Coulomb and nuclear breakup effects in the single neutron removal reaction ^{197}Au(^{17}C,^{16}Cγ)X

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We analyze the recently obtained new data on the partial cross sections and parallel momentum distributions for transitions to ground as well as excited states of the ^{16}C core, in the one-neutron removal reaction ^{197}Au(^{17}C,^{16}Cγ)X at the beam energy of 61 MeV/nucleon. The Coulomb and nuclear breakup components of the one-neutron removal cross sections have been calculated within a finite range distorted wave Born approximation theory and an eikonal model, respectively. The nuclear contributions dominate the partial cross sections for the core excited states. By adding the nuclear and Coulomb cross sections together, a reasonable agreement is obtained with the data for these states. The shapes of the experimental parallel momentum distributions of the core states are described well by the theory.

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The usefulness of the single nucleon transfer reactions in probing the single-particle structure of the stable nuclei, is well established (see e.g. [1–4]). The theory of these reactions developed within the framework of the distorted wave Born approximation (DWBA), has been widely used to analyze the absolute magnitudes and shapes of the measured cross sections to make the angular momentum assignments, and deduce the spectroscopic factors for the ground as well as excited states of the residual nuclei. However, the transfer reactions are not yet routinely used in probing the structure of exotic nuclei near the neutron and proton drip lines. Although the first theoretical [5] and experimental [6] studies of the feasibility of such investigations have already been reported, some formidable difficulties (see e.g. [5]) still persist in the application of this method to probe the exotic nuclei.

Recently, an alternative new and more versatile technique to investigate the spectroscopy of nuclei near the drip line has been developed [7–11]. In this method one nucleon (usually the valence or halo one) is removed from the projectile (a) in its breakup reaction in the field of a target nucleus. The states of the core (b) populated in this reaction are identified by their gamma (γ) decays, whose intensities are used to measure the partial breakup cross sections for these states. The signatures of the orbital angular momentum (ℓ) associated with the relative motion of different core states with respect to the valence nucleon (removed from the projectile), are provided by the corresponding parallel momentum distributions also measured in this experiment.

The practical experimental advantages of this method, such as large partial cross sections for the excitation of various bound states of the core fragment, the possibility of using thick targets, and the strong forward focusing of the reaction products, make it possible to work with the high energy projectiles of low beam intensities. This is in contrast with the existing situation in the case of transfer reactions. Furthermore, while in the latter case the angular distributions of the ejectile loose their characteristic ℓ dependence at high energies [12], the parallel momentum distributions of the core states in the breakup reactions still show strong dependence on the ℓ value [13]. So far, most of the the studies of the (a,bγ) type of reaction have been reported for the ^{11}Be [8], ^{12}Be [9], ^{14}B [10], and ^{16,17,19}C [11] projectiles on a light

^{9}Be target. Therefore, for these cases the breakup process is governed almost entirely by only the nuclear interaction between the projectile fragments and the target; the Coulomb breakup contributions are almost negligible for these reactions.

Using the framework of the post form distorted wave Born approximation, a theory for the Coulomb breakup reactions has recently been developed [14]. The finite range effects are included in this theory, which can be applied to projectiles of any core fragment-valence neutron angular momentum structure. This theory has been applied rather successfully to investigate the inclusive data for the breakup of halo nuclei on heavy targets at beam energies below 100 MeV/nucleon [14]. A recent study within this theory [15] of the A(a,bγ)X type of reaction involving halo projectile nuclei on a ^{208}Pb target, reveals that the characteristics of this reaction are different in a Coulomb dominated process as compared to those in the nuclear dominated one. In the former case, transitions to the excited states of the core fragment are found to be very weak, which has been confirmed in a recent measurement of the ^{197}Au(^{14}B,^{13}Bγ)X reaction [10]. The pure Coulomb breakup cross sections decrease strongly with the increasing separation energy and the ℓ-value of the core-valence neutron relative motion.

Our aim in this paper is to investigate the one-neutron removal reaction of the (a,bγ) type induced by a non-halo nucleus on a heavy target. We would like to see if the predictions of the pure Coulomb breakup reaction in this case are different from those described above. In this context, the ^{17}C is interesting in many respects. The ground state of this nucleus has a spin parity of $\frac{3}{2}^+$ [11,16], which means that the relative motion of the ^{16}C(g.s.)-valence neutron system has a ℓ value of 2. This makes it an unlikely candidate for having a halo structure even though the corresponding one-neutron separation energy (SE) is only 0.729 MeV. Due to its non-halo nature, the breakup of this nucleus is expected to occur in regions around the distance of closest approach. Therefore, nuclear breakup cross sections are likely to be important for this case even if the measurements are performed on a heavy target. Moreover, the excited bound states of ^{16}C can have configurations in which the relative motion between the excited core fragment and the valence neutron has a ℓ value of zero.

This implies that the partial cross sections for these states of ^{16}C may have larger values even in a Coulomb dominated breakup process.

