Finite Range Effects in Cluster Knockout Reactions

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Conventional analysis of the knockout of α-cluster by proton and α projectiles with the distorted wave impulse approximation (DWIA) using zero range (ZR) interaction has resulted in large inconsistencies[1–3]. While the absolute cross section predictions for the $(p, p\alpha)$ reactions are close to the experimental data[1, 4, 5] the corresponding comparison for the (α,2α) reactions lead to almost two orders of magnitude lower predictions [1]. Exceptions to these observations however, were seen for the (α,2α) reactions on ^{9}Be [6] and ^{12}C [7] at 197 and 200 MeV respectively.

Finite Range DWIA calculations for the (α,2α) reactions are performed for the first time to remove huge inconsistencies obtained earlier in conventional Zero Range analyses[8, 9]. Vagaries of the energy dependent experimental observations up to 200 MeV are understood using the well established nuclear radii and distorting optical potentials. The results are found to be sensitive to the short distance behaviour of the α-α interaction, indicating the utility of the knockout reactions as a probe of the knockout vertex at short distances. Based on this novel heavy cluster knockout reactions have been performed for the first time [10]. Our approach paves the way to include finite range effects in atomic and molecular physics as also in neutron multiplication calculations.

We have examined the nature of the α-α knockout vertex transition operator, $t_{\alpha\alpha}(\vec{r})$ at various energies and found it to be of fairly long range[11]. The α-α t-matrix effective interaction was also found to be strongly dependent on the nature of the α-α realistic optical potentials. These optical potentials are not unique and equally good fits to the elastic scattering data can be obtained by very different optical potentials[11]. Two drastically different types of α-α nuclear optical potentials in common use are: (i) with short range repulsive core[12] and (ii) a potential which is purely attractive[13, 14]. These two types of α-α optical potentials, with their phase shifts matched, fit the α-α elastic scattering data. In a detailed study[11] it has been demonstrated that different α-α optical potentials yield different α-α t-matrix effective interactions, $t_{\alpha\alpha}(\vec{r})$'s. For example with a repulsive core[12] the t-matrix effective interaction peak is shifted away from r=0 by about 1.5 fm. On the other hand for a purely attractive α-α optical potential[14] the t-matrix effective interaction, although fairly long ranged peaks close to r=0. Although these $t_{\alpha\alpha}(\vec{r})$'s are seen to be shorter ranged as compared to the α-bound state wave function in the target nucleus, they are fairly long ranged enough to cause a failure of the zero range approximation. This finding suggests the need for finite range (FR)-DWIA calculations for the cluster knockout reactions. In this thesis we present these much needed FR-DWIA analyses and put the results in perspective as a resolution for the inconsistencies mentioned above. Our formalism has immediate application in knockout reactions in atomic, molecular and intermediate energy nuclear physics.

It is seen that the absolute cross sections and S_α values for the $\sim$ 197-200 MeV $(\alpha, 2\alpha)$ reactions on ^9Be and ^{12}C using the purely attractive $t_{\alpha\alpha(A)}(\vec{r})$ are in better agreement with data in comparison to that using $t_{\alpha\alpha(R+A)}(\vec{r})$ where the absolute cross sections are 20 to 35 times larger. For energies at and below $\sim$ 140 MeV, $t_{\alpha\alpha(R+A)}(\vec{r})$ gives much closer to the theoretical values when $t_{\alpha\alpha(R+A)}(\vec{r})$'s are employed. On the other hand, the S_α-values obtained from the $t_{\alpha\alpha(A)}(\vec{r})$'s are 10 to 90 times too large as compared to the theoret-

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From these FR-DWIA results it is obvious that the α-α potential character changes drastically at α-energies, E_α somewhere between 140 and 200 MeV, corresponding to the centre of mass energy $E_{\alpha\text{-}\alpha}$ of 70 to 100 MeV. Again this can be qualitatively understood in the Resonating Group Method, (RGM)-shell model picture (taking care of Pauli's exclusion principle), The four neutrons(n) and four protons(p) of the two α-particles can exist in an overlapping position if the two n's and two p's of one α-particle are in the lowest $1s_{1/2}$ shell model state and the other two n's and two p's of the other α in the next shell model state ($1p_{3/2}$, which is situated around 21 MeV above the ground state of α-particle). The total energy of this overlapping system, $E_{\alpha\text{-}\alpha}$ will thus be $\sim 4\times 21=84$ MeV (corresponding to $E_\alpha \sim 2\times 84=168$ MeV). Thus below this energy, $E_\alpha \sim 168$ MeV, the two α's would find it energetically more favorable to avoid their overlap with a repulsive core in their interaction. Above this energy, however the two α's have no such restriction and are free to have the usual attractive force between them. This understanding of the change in the nature of the α-α interaction is clearly validated by the present FR-DWIA analyses of the (α, 2α) data.

Based on the FR analysis, the heavy cluster knockout experiment $(C, 2C)$ at 119 MeV has been performed for the first time [10]. An enhancement in the cross sections over the ZR-DWIA predictions have been observed and understood by means of a short range repulsion plus long range attractive potential in the C-C interaction. The FR-DWIA analysis of the knockout reaction provides a testimony about the nature of interaction of the vertex at shorter distances.

Extreme sensitivity of the cluster knockout reactions to the short range behavior of the colliding partners opens up the possibility of probing this aspect of the particles involved at the knockout vertex.

The present FR-DWIA formalism paves the way to perform core knock- out reaction on Halo Nuclei, heavy cluster knockout reaction studies, $(e, 2e)$ reactions, knockout of atoms from molecules, neutron knockouts (p, pn) and $(n, 2n)$ reaction cross section evaluation for the Accelerator Driven System (ADS). It also provides a new way to look for the dibaryons and pentaquarks in $(p, 2p)$ and (K^+, K^+n) reactions respectively.

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