Knockout Reactions

Ian Thompson
University of Surrey

Two kinds of knockout:

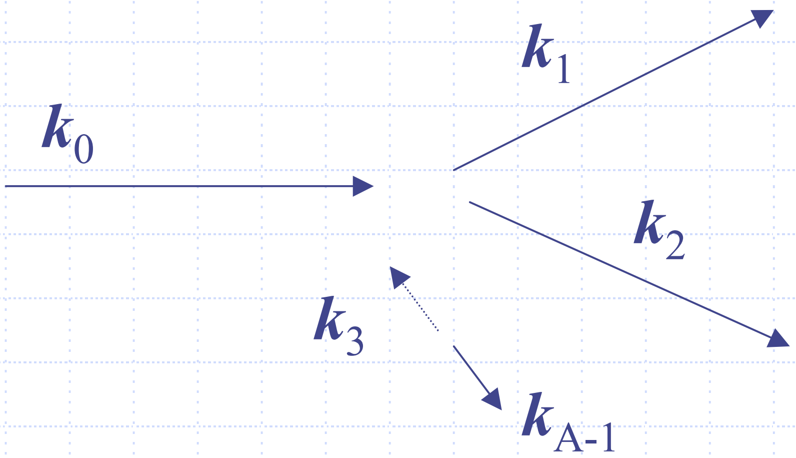
- **(p,2p)**
- Remove one nucleon from a bound state by high-energy knockout
- Large angle scattering
- To resolve nuclear states, need kinematically-complete measurements (ie. exclusive only).

Not used so much now.

- **(p,γX)**
- Remove one nucleon from a bound state by high-energy knockout
- Exclusive (forward angles) & inclusive combined
- To resolve nuclear states, use coincident γ detection.

See J.A. Tostevin et al.

(p,2p) kinematics



Incident proton 1: k_0
Scattered proton 1: k_1

Knocked out proton 2: k_2

Initial proton 2: k_3
Nuclear recoil: k_{A-1}

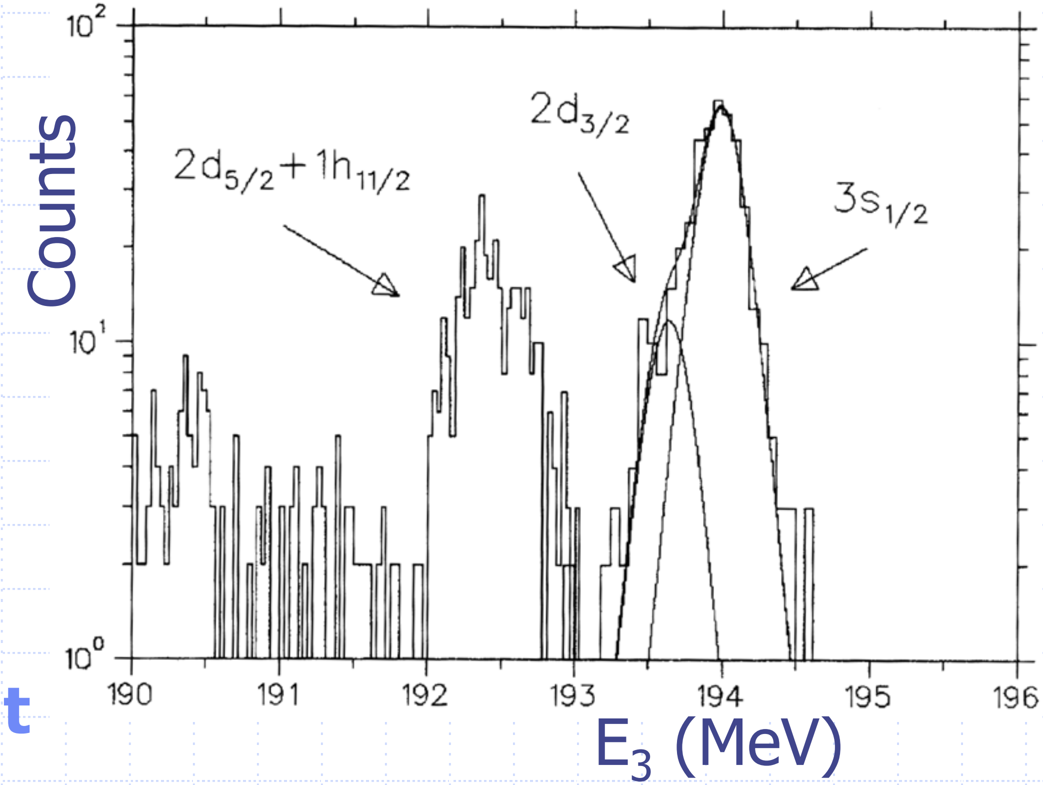
- Momentum conservation: $k_{A-1} = k_0 - k_1 - k_2 = -k_3$
- Energy conservation: the separation energy is
  $E_s = E_i - E_f = T_1 + T_2 + T_f - T_0$ $\quad$ (T_f = core recoil energy)

