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Coulomb diffraction interference in ^{11}be breakup reaction and its sensitivity to the target

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Abstract
The interference between Coulomb and nuclear diffraction breakup mechanism is investigated for ^{11}Be nucleus in single neutron knockout reaction. The investigation is performed for ^{12}C, ^{40}Ca and ^{208}Pb targets at 40, 70 and 150 MeV/nucleon projectile beam energies. The Coulomb interaction between projectile and target is treated to all orders in sudden approximation and nuclear interaction by eikonal approximations. The effect of Coulomb diffraction interference on single neutron knockout cross section with different incident energies and its sensitivity towards target size (atomic number) are examined. The obtained results are quite informative for understanding the breakup mechanisms and helpful for a clear interpretation of ^{11}Be breakup observables.

Keywords: Coulomb nuclear interference, halo breakup, knockout reactions

1. Introduction
The study of excess number of neutron or proton nuclei has attracted lot of attention of nuclear physics in last three decade [1, 3]. These nuclei has been fascinating to examine due to their important roles in astrophysical nucleosynthesis reactions in addition to their novel structural characteristics [4, 6]. These days we have huge number of such nuclei available in big laboratories worldwide [1, 7]. The knockout reactions are frequently used for their structural study. In these knockout reactions mainly the breakup cross section of valence nucleon and longitudinal momentum distribution (LMD) of core fragment after removal of valence nucleon has been the key observables which reveals the nuclear structural features. In these reactions the nuclear and Coulomb interaction with the target nucleus cause the projectile nucleus to breakup. The dominancy of the interactions mechanism causing the breakup depends upon the size (atomic number) of the participating target nuclei, i.e. for heavy target the Coulomb interactions dominates while for light target nuclear interactions dominates. But the situation is more difficult when target is of medium mass then both of the mechanisms equally contribute to the breakup. But recent theoretical works has demonstrated that during the breakup the Coulomb and nuclear interactions mechanisms interfere constructively or destructively with each other and affect the breakup observables magnitude [8, 14]. The effect of interference depends on the target atomic number and also on the incident energy of the projectile.
In present study, I examined the effect of Coulomb diffraction interference on single neutron breakup cross section in case of ^{11}Be nucleus. The effect has been examined for ^{12}C, ^{40}Ca and ^{208}Pb targets (different atomic number targets) at 40, 70 and 150 MeV/nucleon incident energies. ^{11}Be nucleus is a very well known neutron rich nucleus having a core (^{10}Be) plus a valence neutron halo structure. This is a loosely bound system (Neutron binding energy S_n= 0.54 MeV) having a bound state configuration [0^++$2s_{1/2}$] [15-16]. So this would be interesting to examine Coulomb diffraction interference effects clearly for this nucleus. The used theoretical formalism is briefly discussed in section-2, obtained results and conclusions are discussed in section-3 and section-4.

2. Theoretical formalism
The ^{11}Be nucleus is very well assumed as a two-body system having a core (^{10}Be) and a valence neutron attached with it with small binding energy (S_n= 0.54 MeV). The projectile breakup occurs because of nuclear and Coulomb interactions between projectile and target nucleus, but both mechanisms play their dominant role depending on the participating target atomic number.

In breakup reactions the measurement of core fragment longitudinal momentum distribution (LMD) and single neutron breakup cross-section, are the important observable used for the structural investigations. Here, I calculated the single neutron breakup cross section by treating the Coulomb interaction to all orders and nuclear diffraction by eikonal approximation [11, 14, 17, 18]. In theoretical formalism, the Coulomb repulsive potential between core and target nuclei which causes the breakup is

$$V(\vec{r},\vec{R}) = \frac{V_c}{|\vec{R}-\beta_1\vec{r}|} - \frac{V_c}{R}$$

Where, $V_c = Z_c Z_t e^2$ and Z_c, Z_t are the core and target atomic numbers, $\vec{R}$ is the position vector from the target nucleus to the center of mass of the projectile. The projectile and target coordinate system used is shown in Fig.1 [11, 12].

