

The role of knockout
in
nucleon-induced pre-equilibrium reactions

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Knockout reactions

A knockout reaction - one in which the projectile and a target nucleon leave the target after one and only one nucleon-nucleon interaction.

These reactions were first studied systematically in the late 1960's and early 1970's and are used today in studies of the structure of exotic nuclei.

These studies use an intermediate energy beam to obtain exclusive knockout cross sections that are analyzed using the DWIA.

We will study the inclusive knockout cross section.

Our interest is in particle emission rather than the structure of the target.

The one-nucleon removal cross section, in which one and only one target nucleon is emitted is a closely related but distinct quantity.

In general, further emission is possible after knockout of a nucleon.

QM descriptions of pre-equilibrium reactions usually treat all but the lowest energy reactions as direct multi-step inelastic excitation of the target (MSD).

The questions we wish to address here are:

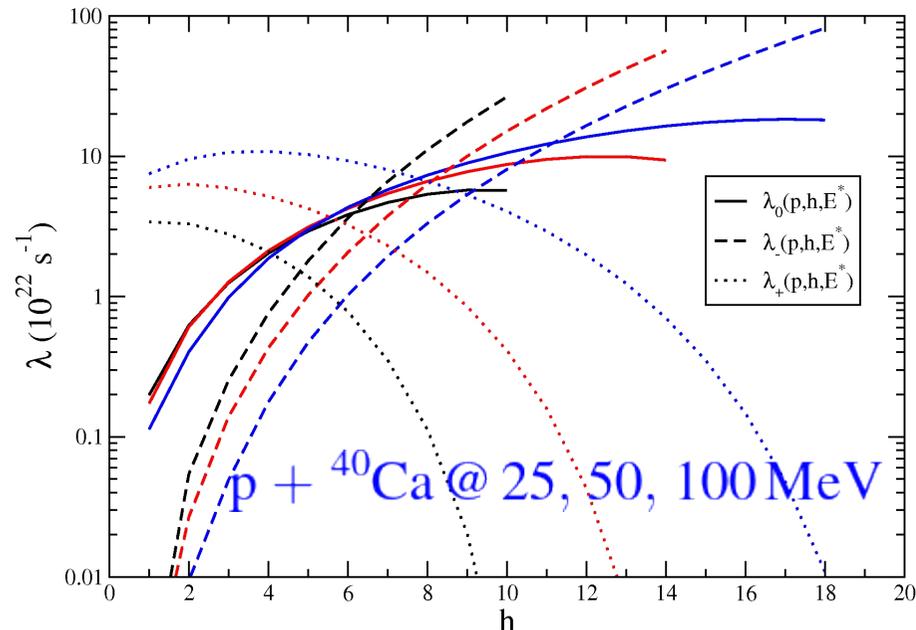
- How much of the nucleon emission is actually due to knockout?
- Can we distinguish knockout from inelastic excitation?

The HMS / DDHMS models

In both the MSD model -
H. Nishioka, H. A. Weidenmüller, S.
Yoshida, Ann. Phys. (NY) (1988) 166.

and the exciton/hybrid models -
J. Bisplinghoff, Phys. Rev. C33 (1986)
1569.

the early stage of a nucleon-induced
pre-equilibrium reaction is dominated
by collisions that increase the number
of particle-hole pairs.



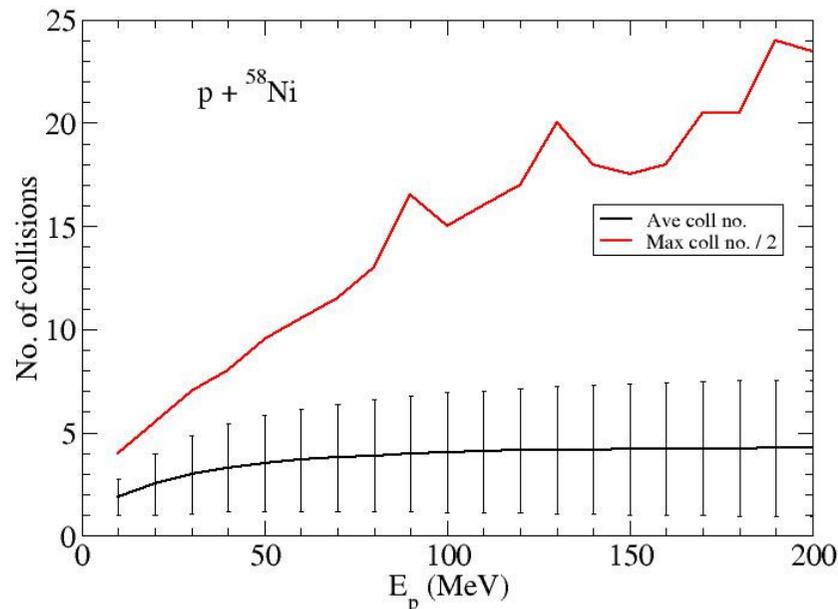
As the most important stages of a pre-equilibrium reaction are the first ones, Blann proposed a model in which only these collisions are taken into account - M. Blann, Phys. Rev. C54 (1996) 1341.

