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Method of Finite-Range Distorted-Wave Born Approximation for Pickup to Unbound Ejectiles

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A method is outlined for performing finite-range distorted-wave Born-approximation calculations for pickup reactions in which the ejectile is unbound with respect to the transferred particle.

As transfer reactions in which the ejectile state is unbound (detected via its decay products in coincidence) become more feasible,[1] methods to analyze such reactions need to be explored. The standard distorted-wave Born-approximation (DWBA) theory[2] for light-ion reactions calculates the matrix element of V_{pa}, the interaction between the transferred particle and the light projectile. In the case of stripping reactions to unbound residual target states, the numerical integrations which must be performed converge slowly because of the unbound state and one must use special techniques[3] to evaluate these integrals. However, the DWBA transition amplitude may be rewritten by use of the post-prior transformation.[4] If in analogy to the usual form of the transition amplitude one keeps V_{pA}, the interaction between the transferred particle and target nucleons, the radial matrix elements now converge. For transfers between heavy ions, this is a satisfactory substitution.[5] However, in the case of light-ion transfer the two neglected terms of the interaction are nonnegligible and the two forms cannot be interchanged. For pickup reactions to unbound *ejectile* states the V_{pa} interaction form for light ions gives the necessary convergence factor to the matrix elements and allows the necessary integrations to be done by the usual techniques.

We wish to report an analysis of the reaction $^{12}C(\alpha, {}^5Li){}^{11}B$(g.s.) at[6] 65 MeV in which the final state of the ejectile is unbound and possesses a width comparable to its resonant energy. The transition amplitude is of the form (for the reaction $a+A \to b+B$ with $b = a+x$)

$$T_{fi} = \langle \chi_f^- \varphi_b^- | V_{pa}(r_{ax}) | \varphi_x \chi_i^+ \rangle,$$

where χ_i^+ (χ_f^-) is the distorted wave for the incident (final) system, φ_x is the bound state of the transferred nucleon in the initial target, and φ_b^- the relative motion between a and x in the ejectile for positive energy with incoming–scattered-wave boundary conditions and is of the form

$$\varphi_b^-(r) = \left(\frac{2}{\pi}\right)^{1/2} \sum_{j,l} i^l \exp[-i(\delta_{jl} + \sigma_l)] u_{jl}(r)(-1)^{l+1/2-j} \left(\frac{j+\frac{1}{2}}{2l+1}\right)^{1/2} [\mathcal{Y}_{l,1/2,j}(\hat{r}) Y_l(\hat{k})]_{1/2},$$

where $\mathcal{Y}_{l,1/2,j}(\hat{r})$ is the coupling of the orbital to the spin angular momentum and is coupled to the $Y_l(\hat{k})$ to give a total spin $\frac{1}{2}$ for the transferred particle. The radial function in φ_b^- has for large r the asymp-

TABLE I. Potential parameters used in the DWBA calculations. Here $V(r) = -V_0 f((r - r_0 A^{1/3})/a) - iW_0 f((r - r_0' A^{1/3})/a') - \lambda(V_0/45.2) r^{-1}[df((r_0 - r_0 A^{1/3})/a)/dr]\vec{L}\cdot\vec{S} + V_c$, where $f(x) = [1+\exp(x)]^{-1}$.

	V_0 (MeV)	W_0 (MeV)	r_0 (fm)	a (fm)	r_c (fm)	$V_{s.o.}$ (MeV)	W' (MeV)	r_0' (fm)	a' (fm)	λ
$\alpha + {}^{12}C$	151.9	28.5	1.24	0.665	1.25	⋯	⋯	1.24	0.64	⋯
${}^5Li + {}^{11}B$	200.0	10.6	1.22	0.72	1.3	⋯	⋯	2.17	0.945	⋯
${}^{11}B + p$	a	⋯	1.25	0.65	1.25	⋯	⋯	⋯	⋯	25.0
$\alpha + p$	45.96	⋯	1.25	0.65	1.415	⋯	⋯	⋯	⋯	38.0

[a]Adjusted to reproduce the binding energy.

totic behavior

$$u_{jl}(r) \to (kr)^{-1}\sin(kr + \delta_l + l\pi/2 + \sigma_l + \eta \ln 2kr),$$

where δ_l and σ_l are the nucleon and Coulomb phase shifts, respectively, and η is the Coulomb parameter.

