Spectroscopy of one-neutron halo nuclei from the Coulomb breakup reactions

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Abstract

We review the current status of obtaining the spectroscopic information on the one-neutron halo nuclei from the Coulomb breakup reactions. The theory of these reactions formulated in the framework of the Distorted Wave Born Approximation, allows the use of the realistic wave functions corresponding to any orbital angular momentum structure for the core-valence neutron relative motion in the ground state of the projectile. The energy, angular and parallel momentum distributions of the projectile fragments calculated within this theory are selective about the ground state wave function of the projectile. Therefore, firm conclusions can be drawn about the structure of the projectile ground state by comparing the calculations with the corresponding data.

1 Introduction

Some nuclei lying close to the neutron drip line, have one or two very loosely bound valence neutrons which extend too far out in the coordinate space with respect to the charged core [1]. The properties of these neutron halo nuclei [2] have been reviewed by several authors (see e.g. [3, 4, 5, 6]). The halo systems are characterized by large reaction and Coulomb dissociation cross sections [7, 8, 9, 10]. Moreover, in the breakup reactions induced by these nuclei, the angular distributions of neutrons measured in coincidence with the core nuclei [11, 12] are strongly forward peaked and the parallel momentum distributions of the core fragments have very narrow widths [13, 14, 15, 16, 17, 18]. Due to their strikingly different properties in comparison to the stable systems, the halo nuclei provide a stringent test of the nuclear structure models developed for the study of the nuclei lying close to the line of stability.

The Coulomb breakup, which is a significant reaction channel in the scattering of the halo nuclei on stable heavy targets, is a convenient tool to investigate their structure. For instance, it would place constraints on their electric dipole response [1, 11, 13, 20]. Of course, in the Serber [21] type of models [22, 23], the

\footnote{Talk presented at the international workshop on Production of Radioactive Ion Beams (PRORIB-2001), held at Puri, India, Feb. 12 - 17, 2001.}
breakup cross sections are directly related to the momentum space wave function of the projectile ground state. The studies of the Coulomb dissociation of the weakly bound nuclei are also of interest due to their application in determining the cross sections of the astrophysically interesting radiative capture reactions at solar temperatures [24]. The distinct advantage of the Coulomb breakup is that the perturbation due to the electric field of the nucleus is known exactly.

Recently, a full quantum mechanical theory of the Coulomb breakup reactions has been formulated [25] within the post form distorted wave Born approximation (DWBA). The finite range effects are included in this theory (to be referred as FRDWBA) which can be applied to projectiles of any ground state angular momentum structure. In this paper, we show that definite information about the ground state structure of the one-neutron halo nuclei (e.g., $^{11}$Be and $^{19}$C) can be obtained by comparing the predictions of this theory with the data on the breakup reactions of these projectiles on heavy target nuclei. This is possible because the calculated energy, angular and longitudinal momentum distributions of the projectile fragments are strongly selective about the ground state wave function of the projectile. We also discuss the application of this theory to the one-neutron removal reactions of the type $A(a,b\gamma)X$ where the partial cross sections for transitions to the excited bound states of the core are measured. These reactions provide a more versatile tool for investigating the spectroscopy of the halo nuclei.

In section 2, we present a very brief review of the post form DWBA theory of the Coulomb breakup reactions. The applications of the theory to two types of the breakup reactions, $A(a,b\text{ or }n)X$ and $A(a,b\gamma)X$, are discussed in section 3. Our conclusions are presented in section 4.

## 2 Formalism

We consider the reaction $a + t \rightarrow b + c + t$, where the projectile $a$ breaks up into fragments $b$ (charged) and $c$ (uncharged) in the Coulomb field of a target $t$. The post form DWBA $T$ - matrix for this case is

$$ T = \sum_{\ell m j_\mu} \langle \ell m j_c \mu_c | j_\mu \rangle \langle j_b \mu_b j_\mu | j_a \mu_a \rangle i^\ell \hat{\beta}_{\ell m}, $$  \hspace{1cm} (1)