- Active particles and holes are treated as independent degrees of freedom.
- Particles can be emitted and both particles and holes can excite further particles and holes.
- Emission and excitation occur in accordance with the particle emission and particle and hole damping widths.
- At each stage, an emission or a particle-hole excitation is chosen randomly, based on the widths.
- The process continues until no particle or hole possesses energy sufficient to lead to further emission.

Particle collision tagging in the HMS

Since all active particles and holes can be followed in an HMS calculation, we can tag them according to the number of collisions.

- Collision 1 is induced by the incident particle and initially labels this particle as well as the particle-hole pair it produces.
- Collision 2 is induced by one of these three and labels it as well as the particle-hole pair it produces.
- The labelling continues for higher collision numbers.



We label emitted protons and neutrons separately by:

inel – particles emitted after 1 collision in which the second particle is in a bound state;

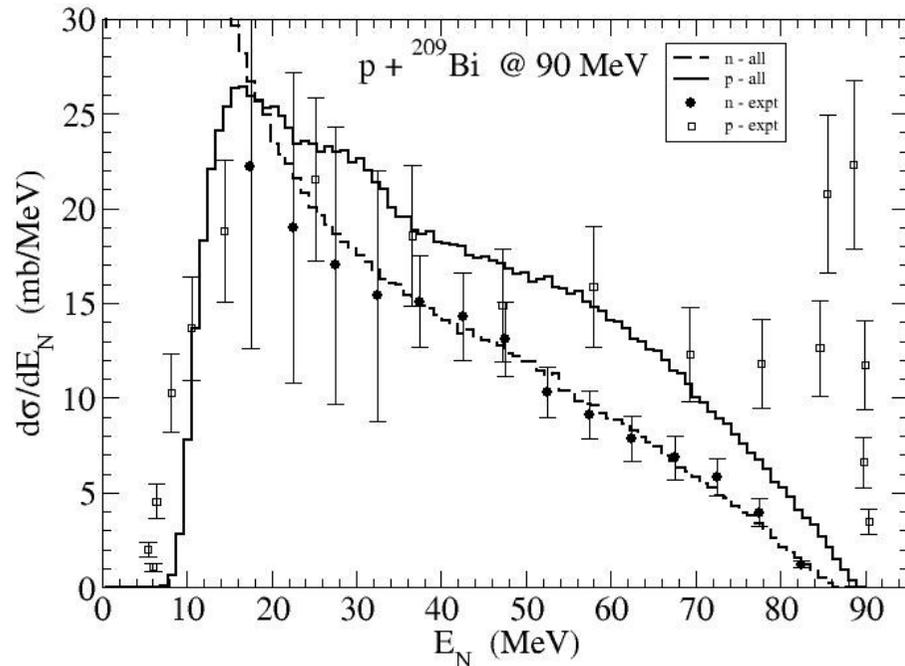
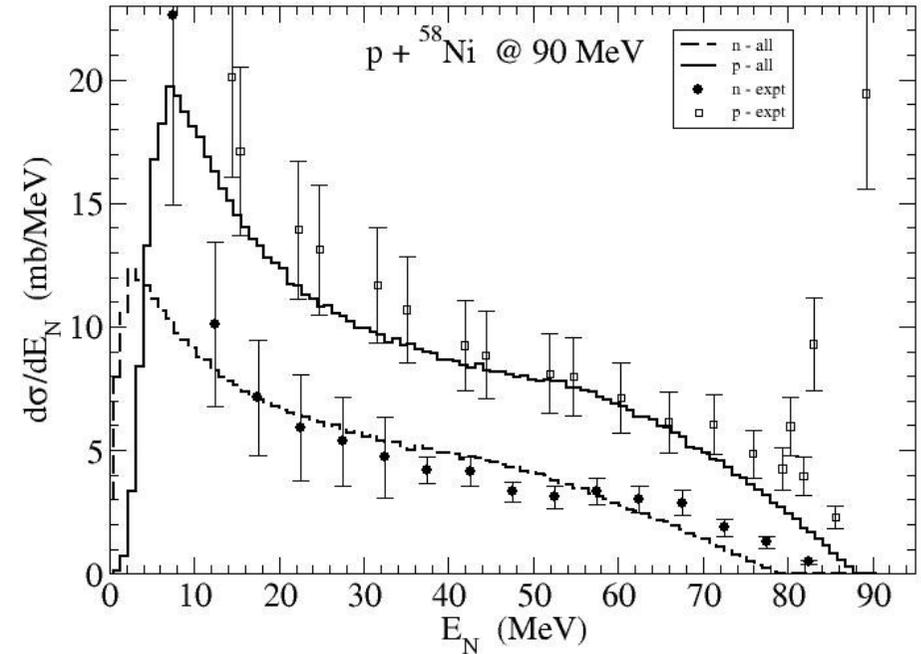
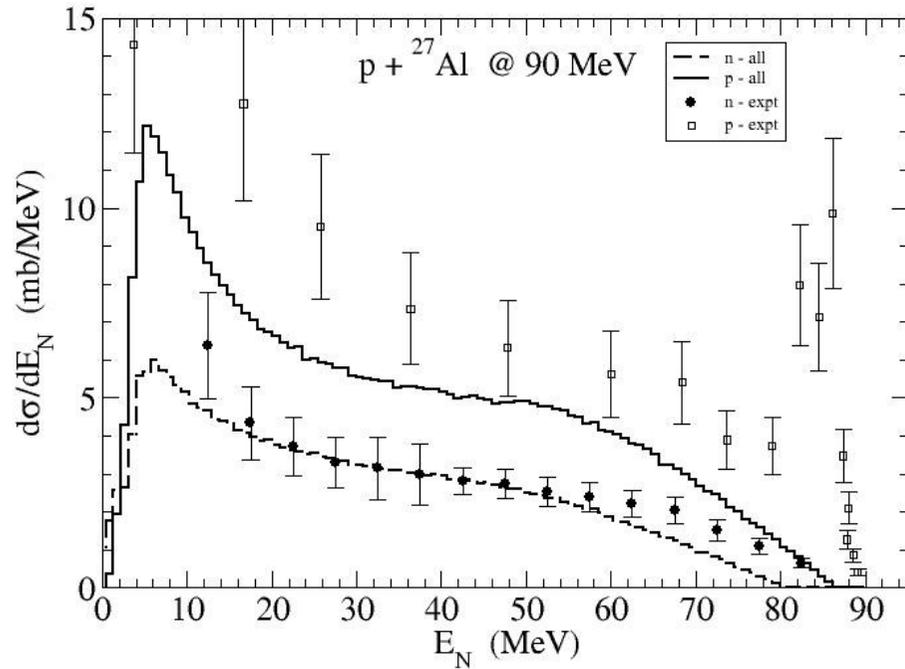
ko – particles emitted after 1 collision when the second particle is also emitted after 1 collision;

