Four-Body Treatment of Inclusive Breakup of Borromean Nuclei

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The inclusive breakup of cluster type nuclei is an important source of information about the interacting sub-system. The spectrum of the observed fragment, b, in reactions of the type,

a + A ----→ b + (x + A),

furnishes the reaction cross section of the (x + A) subsystem, which is otherwise not available from a primary x + A reaction. This is the spirit of the Surrogate method, which is applied in the (d, p) reaction to get the (n + A) "capture" cross section.

The Inclusive Breakup Cross Section

Use the spectator model where the observed fragment, b, suffers only elastic scattering and does not otherwise interact with the target. The spectrum of b was derived by several people and is obtained through judicial application of direct reaction theory in conjuction with operator identities and sum rules.

$$d^2\sigma/d\Omega_b dE_b = d^2\sigma^{(EB)}/d\Omega_b dE_b + d^2\sigma^{(NEBP)}/d\Omega_b dE_b$$

The first term is the elastic breakup (EB) given by,

$$d^2\sigma^{(EB)}/d\Omega_b dE_b = (2\pi/\hbar v_a)$$

$$\Sigma_{(kx)} \;|\langle\chi^{(-)}{}_b\,\chi^{(-)}{}_x\,|V_{xb}|\Psi^{(+)}{}_{(3B)}\rangle|^2$$

$$\delta(E_a - E_x)$$

while the second one is the non-elastic breakup (NEB) cross section.

$$d^2\sigma^{(NEB)}/d\Omega_b dE_b$$

$$= (2/\hbar v)\langle\rho_x|W_x|\rho_x\rangle$$

The source function of the interacting x fragment is:

$$\rho_x = (\chi^{(-)}{}_b|\Psi^{(+)}{}_{3B}\rangle$$

W_x is the imaginary part of x optical potential

We shall concentrate our attention on the NEB cross section.

For this purpose we turn now to briefly review what has become known as the Austern formula given above

$$d^2\sigma^{(NEB)}/d\Omega_b dE_b$$
$$= (2/\hbar v)\rho_b(E_b) \int dr_x \; |(\chi^{(-)}_b|\Psi^{(+)}_{(3B)}>(r_x)|^2 \, W_x(r_x)$$

where $\Psi^{(+)}_{(3B)}$ is the exact three-body, b + x + A, scattering wave function times the intrinsic wf of the projectile, $\chi^{(-)}_b$ is the distorted wave of b, and $E_a = E_b + E_x$

$$[E_x - K_x - K_b - U_x - U_b - V_{xb}]\, \Psi^{(+)}_{(3B)} = 0$$

$$[E_b - K_b - U^{\dagger}_b]\, \chi^{(-)}_b = 0,$$

$\rho_b(E_b)$ is the density of states of b

$W_x(r_x)$ is the imaginary part of the optical potential of x, U_x

The following papers used a DWBA approximation for $\Psi^{(+)}_{(3B)}$ along the lines of IAV (Phys.Rev C. 32, 431(1985)), UT(Phys. Rev. C 24, 1348 (1981)), and HM (Nucl. Phys. A, 445, 124 (1985):

-G. Potel, F. M. Nunes, and I. J. Thompson, Phys. Rev. C 92, 034611 (2015).

-J. Lei and A. M. Moro, Phys. Rev. C 92, 044616 (2015); J. Lei and A. M. Moro, C 92, 061602(R) (2015).

-B.V. Carlson, R. Capote, M. Sin,

Few-Body Syst. 57, 307 (2016).

They calculated the spectrum of the protons in the (d, p) reaction and extracted the neutron "capture" cross section using the IAV expression(DWBA version of the Austern formula). These three DWBA-based theories are related:

$$(\chi^{(-)}_b|\Psi^{(+)}_{(IAV)}> = (\chi^{(-)}_b|\Psi^{(+)}_{(UT)}> + (\chi^{(-)}_b|\Psi^{(+)}_{(HM)}>$$

where,

$$(\chi^{(-)}_b\ |\Psi^{(+)}_{(IAV)}> = G_x(\chi^{(-)}_b\ |V_{xb}|\chi^{(+)}_a\phi_a >$$

$$(\chi^{(-)}_b\ |\Psi^{(+)}_{(UT)}> = G_x(\chi^{(-)}_b|[U_x + U_b - U_a]|\chi^{(+)}_a\phi_a >,$$

$$(\chi^{(-)}_b\ |\Psi^{(+)}_{(HM)}> = (\chi^{(-)}_b\ |\chi^{(+)}_a\phi_a >$$

G_x **is the optical Green's function of the interacting fragment** x**,**

$$G_x = [E_x - K_x - U_x + i\varepsilon]^{-1}$$

We must mention that the extracted "capture" cross section,

$$\sigma_{(xA)} = (k_x/E_x)\int dr_x \ |(\chi^{(-)}_b|\Psi^{(+)}_{(IAV)}>(r_x)|^2 \ W_x(r_x)$$

is the total reaction cross section of x. To obtain the capture or fusion cross section, one must subtract the direct part. This latter part would account for inelastic neutron scattering from the target .