where

$$ \hat{\beta}_{\ell m} = \int d\mathbf{r}_1 d\mathbf{r}_i \chi_b^{(-)*}(\mathbf{k}_b, \mathbf{r}) e^{-i\mathbf{k}_c \cdot \mathbf{r}_c} V_{bc}(\mathbf{r}_1) u_\ell(\mathbf{r}_1) Y_{\ell m}(\hat{\mathbf{r}}_1) \chi_a^{(+)}(\mathbf{k}_a, \mathbf{r}_i), $$  \hspace{1cm} (2)

with $\hat{\ell} = \sqrt{2\ell + 1}$. In Eq. (1), $\ell$ is the orbital angular momentum for the relative motion between $b$ and $c$. This is coupled to the spin of $c$ and the resultant $j$ is coupled to the spin of (the inert core) b to get the spin of $a$ ($j_a$). $\chi$’s are the distorted waves for relative motions of the respective systems ($b$ or $a$) with respect
to the target. $V_{bc}(r_1)$ is the interaction between $b$ and $c$. The charged fragment $b$ interacts with the target by a point Coulomb interaction and hence $\chi_b^{(-)}(k_b, r)$ is a Coulomb distorted wave with incoming wave boundary condition. For the pure Coulomb breakup, relative motion wave function between the target and the uncharged fragment $c$ is a plane wave. The radial and angular parts of the wave function associated with the relative motion of $b$ and $c$ in the ground state of the projectile is given by $u_\ell(r_1)$ and $Y_{\ell m}(\hat{r}_1)$, respectively. It should be noted that in Eq. (2), the interaction of the target with the fragments is included to all orders.

Eq. (2) involves a six dimensional integral which makes its evaluation quite complicated. The problem gets further acute due to the fact that the integrand involves three scattering waves which have oscillatory behavior asymptotically. Therefore, approximate methods have been used, such as the zero range approximation (ZRA) [26], in which $u_\ell(r_1)Y_{\ell m}(\hat{r}_1)$ is replaced by a delta function, or the Baur-Trautmann approximation (BTA) [27], where the coordinate of the projectile-target system is replaced by that of the core-target system. Both these approximations lead to a factorization of the amplitude (Eq. 3) into two independent parts, which reduces the computational complexity. However, both these methods have limitations and their application to the reactions of the halo nuclei is questionable.

In the FRDWBA theory, the Coulomb distorted wave of particle $b$ in the final channel is written as

$$\chi_b^{(-)}(k_b, r) = e^{-i\alpha K r} \chi_b^{(-)}(k_b, r_i).$$

Eq. (3) represents an exact Taylor series expansion about $r_i$ if $K(= -i\nabla r_i)$ is treated exactly. However, instead of doing this we employ a local momentum approximation, where the magnitude of the local momentum $K$ is taken to be

$$K(R) = \sqrt{\frac{2m}{\hbar^2}(E - V(R))}.$$

In Eq. (4), $m$ is the reduced mass of the $b-t$ system, $E$ is the energy of particle $b$ relative to the target in the c.m. system and $V(R)$ is the Coulomb potential between $b$ and the target at a distance $R$. Therefore, the local momentum $K$ is evaluated at some distance $R$, and its magnitude is held fixed for all the values of $r$. As is discussed in [25], the results of our calculations are almost independent of the choice of the direction the local momentum. Therefore, we have taken the directions of $K$ and $k_b$ to be the same in all the calculations presented in this paper. For more details, we refer to [25].

Substituting Eq. (3) into Eqs. (1, 2) we get the following factorized form of the reduced amplitude