1 – particles emitted after 1 collision, independently of what happens to the collision partners;

2 – particles emitted after at most 2 collisions (although the second collision might be the particle's first), independently of what happens to the collision partners.

In all of these cases, the residual nucleus might still emit other particles.

Nucleon emission at 90 MeV – HMS vs experimental data



Data:

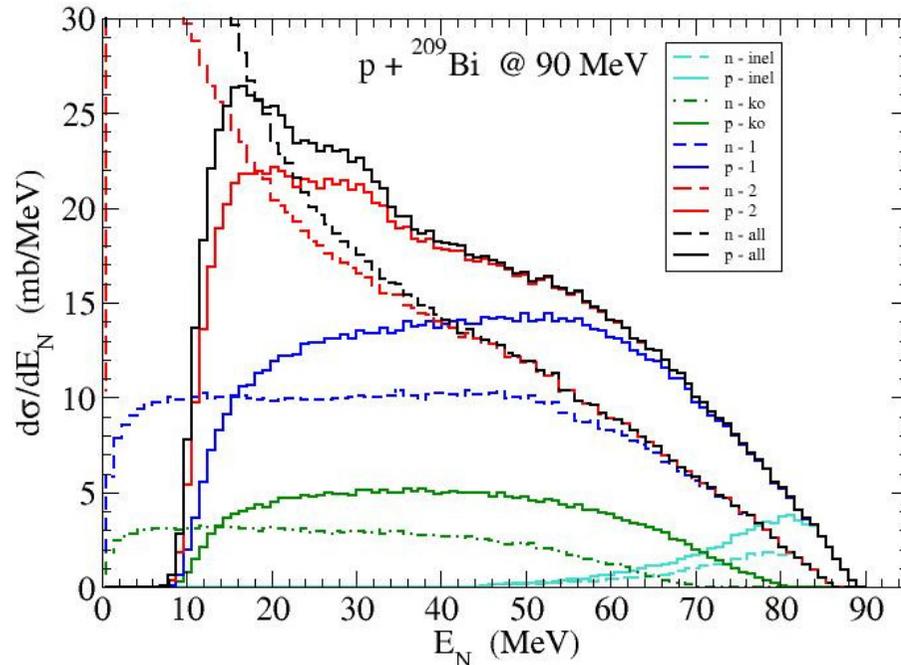
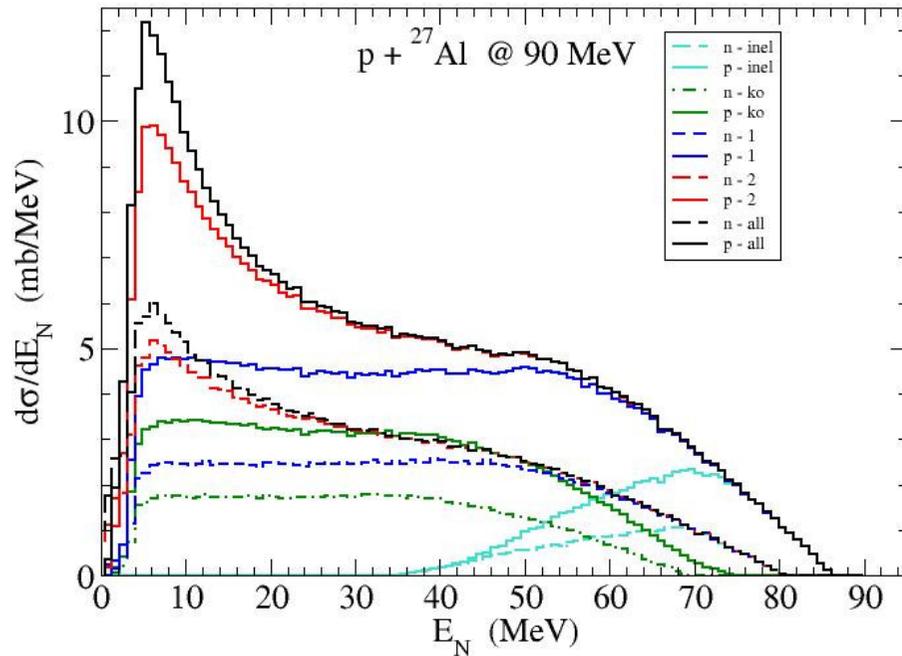
(p,p') - J. R. Wu, C. C. Chang, H. D. Holmgren, Phys. Rev. C19 (1973) 698.