Result for $^{208}Pb(p,2p)^{207}Tl$

Detecting hole states in ^{207}Tl

From iThemba (NAC): see N.P.N. 14/1 (2004)

This is what we want for exotic nuclei!!



Binding-energy spectrum for $^{208}Pb(p,2p)^{207}Tl$ at 202 MeV.

Breakup Theory

- Both kinds of knockout include elastic breakup, in which all particles survive.
- Theories of elastic breakup: good for
  - Semiclassical Coulomb, for high energies, no nucl.
  - Glauber/eikonal, for small scattering angles
  - Low excitation energy of projectile, for CDCC
  - Zero-range binding potential, for Baur/Trautmann
- None of these limits apply here!
  - So use an impulse approximation, for high energies

Plane Wave Impulse Approx.

- Neglecting initial- and final-state interactions, expect cross section ~

$$\frac{d^6\sigma}{dE_1 d\Omega_1 dE_2 d\Omega_2} = F_{\text{kin}} \; S_{E_3}(\mathbf{k}_3) \; \frac{d\overline{\sigma_{\text{fr}}}}{d\overline{\Omega}}$$

where $S_{E_3}(\mathbf{k}_3)$ = spectroscopic factor

and $d\overline{\sigma_{\text{fr}}}/d\overline{\Omega}$ = free particle-nucleon cross section (in some cm. frame).

Pure shell model spectroscopy

- In a pure, single-particle shell model, the spectroscopic strength is

$$S_{E_3}(\mathbf{k}_3) = \sum_i |g_i(\mathbf{k}_3)|^2 \delta(E_i - E_3)$$

Here $|g_i(\mathbf{k}_3)|^2$ is the momentum distribution (Fourier transform of the gs wave function) of the single-particle state i at energy E_3

Distortions: the DWIA

Now include potentials for particles 0, 1 and 2 that give distorted incoming and outgoing waves: $\chi_{\mathbf{k}_j}(\mathbf{r})$

So, neglecting recoil effects in the radii:

$$\frac{d^6\sigma_{fi}}{dE_1 d\Omega_1 dE_2 d\Omega_2} = F_{\rm kin}\; g'_{fi}(\mathbf{k}_3)\; \frac{d\overline{\sigma_{\rm fr}}}{d\overline{\Omega}}$$

where kinematic factor is $F_{\rm kin} = \frac{4}{(\hbar c)^2}\frac{k_1 k_2 \overline{E}_0^2}{k_0 E_3}$

and overlap integral $g'_{fi}(\mathbf{k}_3)$ has bound st $\psi_i(\mathbf{r})$:

$$g'_{fi}(\mathbf{k}_3) = \int d^3\mathbf{r}\;\chi^{-*}_{\mathbf{k}_1}(\mathbf{r})\chi^{-*}_{\mathbf{k}_2}(\mathbf{r})\psi_i(\mathbf{r})\chi^{+}_{\mathbf{k}_0}(\mathbf{r})$$

This integral is hard by partial waves. Try doing 3D integral! (THREEDEE of Chant)