$$\hat{\theta}^{FRDWBA}_{\ell m} = \langle e^{i\gamma k_c - \alpha K} r_1 | V_{bc} | \phi^\ell_a(r_1) \rangle \langle \chi_b^{(-)}(k_b, r_i) e^{i\delta K c - \alpha} r_1 | \chi_a^{(+)}(k_a, r_i) \rangle.$$
Recently, a theory of the Coulomb breakup has been developed within an adiabatic (AD) model \[28, 29\], where one assumes that the excitation of the projectile is such that the relative energy \((E_{bc})\) of the \(b - c\) system is quite small as compared to the total incident energy, which allows \(E_{bc}\) to be replaced by the constant separation energy of the fragments in the projectile ground state. It was shown in \[29\] that under these conditions the wave function \(\Psi_a^{(+)}(\xi_a, r_1, r_i)\) has an exact solution which when substituted in the post form T-matrix leads to its factorization in the same way as Eq. (5). This amplitude differs from that of the FRDWBA only in the form factor part (first term), which is evaluated here at the momentum transfer \((k_c - \alpha k_a)\). It has been shown \[24, 30\] that for the breakup of projectiles with very small one-neutron separation energies and a \(s\)-wave neutron-core relative relative motion in its ground state, the results of the adiabatic model and the FRDWBA are almost identical to each other. Although the adiabatic model does not make the weak coupling approximation of the DWBA, yet it necessarily requires one of the fragments (in this case \(c\)) to be chargeless. In contrast, the FRDWBA can, in principle, be applied to cases where both the fragments \(b\) and \(c\) are charged \[31\].

3 Applications to the breakup reactions of \(^{11}\text{Be}\) and \(^{19}\text{C}\)

3.1 Structure models of \(^{11}\text{Be}\) and \(^{19}\text{C}\)

For the ground state of \(^{11}\text{Be}\), we have considered the following configurations:

(a) a \(s\) - wave valence neutron coupled to the \(0^+\) \(^{10}\text{Be}\) core \([1s_{1/2}^1\nu \otimes ^{10}\text{Be}(0^+)]\) with a one-neutron separation energy \((S_{n-^{10}\text{Be}})\) of 504 keV and a spectroscopic factor (SF) of 0.74 \[32\],

(b) a \(d\) - wave valence neutron coupled to the \(2^+\) \(^{10}\text{Be}\) core \([0d_{5/2}^1\nu \otimes ^{10}\text{Be}(2^+)]\) with a one-neutron separation energy of 3.872 MeV (which is the sum of energy of the excited \(2^+\) core (3.368 MeV) and \(S_{n-^{10}\text{Be}}\) with a SF of 0.17, and

(c) an admixture of these two configurations with the SF values of 0.74 and 0.20 respectively \[33\].

In each case, the single particle wave function is constructed by assuming the valence neutron-\(^{10}\text{Be}\) interaction to be of the Woods-Saxon type whose depth is adjusted to reproduce the corresponding value of the binding energy with fixed values of the radius and the diffuseness parameters (taken to be 1.15 fm and 0.5 fm, respectively). For configuration (a), this gives a potential depth of 71.03 MeV, a root mean square (rms) radius for the valence neutron of 6.7 fm, and a rms radius for \(^{11}\text{Be}\) of 2.91 fm when the size of the \(^{10}\text{Be}\) core is taken to be 2.28 fm \[34\].

For the case of \(^{19}\text{C}\), there is a large uncertainty in the value of the last neutron separation energy \((S_{n-^{18}\text{C}})\) with quoted values varying between 0.160 MeV –
1.0 MeV [10, 25]. Most of the available data on the Coulomb dissociation of $^{19}$C can be satisfactorily explained within the finite range DWBA theory with the one-neutron separation energy of 530 keV [24]. The relativistic mean field (RMF) [36] as well as shell model (with Warburton-Brown effective interaction) [37] calculations predict the spin-parity of the ground state of this nucleus to be $1/2^+$. We have examined two possibilities for the ground state structure of $^{19}$C:

(i) different binding energies (530 keV and 160 keV) with the same configuration for the $^{19}$C ground state $[1s_{1/2}\nu \otimes ^{18}$C($0^+$)], and
(ii) different configurations $[1s_{1/2}\nu \otimes ^{18}$C($0^+$)] and $[0d_{5/2}\nu \otimes ^{18}$C($0^+$)] with the same binding energy (530 keV) for the $^{19}$C ground state. A spectroscopic factor of 1.0 has been used for each of the configuration, and the corresponding single particle wave functions have been constructed in the same way as in the case of $^{11}$Be.

### 3.2 A(a,b or n)X type of reactions

![Figure 1](image-url)  

**Figure 1:** The calculated neutron angular distributions for the breakup of $^{11}$Be on a Au target at the beam energy of 41 MeV/nucleon. The solid and the dot-dashed lines show the results of the FRDWBA calculation performed with the pure s-wave and d-wave configurations for the ground state of $^{11}$Be, respectively.