(p,n) – A. M. Kalend et al., Phys. Rev. C28 (1983) 105.

Calculations:

EMPIRE 3.2.3 – only DDHMS emission

Nucleon emission at 90 MeV – components of HMS calculations



- Emission after 1 collision describes emission down to about 60 MeV;
- Emission after at most 2 collisions describes emission down to about 35 MeV;
- Inelastic excitation of “bound” states describes the first 10 to 20 MeV of the emission;
- Knockout constitutes a substantial fraction of the 1 collision emission from ${}^{27}\text{Al}$ but a smaller fraction of that from ${}^{209}\text{Bi}$;
- The knockout fraction of 1 collision emission is about the same for neutrons and protons.

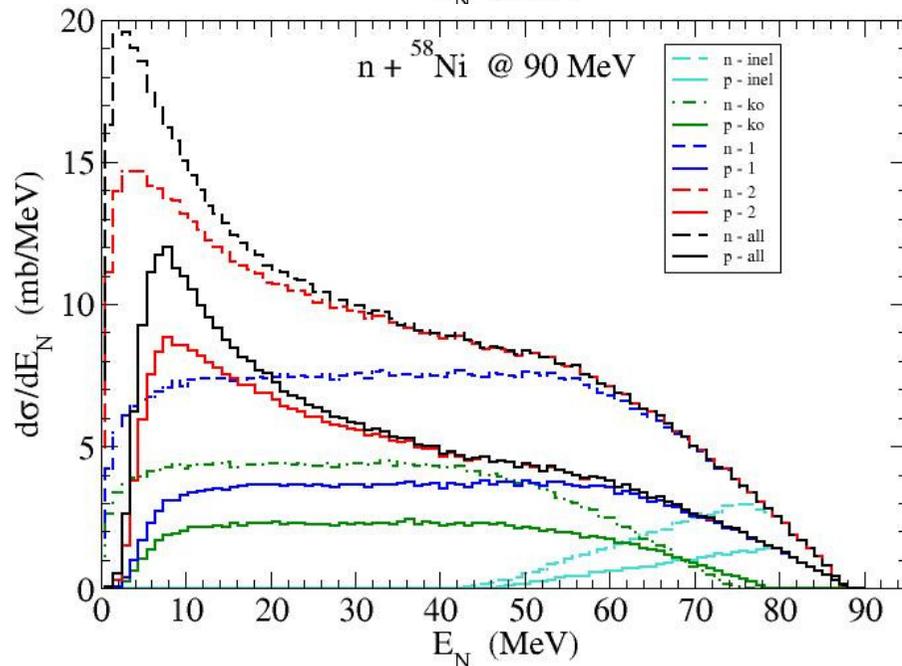
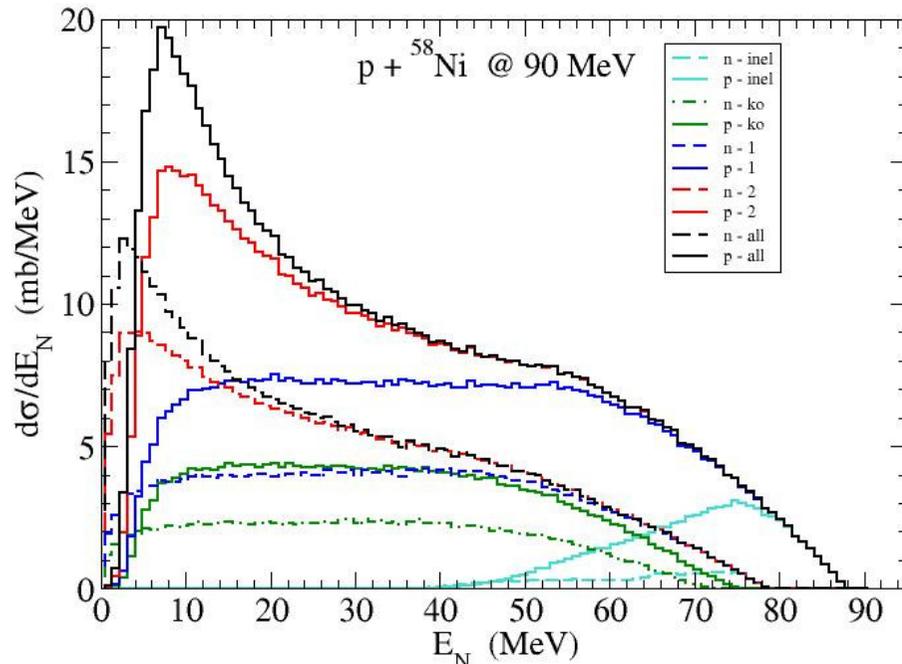
Neutron knockout production:

$$\sigma_{ko}(p \rightarrow pn)$$

Proton knockout production:

$$2\sigma_{ko}(p \rightarrow pp) + \sigma_{ko}(p \rightarrow pn)$$

Nucleon emission at 90 MeV – proton- vs neutron-induced reactions

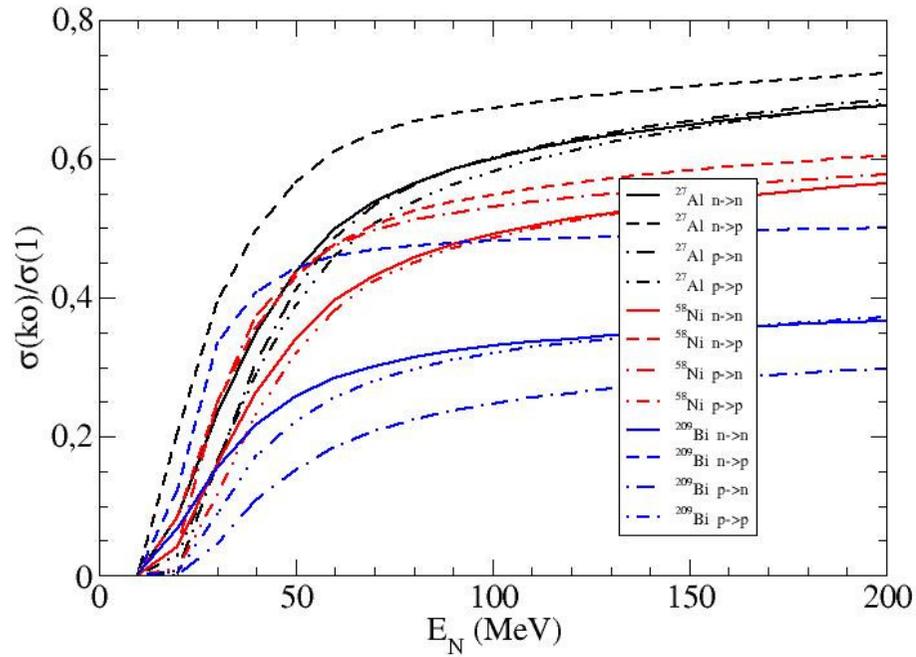


- Knockout from ${}^{58}\text{Ni}$ constitutes an intermediate fraction of the 1 collision emission – between that of ${}^{27}\text{Al}$ and that of ${}^{209}\text{Bi}$;

- The spectra in the neutron-induced reaction are very similar to those of the proton-induced reaction, with the roles of protons and neutrons interchanged;

- The observations of the previous slide concerning the inelastic excitation and the emission after 1 or at most 2 collisions hold equally well for proton- and neutron-induced reactions.