Off-shell Effects

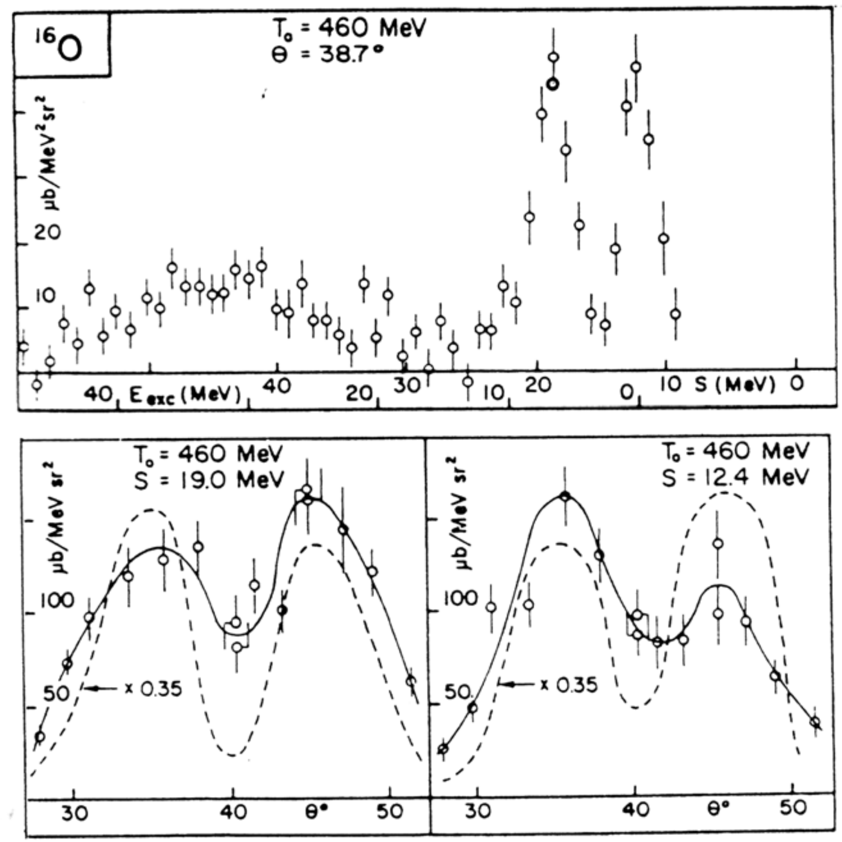
- The free cross section $d\overline{\sigma_{\mathrm{fr}}}/d\overline{\Omega}$ should be taken at the momenta transformed to the centre of mass system [overline notation].
- However, the cm systems are different before and afterwards, and also relative energy changes! Hence ‘off shell’.
- Usually: try initial and final energy prescription, and see if any differences.
- Better: use potential $\Rightarrow$ off shell t-matrix

Results: $^{16}O(p,2p)^{15}N$ at 460 MeV

Energy spectrum, showing (from right) $0p_{1/2}$, $0p_{3/2}$, $1s_{1/2}$.

Angular correlations,
Right: $0p_{1/2}$ peak.
Left: $0p_{3/2}$ peak.

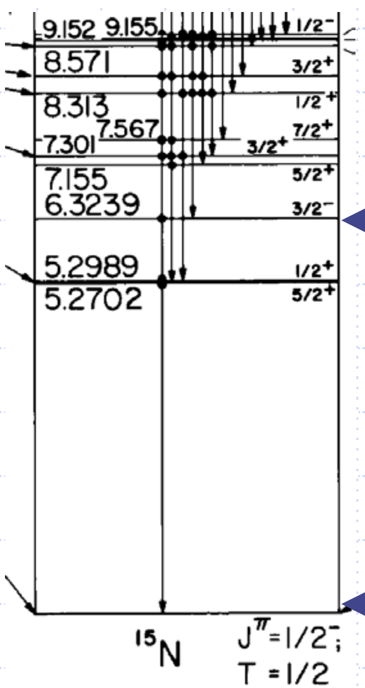
From: Tyren et al, NP 79 (1966) 321.