The measured neutron angular distribution in the exclusive $^{11}$Be + $A \rightarrow ^{10}$Be + n +$A$ reaction below the grazing angle is shown to be [25] dominated by
the Coulomb breakup process. This reflects the narrow width of the transverse
momentum distribution of the valence neutron. The neutron halo structure is
also reflected in the narrow widths of the parallel momentum distribution (PMD)
of the charged breakup fragments emitted in breakup reactions induced by the
halo nuclei. This is because the PMD has been found to be least affected by
the reaction mechanism [13, 14, 15, 16, 17] and therefore, a narrow PMD can
be related to a long tail in the matter distribution in the coordinate space via
Heisenberg’s uncertainty principle.

In Fig. 1, we compare the calculated and measured exclusive neutron angular
distribution $d\sigma/d\Omega_n$ as a function of the neutron angle $\theta_n$ for the above reaction
on a Au target at the beam energy of 41 MeV/nucleon. Calculations are shown
for both configurations (a) (solid line) and (b) (dot-dashed line) for the $^{11}$Be
ground state. It is clear that experimental angular distributions are reproduced
by configuration (a) only. In Fig. 2, we present the PMD of the $^{10}$Be fragment

![Figure 2: Parallel momentum distributions of $^{10}$Be in the breakup of $^{11}$Be on U (top half) and Ta (bottom half) at the beam energy of 63 MeV/nucleon, in the rest frame of the projectile, with s-wave (solid line) and d-wave (dot-dashed line) configurations for the $^{11}$Be ground state. The same normalization has been used for both the cases. The data are taken from [14].](image)

emitted in the breakup of $^{11}$Be on U and Ta targets at the beam energy of 63
MeV/nucleon. Calculations performed with both the configurations (a) and (b)
are shown in this figure. The calculated cross sections are normalized to the
peak values of the data points in both the cases. While the full widths at half
maximum (FWHM) of the distributions calculated with the s-wave configuration are narrow for both the targets (44 MeV/c and 43 MeV/c for the U and Ta, respectively), they turn out to be quite broad with the d-wave configuration. The narrow widths agree well with the averaged experimental value of 43.6±1.1 MeV/c [14]. Therefore, the configuration (a) is favored by this data too. The very narrow widths of the parallel momentum distributions signal the presence of a neutron halo structure in $^{11}$Be.

![Figure 3: Relative energy spectra for the Coulomb breakup of $^{11}$Be on a Pb target at the beam energy of 72 MeV/nucleon with the s-wave (solid line) and the d-wave (dot-dashed line) configurations for the $^{11}$Be ground state. The data are taken from [9].](image)

The relative energy spectrum for the breakup of $^{11}$Be on a Pb target at the beam energy of 72 MeV/nucleon is shown in Fig. 3. The results obtained with both the configurations [(a) and (b)] for the ground state of $^{11}$Be are shown. We see that, while the calculations done with the s-wave configuration reproduce the data well near the peak region, the d-wave configuration underpredicts the data by several orders of magnitude. However, the data at higher relative energies cannot be explained by our calculations. This can be attributed to the fact that the nuclear breakup effects, which can contribute substantially [38, 39] at the higher relative energies (for $E_{rel} > 0.6$ MeV), are not included in these calculations. Of course, the authors of Ref. [9] claim that their data have been corrected for these contributions. However, the procedure adopted by them for this purpose
may not be adequate \[23\]. For a proper description of the data, both Coulomb and nuclear breakup contributions should be calculated on the same footing and corresponding amplitudes should be added coherently to get the cross sections.

Therefore, for $^{11}$Be, a $s$ - wave configuration $[1s_{1/2}\nu\otimes{}^{10}\text{Be}(0^+)]$ spectroscopic factor of 0.74 for its ground state provides best agreement with the experimental data in all the cases. Our calculations cannot distinguish between this and configuration (c) of section 3.1.