Knockout fraction of first collision – $\sigma(\text{ko})/\sigma(1)$



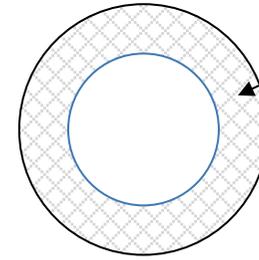
At high incident energy, the ratios tend to saturate at about

$${}^{27}\text{Al} : \quad \sigma(\text{ko})/\sigma(1) \approx 0.70$$

$${}^{58}\text{Ni} : \quad \sigma(\text{ko})/\sigma(1) \approx 0.50$$

$${}^{209}\text{Bi} : \quad \sigma(\text{ko})/\sigma(1) \approx 0.35$$

Peripheral collision



Knockout region

$$\Delta R$$

$$\text{Radius } R = r_0 A^{1/3} \quad r_0 \approx 1.25 \text{ fm}$$

$$\sigma(1) \approx \pi R^2$$

$$\sigma(\text{ko}) \approx \pi(R^2 - (R - \Delta R)^2)$$

$$\sigma(\text{ko})/\sigma(1) \approx 1 - (1 - \Delta R/R)^2$$

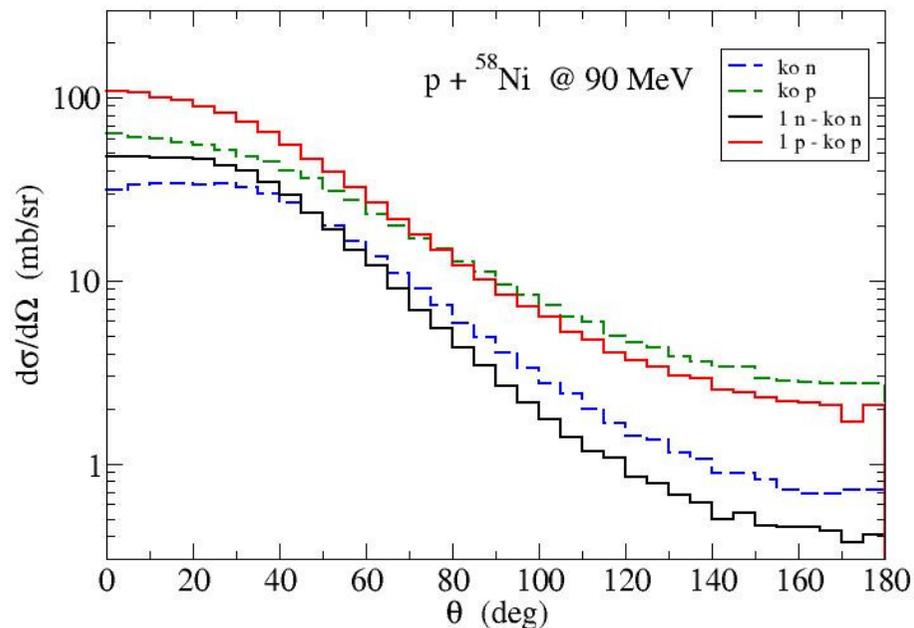
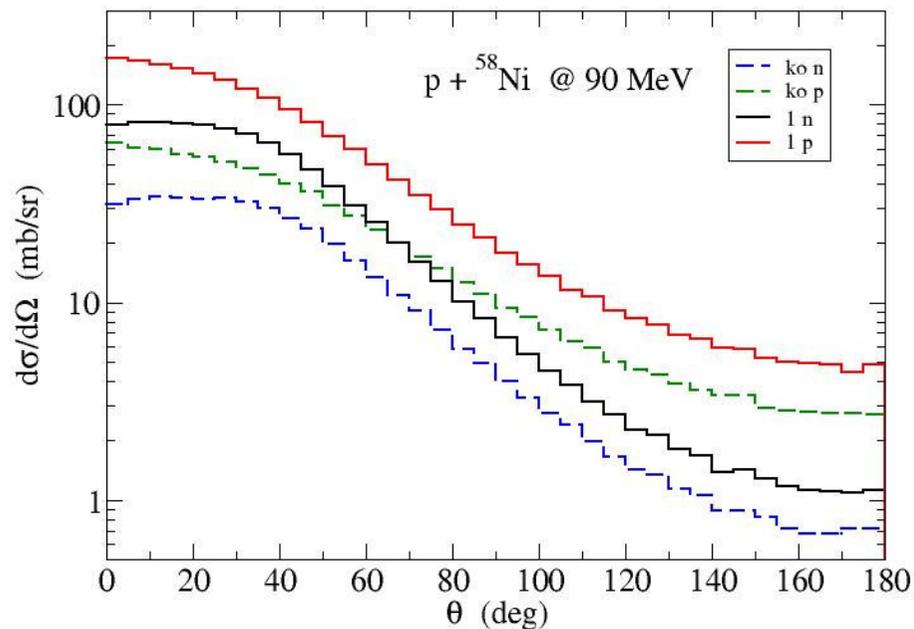
Inverting to obtain ΔR

$${}^{27}\text{Al} : \Delta R \approx 1.7 \text{ fm}$$

$${}^{58}\text{Ni} : \Delta R \approx 1.4 \text{ fm}$$

$${}^{209}\text{Bi} : \Delta R \approx 1.4 \text{ fm}$$

Angular distributions of knockout and of first emission



- Angular distributions in the HMS model are calculated using the Chadwick-Oblozinský model of momentum transfer in nucleon-nucleon collisions -