Motivated by these facts, we undertook the analysis the ^{197}Au(^{17}C,^{16}Cγ)X reaction at the beam energy of 61 MeV/nucleon, which was measured in the same experiment in which the data were taken on a ^{9}Be target [11]. The detailed description of the technique and data analysis is presented in [11]. The Doppler corrected γ-ray spectrum from the decay of the ^{16}C residues produced in this reaction, is shown in Fig. 1. It shows feeding to the same states as those seen in the experiment with a ^{9}Be target. The partial cross sections (PCS) for transitions to these states, extracted from the absolute gamma branching ratios, are shown in table I. It can be seen that the PCS to the excited states are quite substantial, which is contrary to the results of the measurements performed [10] with ^{14}B (a one-neutron halo nucleus) on the same target and beam energy where no transition to the excited core states (of ^{13}B) was observed.

In the theoretical analysis of the data, we assume that the nuclear and Coulomb breakup cross sections (calculated with different theories) can be added and that the Coulomb-nuclear interference term can be neglected. Since this reaction is essentially inclusive in nature (as the measurements are performed only for the heavy fragment), the nuclear partial cross sections (NPC) have contribution from both elastic (also known as diffraction dissociation) and inelastic (also known as stripping or breakup-fusion) breakup modes [17,18]. Cross sections for both these modes were calculated [19] within an eikonal model [20–23] where the core-target and neutron-target interactions are treated in the black disc approximation and the optical limit of the Glauber theory [19,24,25], respectively. The data of Refs. [7–11] have been analyzed within this model. For the semiclassical methods to calculate the nuclear breakup cross sections, we refer to [26].

The pure Coulomb breakup cross sections have been calculated by using a theory formulated [14] within the framework of the post form distorted wave Born approximation (DWBA). Within this theory, the triple differential cross section for the reaction, $a + t \to b + c + t$, where a is the projectile, t the target, and b (charged core) and c

(valence neutron) are the breakup fragments in the final channel, is given by

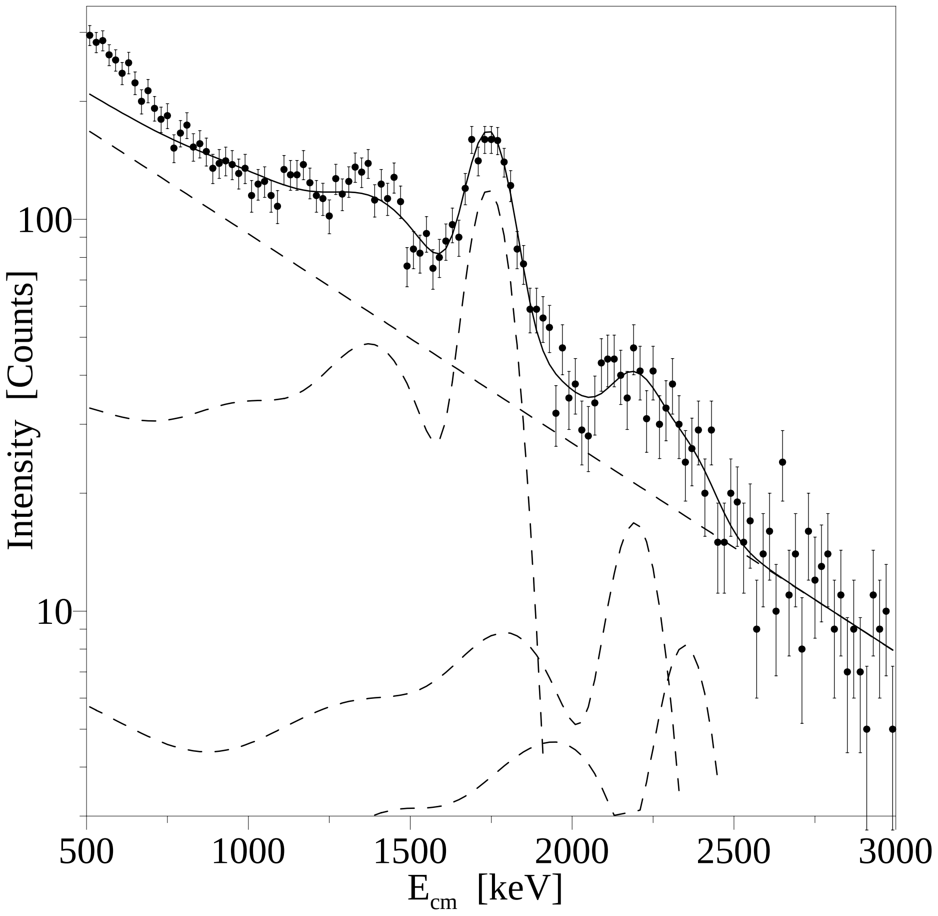

FIG. 1. Doppler-corrected γ-ray spectrum measured in ^{197}Au(^{17}C, ^{16}C+γ)X. The black curve is a fit to the spectrum using a single exponential curve for the background and Monte-Carlo simulated response functions (dashed curves) for each of the γ-ray transitions. The spectrum was fitted using the procedure described in [11].