Figure 4: FRDWBA results for the parallel momentum distribution of $^{18}$C in the breakup of $^{19}$C on Ta target at the beam energy of 88 MeV/nucleon. The top half shows the results obtained with the configuration $[1s_{1/2}\nu\otimes{}^{18}\text{C}(0^+)]$ and single particle wave function for the ground state of $^{19}$C with one-neutron separation energies of 530 keV (solid line), 160 keV (dashed line). The bottom half shows the result obtained with the configurations $[1s_{1/2}\nu\otimes{}^{18}\text{C}(0^+)]$ (solid) and $[0d_{5/2}\nu\otimes{}^{18}\text{C}(0^+)]$ (dot-dashed), with the same value of the one-neutron separation energy (530 keV). The data have been taken from \[15\].

In Fig. 4, we present the PMD (calculated within the FRDWBA formalism) of the $^{18}$C fragment in the breakup of $^{19}$C on a Ta target at the beam energy of 88 MeV/nucleon. We have normalized the peaks of the calculated PMDs to that of the data (given in arbitrary units) \[15\] (this also involves coinciding the position of maxima of the calculated and experimental PMDs). As can be seen from the upper part of this figure, the experimental data clearly favor $S_{n-^{18}C} = 0.53$ MeV with the $s$ - wave $n-^{18}\text{C}$ relative motion in the ground state of $^{19}\text{C}$.

In the lower part of Fig. 4, we have shown the results obtained with the
$d$– wave relative motion for this system (with $S_{n-18C} = 0.53$ MeV) and have compared it with that obtained with a $s$– wave relative motion with the same value of the binding energy. As can be seen, the FWHM of the experimental PMD is grossly over-estimated by the $d$– wave configuration. The calculated FWHM with the $s$– state configuration (with $S_{n-18C} = 530$ keV) is 40 MeV/c, which is in excellent agreement with the experimental value of 41±3 MeV/c [15]. Thus these data favor a configuration [1$s_{1/2}ν$⊗$^{18}$C(0$^+$)], with a one-neutron separation energy of 0.530 MeV for the ground state of $^{19}$C. The narrow width of the PMD provides support to the presence of a one-neutron halo structure in $^{19}$C.

Figure 5: Calculated relative energy spectra for the Coulomb breakup of $^{19}$C on Pb at 67 MeV/nucleon. The $d$– state results, for binding energies 160 keV (long dashed) and 530 keV (dot-dashed), are multiplied by 10. The 160 keV $s$– state result (short dashed) is multiplied by 0.086. The 530 keV $s$– state result is represented by the solid line. The data have been taken from [10].

In Fig. 5, we have shown the results of our FRDWBA calculations for the relative energy spectrum for the breakup of $^{19}$C on Pb at the beam energy of 67 MeV/nucleon. The experimental data is taken from [10]. The angular integration for the $^{19}$C center of mass is done up to the grazing angle of 2.5°. It can be seen that in this case also the best agreement with the data (near the peak position) is obtained with the $s$– wave configuration with $S_{n-18C} = 0.53$ MeV. Calculations done with the $d$– state configuration for both 530 keV and 160 keV one-neutron separation energy fails to reproduce the data. At the same
time, those performed with the $s$–state configuration but with $S_{n^{-18C}} = 0.16$ MeV overestimates the data by at least an order of magnitude and also fail to reproduce its peak position. However, as in the case of $^{11}$Be, the calculations underestimate the relative energy spectrum for larger values of relative energies, and the proper consideration of the nuclear breakup effects is necessary to explain the data in this region.

Therefore, the results for the PMD of $^{18}$C and the relative energy spectrum of the $n + ^{18}$C system are described best with a ground state configuration of $^{19}$C of $[1s_{1/2} \nu \otimes ^{18}\text{C}(0^+)]$, with a one-neutron separation energy of 530 keV and a spectroscopic factor of 1.

### 3.3 $A (a, b\gamma) X$ type of reaction

In the $(a, b\gamma)$ type of reactions, one nucleon (usually the valence or halo) is removed from the projectile $(a)$ in its breakup reaction in the field of a target nucleus and the states of the core fragment $(b)$ populated in this reaction are identified by their gamma ($\gamma$) decay. The intensities of the decay photons are used to determine the partial breakup cross sections to different core states. The signatures of the orbital angular momentum $\ell$ associated with the relative motion of core states with respect to the valence nucleon (removed from the projectile) are provided by the measured parallel momentum distributions of the core states (see Fig. 2, 4). This provides a new and more versatile technique for investigating the spectroscopy of nuclei near the drip line [33, 35, 40]. It mixes the power of the conventional transfer reaction (sensitivity to the $\ell$ value of the removed neutron) with the practical advantage of the breakup reactions (larger cross sections).