M. B. Chadwick, P. Oblozinský, Phys. Rev. C46 (1992) 2028.

As implemented in the DDHMS model -

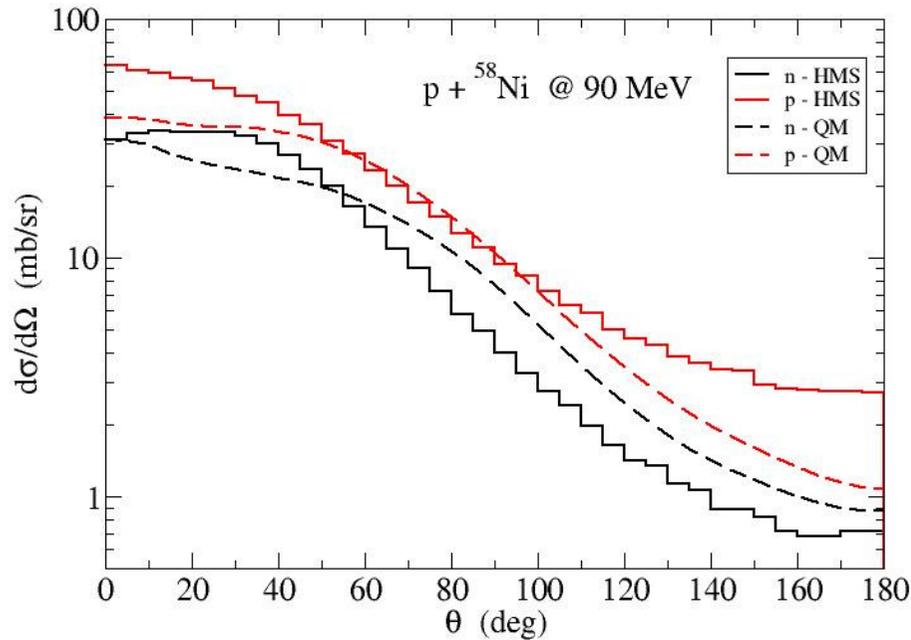
M. Blann, M. B. Chadwick, Phys. Rev. C57 (1998) 233.

-The energy-integrated angular distributions for knockout and nucleon emission after 1 collision are fairly similar.

- The 1 collision angular distribution **without** the contribution of knockout clearly falls faster with angle than the knockout angular distribution.

How might one observe the difference?

Comparison of knockout in HMS and QM calculations

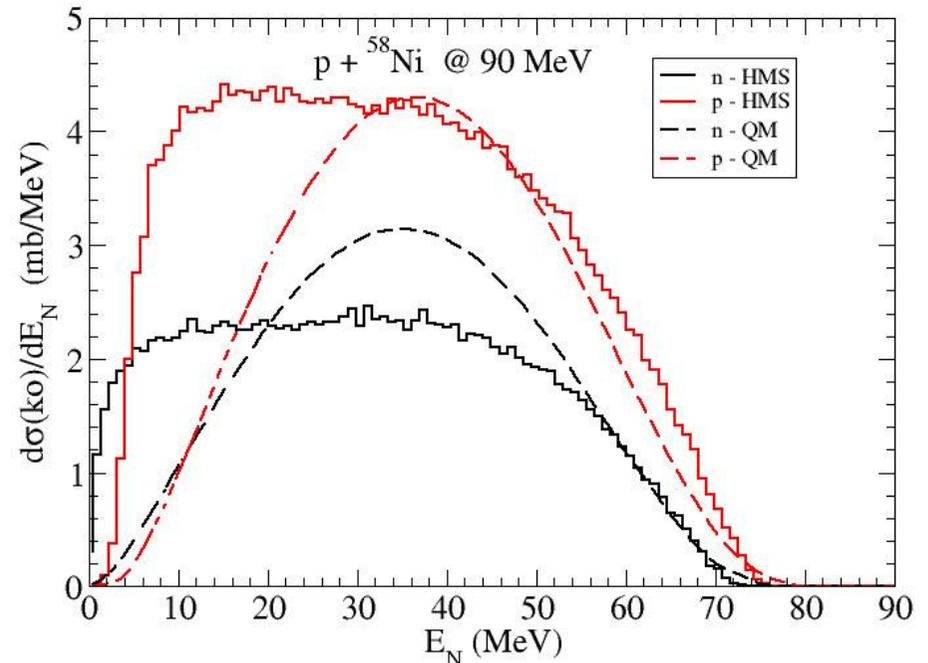


The energy-integrated angular distributions fall more slowly with angle than those of the DDHMS calculations, although they still are reasonably similar.

The spectra of the two calculations show quite different behavior and are comparable only at high emission energy.