Recent extensions: Inclusive Breakup of Three-Fragment Projectiles

For a three-fragments, clustered projectiles, the inclusive breakup cross section has been recently derived. Calling the projectile

$a = b + x_1 + x_2$, the spectrum of b

in the reaction $a + A \rightarrow b + (x_1 + x_2 + A)$ is

$$d^2\sigma/d\Omega_b dE_b = d^2\sigma^{(EB,4B)}/d\Omega_b dE_b + d^2\sigma^{(NEB,4B)}/d\Omega_b dE_b$$

The 4B elastic breakup cross section,

$$d^2\sigma^{(EB,4B)}/d\Omega_b dE_b = (2\pi/\hbar v_a) \Sigma_{(kx1,\, kx2)}$$
$$|<\chi^{(-)}_b \psi_X^{(-)} | [V_{x1,b} + V_{x2,b}] | \Psi^{(+)}_{(4B)}>|^2 \delta(E_a - E_{x1} - E_{x2})$$

where $\psi^{(-)}{}_X \equiv \psi^{(-)}{}_{(x1+x2)}$ is the 3B scattering wf of the unobserved fragments.

These fragments interacts with each other through $V_{x1\ x2}$ as they scatter off the target through the optical potentials

U_{x1} and U_{x2}

$$[E_{(x1 + x2)} - K_{x1} - K_{x2} - U_{x1} - U_{x2} - V_{x1x2}]\ \psi^{(+)}{}_{(x1+x2)} = 0.$$

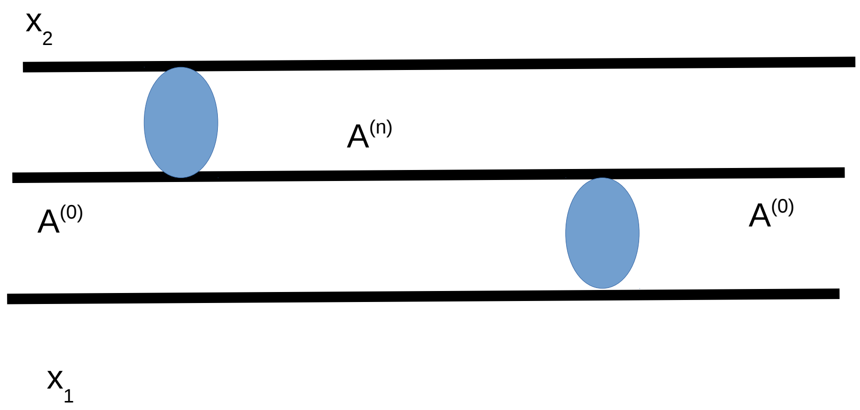
The NEB is derived to be

$$d^2\sigma^{(NEB,4B)}/d\Omega_b dE_b = (2/\hbar v_a)\, \rho_b(E_b)$$

$$\int dr_{x1}\; dr_{x2}$$

$$|(\chi^{(-)}{}_b|<\Psi^{(+)}{}_{(4B)}>|^2$$

$$[W_{x1}(r_{x1}) + W_{x2}(r_{x2}) + W_{3B}(r_{x1}, r_{x2})]$$



x2
A(n)
A(0)
A(0)
x1

The calculation of the total “reaction cross section” of the three-body sub-system $x_1 + x_2 + A$, namely,

$$\sigma\,(R,\,(x_1 + x_2)A) = F(k_{x1},k_{x2}) \int dr_{x1}\, dr_{x2} \,|(\chi^{(-)}_{b}|<\Psi^{(+)}_{(4B)}>|^2\, [W_{x1}(r_{x1}) + W_{x2}(r_{x2}) + W_{3B}(r_{x1},r_{x2})].$$

Can it be done (the first two terms) by integrating the three-body NEB cross section over energy and solid angle? This amounts to getting the yield of x_2 and that of x_1.

The three-body absorption term related to $W_{3B}(r_{x1},r_{x2})$ needs a theory! We are working on this. This can be of great importance in nuclear structure e.g. The transfer of two correlated neutrons to the target, in say, (t,p) reactions, and the possible excitation of Giant Pairing Vibration Resonance (GPVR)(pp-hh coherent excitations).

Inclusive Breakup of Borromean Nuclei

The cases of ^{6}He, ^{11}Li, ^{14}Be, ^{22}C are of interest, as the three-body system has the interesting property of not having any of its two-body subsystems bound on their own. Accordingly two-body correlations are very important.

These correlations are clearly felt in the

1)EB cross section through the two neutron scattering wave function, $\psi^{(-)}_{(2n)}$

and through

2)The three-body absorption in the NEB cross section, represented by W_{3B}**, where 3B stands here for the n + n + A system**.

Conclusions

- **The inclusive breakup cross section contains invaluable information about the reaction cross section of the two-body subsystem in the case of two-fragments clustered projectile.**
- **The Surrogate method as applied to (d, p) reactions uses the theory to obtain the reaction cross section of the n+A subsystem.**

- **The inclusive breakup cross section contains invaluable information about the reaction cross section of the two-body subsystem in the case of two-fragments clustered projectile.**
- **The Surrogate method as applied to (d, p) reactions uses the theory to obtain the reaction cross section of the n+A subsystem.**

- **The new theory of 4B inclusive breakup in the case of three-fragments clustered projectiles will allow the extension of the Surrogate method, to reactions of the type**

(t, p), and the application to the breakup of two-neutron halo, Borromean, Nuclei.

THANK YOU!