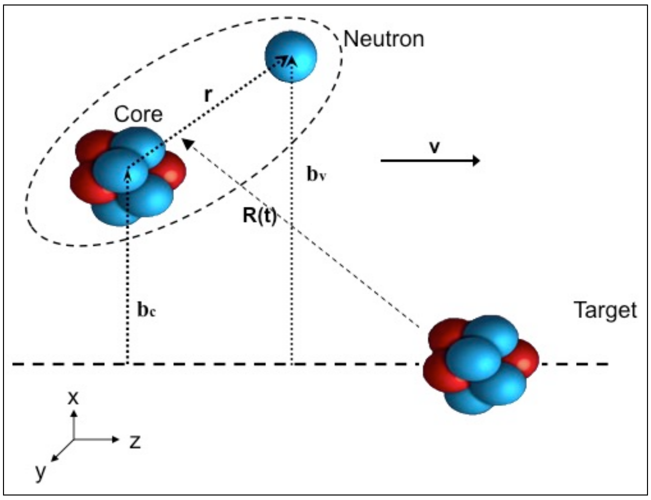

Fig 1: Coordinate system

The core-target Coulomb scattering amplitude g^{Coul} (also known as g^{Recoil} (b_c) in all orders sudden approximation formalism [11,17,18] is

$$g^{Coul} = \int d\vec{r}\, e^{-i\vec{k}.\vec{r}} \phi_i(\vec{r}) \left(e^{i\frac{2V_c}{\hbar v}\log\frac{b_c}{R_\perp}} - 1 - i\frac{2V_c}{\hbar v}\log\frac{b_c}{R_\perp} + i\chi(\beta_1, V_c) \right)$$

and nuclear diffraction scattering amplitudes (g^{Diff}) in eikonal approximation is respectively

$$g^{Diff} = \int d\vec{r}\, e^{-i\vec{k}.\vec{r}} \phi_i(\vec{r}) |S_{nt}(\vec{b}_v) - 1|$$

and the single-neutron knockout cross-section in Coulomb and diffraction dissociation mechanism is calculated by

$$\sigma = \frac{1}{8\pi^3}\int d\vec{k} \int d\vec{b_c}\, |S_{ct}(\vec{b_c})|^2 |g^{Coul.} + g^{Diff}|^2$$

Where, $S_{ct}(b_c)$ and $S_{nt}(b_v)$ are the core-target and neutron–target s-matrices, calculated using MOMDIS code with Hartree-Fock nuclear density forms of core and target nucleus [19, 20]. b_c *and* b_v are the core and valence nucleon impact parameters respectively and $\phi_i(\vec{r})$ is the projectile nucleus bound state wave function, calculated by MOMDIS code by solving the Schrodinger wave equation to fit the depth of nuclear potential to the binding energy of the valence neutron i.e. S_n=0.54 MeV.

3. Results and Discussion

I have calculated exclusively the single neutron knockout cross section independently for each breakup mechanism i.e. nuclear diffraction, pure Coulomb mechanisms, and also jointly for both the mechanisms using the aforesaid theoretical formalism. Here I took these incident energies i.e. 40-150 MeV/nucleon for each target case because of the reason that mostly the knockout reactions using the exotic nuclei are being studied in this incident energy range, therefore it is quite intriguing to investigate the presence of Coulomb diffraction interference ^{11}Be breakup reactions and also its sensitivity with target size and incident energy. The obtained results are depicted in Table 1, 2 and 3 for ^{12}C, ^{40}Ca and ^{208}Pb targets respectively.

Table 1, for ^{12}C target, shows that magnitude of breakup cross section jointly calculated for Coulomb and diffractions is more than that of their simple sum of separately calculated Coulomb and diffraction cross sections. This enhancement is observed 2.87%, 2.41% and 1.66% respectively for 40, 70 and 150 MeV/nucleon incident energy. The positive sign represents the constructive nature of interference among Coulomb and diffraction mechanism and for this energy range it looks decreasing slightly with increase in incident energy. Similar enhancement in breakup cross section is observed for ^{40}Ca target case, as shown in Table 2, but here the enhancement are 14.97%, 10.57% and 7.03% for 40, 70 and 150 MeV/nucleon incident energy.

Table 1: Calculated single neutron knockout cross section exclusively for Coulomb, diffraction and both dissociation mechanisms together in case of ^{12}C target

Reaction Mechanism	**E_{lab} (in MeV/nucleon)**		
	40 MeV/ nucleon	**70 MeV/ nucleon**	**150 MeV/ nucleon**
σ^{Diff} (in mb)	77.34	56.82	34.62
$\sigma^{Coul.}$ (in mb)	15.42	10.52	6.31
$\sigma^{Coul.} + \sigma^{Diff}$ (Simple sum) (in mb) [A]	92.76	67.34	40.93
$\sigma^{Coul.+Diff}$ Calculated together (in mb) [B]	95.43	68.96	41.61
% Enhancement in cross section ([B]- [A]) / [A]X100%	+2.87%	+2.41%	+1.66%

This enhancement is 5 to 6 time more than that of ^{12}C target, which seems reasonable that in medium mass targets both the breakup mechanism dominates equally to the breakup so the possibility of interference among Coulomb and diffraction is more as compared to the light target where Coulomb contribution is very small. On the other hand for ^{208}Pb target, in Table 3, the results show that for 40 MeV/nucleon energy, the together cross section reduces by 0.58%, showing the presence of destructive interference between Coulomb and diffraction mechanisms.