We are attempting to perform quantum mechanical calculations of the double differential knockout spectra / angular distributions, which have scattering amplitudes of the form

$$\langle \vec{k}_{f1}, \vec{k}_{f2}; h | T | \vec{k}_i \rangle$$



The QM calculation

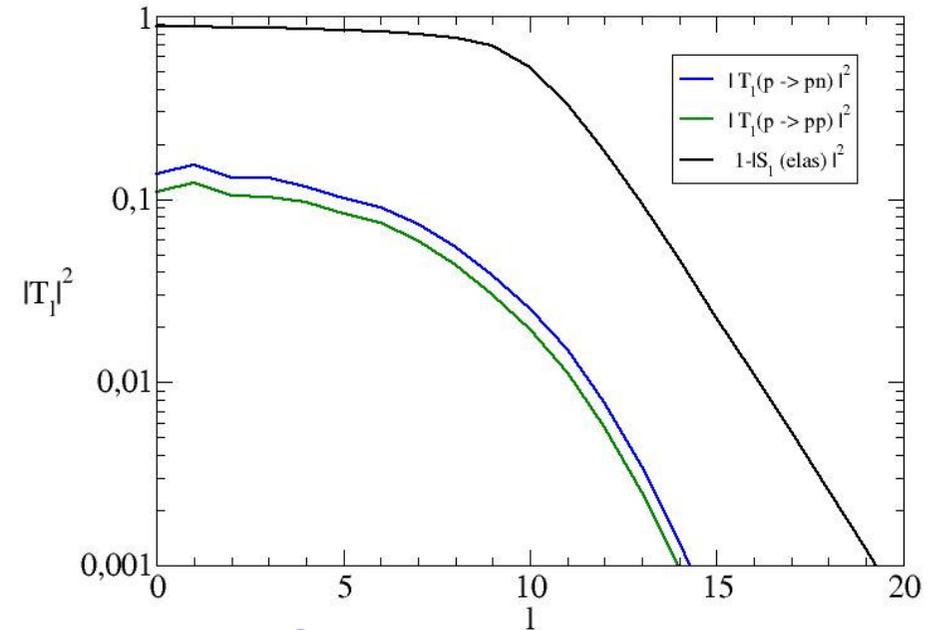
$$\begin{aligned}
 \langle \vec{k}_{f_1}, \vec{k}_{f_2}; h | T | \vec{k}_i \rangle = & \\
 & (4\pi)^3 \sum_{f_1 f_2 i} i^{l_{f_1} + l_{f_2} + l_i} e^{i\sigma_{l_{f_1}} + i\sigma_{l_{f_2}} + i\sigma_{l_i}} \mathcal{Y}_{l_{f_1} j_{f_1} n_{f_1}}(\hat{k}_{f_1}) \mathcal{Y}_{l_{f_2} j_{f_2} n_{f_2}}(\hat{k}_{f_2}) \mathcal{Y}_{l_i j_i n_i}^\dagger(\hat{k}_i) \\
 & \times \sum_{sl} T_{l_{f_1} j_{f_1} l_{f_2} j_{f_2} l_i j_i l_h j_h}^{sl}(k_{f_1}, k_{f_2}, k_i) \\
 & \times \sum_{jn} (-1)^{n_i - n_{f_2}} (l_i j_i | \hat{V}_{slj} | l_{f_1} j_{f_1}) (l_{f_2} j_{f_2} | \hat{V}_{slj} | l_h j_h) \begin{pmatrix} j_{f_1} & j & j_i \\ n_{f_1} & n & -n_i \end{pmatrix} \begin{pmatrix} j_h & j & j_{f_2} \\ n_h & n & -n_{f_2} \end{pmatrix}
 \end{aligned}$$

We use:

- Gaussian bound state wave functions;
- Koning-Delaroche potentials;
- a contact interaction;
- parametrized interaction strength from R. Bonetti et al., Phys. Rep. 247 (1994) 1.

$$\sigma_{ko}(n) = \frac{\pi}{k^2} \sum_l (2l+1) |T_l(p \rightarrow pn)|^2$$

$$\sigma_{ko}(p) = \frac{\pi}{k^2} \sum_l (2l+1) (2|T_l(p \rightarrow pp)|^2 + |T_l(p \rightarrow pn)|^2)$$



Conclusions

- Knockout does indeed play a role in nucleon-induced pre-equilibrium reactions.
- Its contribution to nucleon emission cross sections becomes more and more important as the incident increases above about 30 MeV.
- The knockout fraction of first-step emission is biggest for light nuclei and decreases for heavier nuclei.
- The knockout cross section is consistent with a peripheral one-step collision mechanism. In more central collisions, the chances are greater that one or both of the nucleons interact at least a second time.
- Due to the bothersome fact that two nucleons are emitted in a knockout reaction rather than the single nucleon emitted in an MSD inelastic scattering, it seems that it will be necessary to take both processes into account explicitly.
- Might there be an easy way to do this?

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