Most of the studies of the $(a, b\gamma)$ reaction performed so far involve a light $^9$Be target, where the breakup process is governed almost entirely by only the nuclear interaction between the projectile fragments and the target. It would be interesting to know if there are quantitative differences in the relative populations of the core states in the pure Coulomb breakup mechanism, as compared to those observed in the pure nuclear breakup process. In Fig. 6, we compare the pure Coulomb partial cross sections for the $^{11}$Be breakup on a $^{208}$Pb target (shown in the left panel) with the pure nuclear ones (shown in the right panel) corresponding to the breakup of $^{11}$Be on a $^9$Be target (taken from [34]) at the beam energy of 60 MeV/nucleon. Both the cross sections are calculated for transitions to the four $^{10}$Be final states. The ground $(0^+)$ and excited (3.368 MeV) $(2^+)$ states were assumed to correspond to the configurations $[1s_{1/2}\nu \otimes ^{10}\text{Be}(0^+)]$ and $[0d_{5/2}\nu \otimes ^{10}\text{Be}(2^+)]$, respectively. The corresponding SF values for these two configurations were taken to be 0.74 and 0.20, respectively. The excited $1^- (5.956$ MeV) and $2^- (6.256$ MeV) states were assumed to stem from the configurations $[0p_{3/2}\nu \otimes ^{10}\text{Be}(1^-)]$ and $[0p_{3/2}\nu \otimes ^{10}\text{Be}(2^-)]$, respectively, with the SF values of 0.69 and 0.58, respectively. In each case, the neutron single particle wave function is calculated in the same way as described in section 3.1.
It is evident that in the case of pure Coulomb breakup of a projectile with a halo ground state, most of the cross section goes to the ground state ($0^+$) of the core. The sum of the partial cross sections corresponding to all the excited states is less than 1% of that to the ground state. This is in sharp contrast to the case of the lighter target where partial cross sections corresponding to all the excited states represent about 22% of the total. Similar results have been obtained for the $^{19}$C projectile (see [30] for more details). Indeed, in the measurements [41] of the (a,b$\gamma$) type of reactions with $^{14}$B projectile on $^{197}$Au gold target at the beam energy of 60 MeV/nucleon no core-excited transitions were seen. Therefore, this lends support to our observation. The transitions to the excited states of the core corresponding to the non-zero $\ell$-values of the neutron-core relative motion, are quite weak in the pure Coulomb breakup reaction as compared to those in the nuclear breakup process. Therefore, (a,b$\gamma$) type of reaction on a heavy target is potentially a more useful tool for investigating the properties of the ground state of the core fragments.

The suppression of the cross sections to the higher states can be understood from the strong dependence of the Coulomb breakup cross sections on the one-neutron separation energy (SE). In the case of the nuclear breakup, the dependence of the cross section on SE is comparatively weaker. This could be un-
derstood from the fact that nuclear breakup cross sections are sensitive to the $b-c$ relative wave functions at shorter distances which do not change much with changes in the value of SE.

4 Concluding remarks

Finite range DWBA theory of the Coulomb breakup reactions provides a very powerful tool to probe the ground state structure of the one-neutron halo nuclei. Its predictions for most of the breakup observable are quite sensitive to the ground state configuration of the projectile. Therefore, their comparison with the experimental breakup data can be used to put constraints on the ground state structure of the one-neutron halo nuclei.

The Coulomb dominated one-neutron removal reaction of the type (a,$\gamma$) populates predominantly the ground state of the core fragment. Therefore, such studies would be very useful in investigating the ground state structure of the halo nuclei for those partitions in which the core fragment remains in its ground state.

Useful discussions with Prabir Banerjee, Pawel Danielewicz, Gregers Hansen, and Stefan Typel are gratefully acknowledged.

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