Table 2: Calculated single neutron knockout cross section exclusively for Coulomb, diffraction and both dissociation mechanisms together in case of ^{40}Ca target

Reaction Mechanism	E_{lab} (in MeV/nucleon)		
	40 MeV/ nucleon	70 MeV/ nucleon	150 MeV/ nucleon
σ^{Diff} (in mb)	142.22	110.51	73.19
$\sigma^{Coul.}$ (in mb)	8.49	3.13	0.88
$\sigma^{Coul.} + \sigma^{Diff}$ (Simple sum) (in mb) [A]	150.71	113.64	74.07
$\sigma^{Coul.+Diff}$ Calculated together (in mb)[B]	173.28	125.65	79.28
% Enhancement in cross section ([B]- [A]) / [A]X100%	+14.97%	+10.57%	+7.03%

Table 3: Calculated single neutron knockout cross section exclusively for Coulomb, diffraction and both dissociation mechanisms together in case of ^{208}Pb target

Reaction Mechanism	E_{lab} (in MeV/nucleon)		
	40 MeV/ nucleon	70 MeV/ nucleon	150 MeV/ nucleon
σ^{Diff} (in mb)	215.54	184.98	149.03
$\sigma^{Coul.}$ (in mb)	2660.28	1679.06	952.62
$\sigma^{Coul.} + \sigma^{Diff}$ (Simple sum) (in mb) [A]	2875.82	1864.04	1101.65
$\sigma^{Coul.+Diff}$ Calculated together (in mb)[B]	2859.13	1903.82	1153.04
% Enhancement in cross section ([B]- [A]) / [A]X100%	-0.58%	+2.13%	+4.66%

While for 70 and 150MeV/nucleon the cross section enhances by 2.13% and 4.66% which shows the constructive interference. Here, a point is to be notice that the effect of interference is lesser in comparison to ^{40}Ca target case, also on the lower incident energy side it is of destructive nature which suppress the magnitude of breakup cross section. This effect could be reasonable because, in case of ^{208}Pb target the Coulomb interaction prominently dominates over the nuclear interactions so the interference effect is observed lesser in comparison to medium mass target. So the calculations show that inference among Coulomb diffraction breakup mechanisms do exists in different magnitude for all the target cases and also sensitive to the incident energy. The effect of interference is more in case of medium atomic number target where both the mechanism dominate equally. However, this interference may have destructive or constructive behavior depending upon the target size and incident energy. The obtained results are in accord with the previous results reported by ref. [11, 13]. I hope that present analysis of Coulomb and nuclear diffraction interference is informative for the theoretical understanding of ^{11}Be breakup reaction and interpretation of experimental results.

4. Conclusions

The interference effect of Coulomb and nuclear diffraction mechanisms on neutron knockout cross section have been analysed for ^{11}Be nucleus in single knockout reaction for ^{12}C, ^{40}Ca and ^{208}Pb targets at 40, 70 and 150 MeV/nucleon incident energy. The Coulomb and nuclear interactions are treated to all order in sudden approximation and eikonal approximation respectively. The single neutron knockout cross section in case of ^{12}C target is fond effected by +2.87% to +1.66% with rise in incident energy, on the other hand this effect is 14.97% to 7.03% for ^{40}Ca, but for ^{208}Pb target, the cross section effects from -0.58% to +4.66%. The Coulomb diffraction interference is found mostly of constructive nature for all the chosen targets which enhances the single neutron breakup cross section but for ^{208}Pb target at 40 MeV/nucleon beam energy, destructive interference is observed which reduces the magnitude of cross section. Also the magnitude of interference seen sensitive to the incident energy, especially in medium size targets cases. These observations show that enough care is required while dealing with knockout reactions using medium size targets (medium atomic number) because due to this Coulomb diffraction interference get affected and may lead to misinterpretation of experimental data. From these examinations, I believe this work is helpful for better understanding the reaction mechanism and clear interpretation of experimental data.

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