- beams of different carbon isotopes $^{9-16}$C
- beam kinetic energy of 250 A MeV
- solid-hydrogen target
- knockout of valence *p*-state as well as deeply bound *s*-state protons
- two final protons detected at angles $\pm 39^\circ$
- residual nucleus (fragments) detected using a forward magnetic spectrometer
- selection of the reaction through boron detection and appropriate energy gates

(T. Kobayashi et al., Nucl. Phys. 805, 431c (2008))

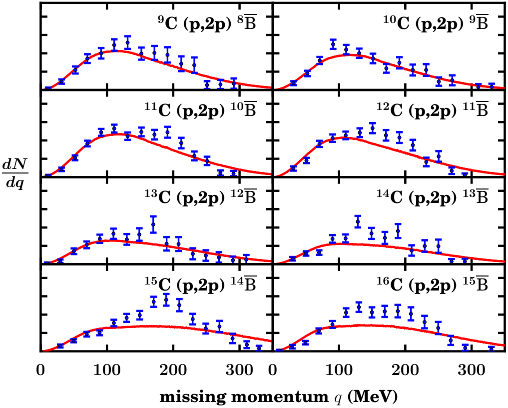
T. Kobayashi: C(p,2p)B reactions on $^{9-16}$C

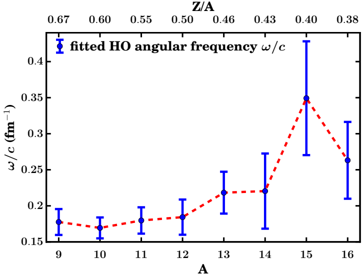




Fit of the theoretical **PWIA cross sections** to the experimental **momentum distributions** for the knockout of *p*-**state protons**.

T. Kobayashi: C(p,2p)$\overline{\mathrm{B}}$ reactions $^{9-16}$C





Fit of the theoretical **PWIA cross sections** to the experimental **momentum distributions** for the knockout of *s*-**state protons**.

OUTLOOK

- Include **initial and final state interactions** in the results
  - Kobayashi et al.: use RMSGA as low-order approximation
- Include **single charge exchange**
- Include **short range correlation** (SRC) effects
- Model **two-nucleon knockout** reactions A(p,pNN')B (sensitive to **SRC**)
- Apply the model to data from other experiments
- Experiments at
  - **NUSTAR@FAIR**
  - **RIKEN**
  - **HIMAC**

  can provide **new data to model**

THANK YOU FOR YOUR ATTENTION

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