If the experiment sums over all the directions of the momentum $\hbar k$ in the $a+x$ system, which is the usual case, we have an incoherent sum over the different (lj) amplitudes for the cross sections,

$$d\sigma/dE\,d\Omega = \sum_{j,l} d\sigma_{jl}/dE\,d\Omega,$$

where

$$\frac{d\sigma_{jl}}{dE\,d\Omega} = \frac{2\mu k}{\pi\hbar^2}\,\frac{j+\frac{1}{2}}{2l+1}\,\sigma_{\rm DW}{}^{jl},$$

and μ is the reduced mass for the ejectile-light-projectile systems. Since the main component of the ejectile wave function is a p wave, the calculations must be done in finite range. We have used the computer code DWUCK5[7] for all the calculations. In order to represent the ${}^5Li$ state we chose a Woods-Saxon potential to reproduce the energy variation[8] of phase shifts for the proton-plus-alpha-particle system. This potential is given in Table I along with the optical potentials for the distorted waves. The resulting fit (solid line) to the phase shifts is shown in Fig. 1(c). For each energy the wave function was then used to compute the differential cross section. The resulting energy-dependent cross section is depicted by the solid line in Fig. 1(b). The dashed line in Fig. 1(b) shows the resulting line shape from the $\alpha({}^3He, d){}^5Li$ experiment[9] with the height scaled to fit the $(\alpha, {}^5Li)$ data. The addition of the

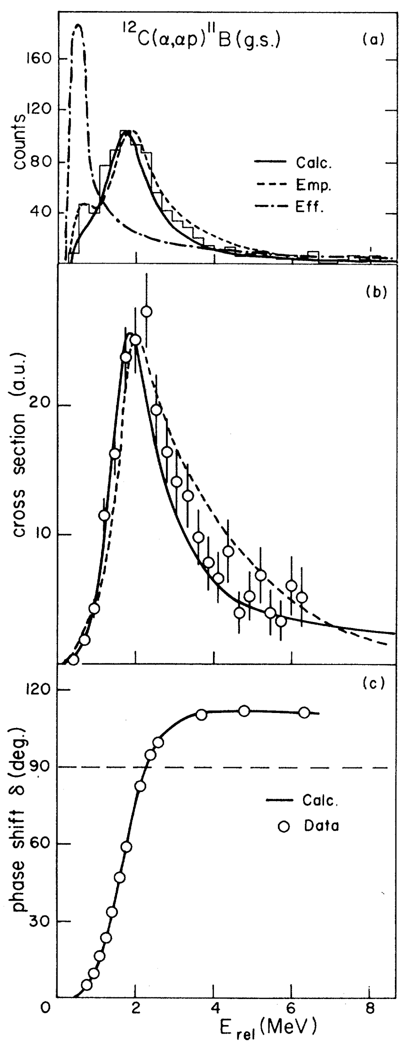

FIG. 1. (a) The counting rate in the experiment at 12° angle is shown by the stepped curve along with the calculated cross sections (solid line) and empirical (Ref. 9) shape (dashed line) multiplied by the detector efficiency (dot-dashed line). (b) The data from the counting rates and detector efficiency of (a) are shown along with the calculated (solid line) and empirical shape (dashed line). (c) The fit to $p_{3/2}$ phase-shift data is shown by the solid line.

$s_{1/2}$ and $p_{1/2}$ states to the cross section is at most a 10% contribution for the range of energies shown here.

Also in the experimental setup of Ref. 6 the efficiency of detecting the $^5Li^*$ is a function of the relative energy [see Fig. 1(a)] and the method of calculating this efficiency is still open to question. This difficulty may be responsible for the difference between the peak positions of the calculation and experimental results.

In conclusion, whenever the ejectile state is unbound, the present method of calculating the energy dependence explicitly is appropriate and gives rather good agreement with the experimental results.

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Maser Oscillation and Microwave Superradiance in Small Systems of Rydberg Atoms

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Superradiance and transient maser action have been obtained at millimeter wavelengths with alkali Rydberg atoms as the active medium. The emission was detected by monitoring the evolution of Rydberg-state populations using field ionization. Because of the strong Rydberg-atom–radiation-field coupling, the number of radiators at threshold is far smaller than in conventional masers. The estimated radiated energy is extremely low, 10 to 10^3 eV. Applications for spectroscopy and microwave detectors are considered.

Because of their unusually large electric-dipole matrix elements, Rydberg atoms interact very strongly with far-infrared or microwave radiation resonant on transitions connecting nearby levels. This feature explains the strong radioemission by Rydberg states in the interstellar medium.[1] It also accounts for the extreme sensitivity of Rydberg atoms to microwave absorption,[2] for the superradiant cascade effects recently observed in Rydberg-atom fluorescence experiments,[3] and for radiative effects induced on these atoms by blackbody radiation.[4] We show in this Letter that these characteristics can also be exploited to develop "microscopic" coherent microwave sources which operate with a number of emitting atoms several orders of magnitude smaller than other atomic or molecular devices working at similar wavelengths. We report here on the operation of these new superradiant and maser systems, whose active medium is made of alkali-atom (Cs and Na) Rydberg states.[5] These devices, which behave as small single- or multiple-pass amplifiers of blackbody radiation, should provide new information about superradiance of small systems made of only a few atoms. More practically, they could become useful tools in spectroscopy or microwave detection technology.

Figure 1 shows the schemes of our Rydberg superradiant and maser systems [Figs. 1(a) and 1(b), respectively]. In both cases, a collimated atomic beam of alkali (10^{12} to 10^{14} atoms per second) is intersected at right angles by two pulsed, collinear, N_2-laser-pumped dye-laser beams