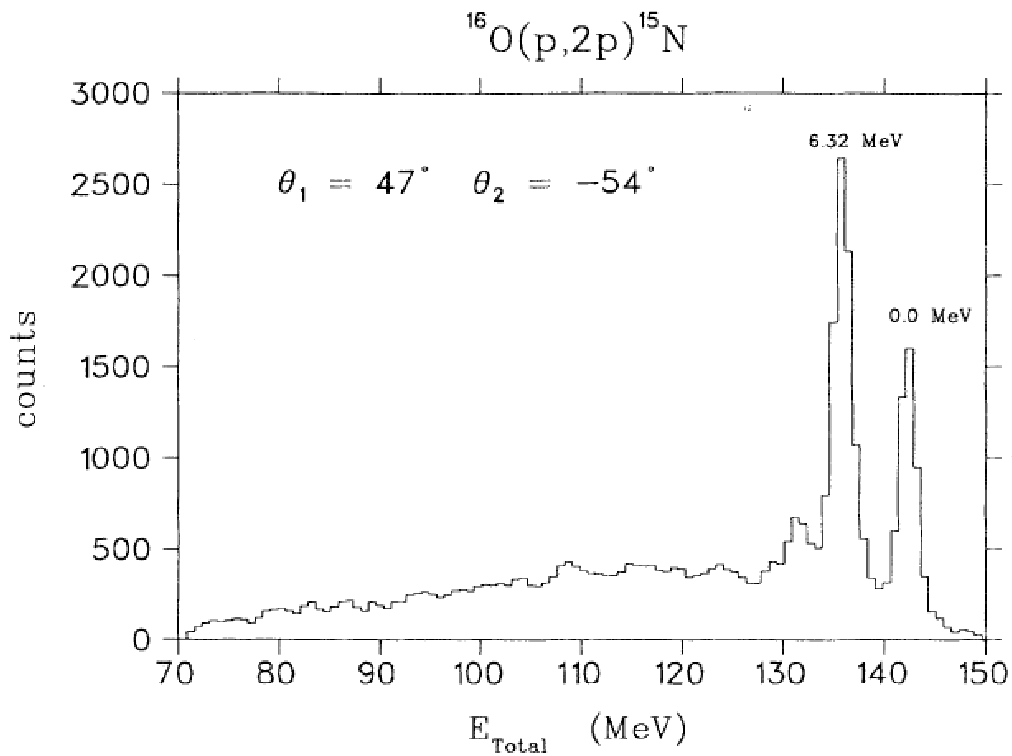


Dashed curves: Bergren's theory * factor shown.

Results: $^{16}O(p,2p)^{15}N$ at 151 MeV

Energy spectrum, showing (from right) $1/2^-$ and $3/2^-$ states.



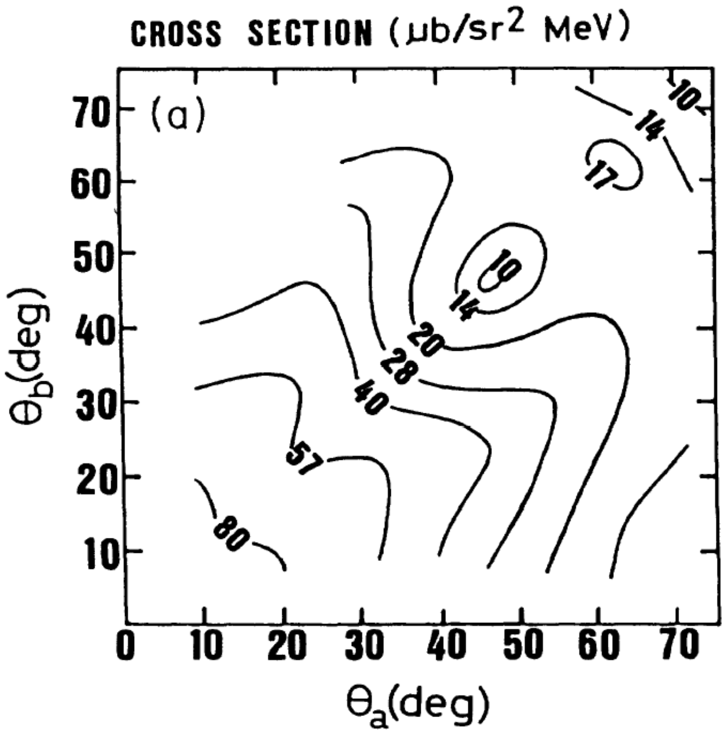


Data from Cowley et al, PRC 44 (1991) 329.

Angular Correlations

We often think that $\mathbf{k}_1$ and $\mathbf{k}_2$ are 90 deg apart.

Experimental cross sections for the $1p_{3/2}$ peak in the $^{12}C(p,2p)$ reaction at E_p = 84 MeV.



From Kudo et al, PRC 38 (1988) 1126

Data: Noro et al, Osaka Report 1986.

Other topics

- Analysing powers for polarised protons
  - New ball game.
  - Need entrance and exit spin-orbit forces.
- Off-shell effects
  - Both ‘impact’ and ‘binding’ are off-shell!
- Factorisation: is it good?
  - Probably at high energies, such as at GSI.

Review Articles

[1] G. Jacob, T.A.J. Maris, Rev. Mod. Phys. 38 (1966) 121.

[2] G. Jacob, T.A.J. Maris, Rev. Mod. Phys. 45 (1973) 6.

[3] P. Kitching, W.J. McDonald, T.A.J. Maris, C.A.Z. Vasconcellos, Adv. Nucl. Phys. 15 (1985) 43.