$$\frac{d^3\sigma}{dE_b d\Omega_b d\Omega_c} = \frac{2\pi}{\hbar v_a}\rho(E_b, \Omega_b, \Omega_c)\sum_{\ell m}|\beta_{\ell m}|^2, \tag{1}$$

where $\rho(E_b, \Omega_b, \Omega_c)$ is the appropriate [14] three-body phase space factor. The reduced amplitude $\beta_{\ell m}$ is defined as,

$$\hat{\ell}\beta_{\ell m} = Z_\ell \int d\mathbf{r}\chi_b^{(-)*}(\mathbf{k}_b, \mathbf{r})e^{-i\delta\mathbf{k}_c\cdot\mathbf{r}}\chi_a^{(+)}(\mathbf{k}_a, \mathbf{r}), \tag{2}$$

where

$$Z_\ell = \int d\mathbf{r}_1 e^{-i(\gamma \mathbf{k}_c - \alpha \mathbf{K})\cdot \mathbf{r}_1} V_{bc}(\mathbf{r}_1) u_\ell(r_1) Y_{\ell m}(\hat{r}_1), \tag{3}$$

$$\hat{\ell} = \sqrt{2\ell+1}. \tag{4}$$

In Eq. (2) $\chi' s$ are the distorted waves for relative motions of the center of mass (c.m.) of a and t and fragment b and t, respectively. $\mathbf{k}_a$, $\mathbf{k}_b$, and $\mathbf{k}_c$ are the Jacobi wave vectors associated with the relative motions of a, b and c, respectively. The charged fragment b interacts with the target by a point Coulomb interaction, and hence $\chi_b^{(-)}(\mathbf{k}_b, \mathbf{r})$ is a Coulomb distorted wave with incoming wave boundary condition. The structure function Z_ℓ involves the radial part of the wave function (u_ℓ) for the relative motion of the b-c system and the corresponding interaction $V_{bc}(\mathbf{r}_1)$. For further theoretical details and definitions of other variables, we refer to [14]. It may be noted that Eq. (2) treats the interaction V_{bc} to all orders.

An alternative theory of Coulomb breakup has also been developed [27] within the framework of an adiabatic model. The expressions for the breakup amplitudes, within this theory, are similar to those of the finite range DWBA theory, although the two have been obtained from quite different assumptions. In the studies of breakup reactions carried out so far, the two theories produced almost identical results in most of the cases [14].

In calculations of both nuclear and Coulomb partial cross sections for populating a given final core fragment state, the projectile ground state is described as having a configuration in which a valence nucleon, with single particle quantum numbers ($n\ell j$) (see e.g. ref [14]) and an associated spectroscopic factor (C^2S), is coupled to the specific core state (I^π). The total cross section in each case is the sum [7,19] of the cross sections calculated with configurations (having non-vanishing spectroscopic factors) corresponding to all the allowed values of the channel spin.

We assume the ground state (0^+) of ^{16}C to arise from the removal of the valence neutron from the configuration ($0d_{3/2}\otimes 0^+$, SE = 0.729 MeV) of the ^{17}C ground state. For the excited 2^+ state at 1.77 MeV, two configurations, ($0d_{5/2} \otimes 2^+$, SE = 2.499 MeV) and ($1s_{1/2} \otimes 2^+$, SE = 2.499 MeV) are considered. For the group of excited states near 4.1 MeV (2,$3^{(+)}$,4^+), we assume the configurations, ($0d_{5/2} \otimes I^\pi$, SE = 4.829 MeV) and ($1s_{1/2} \otimes I^\pi$, SE = 4.829

MeV). The corresponding spectroscopic factors (C^2S) are taken from [16]. In each case, the neutron single particle wave function has been calculated in a central Woods-Saxon well of radius 1.25 fm and diffuseness 0.7 fm. The depth of this well is adjusted to reproduce the corresponding value of SE.

Our results for the partial cross sections are shown in table I. It is evident that the theoretical partial cross sections (even the pure Coulomb breakup ones) to the excited states are quite substantial. This is in sharp contrast to the results seen in the case of such reaction studied with halo nuclei having a s-wave core(g.s.)-neutron relative motion in their ground states. It is interesting to note that the nuclear partial cross sections are quite large. For the ground state of ^{16}C, NPC is of the similar magnitude as the corresponding Coulomb

TABLE I. Calculated partial cross sections to the final states of ^{16}C in the one-neutron removal reaction of ^{17}C on a ^{197}Au target at the beam energy of 61 MeV/nucleon. σ_C and σ_N represent the partial cross sections due to Coulomb and nuclear breakup processes. The latter is the sum of the cross sections obtained in diffraction dissociation (DD) and stripping (str) mechanisms. I^π and E_x represent the spin-parity and excitation energy of the core states respectively.

I$^\pi$	E_x (MeV)	ℓ	C^2S	σ_C (mb)	σ_N^{DD} (mb)	σ_N^{str} (mb)	σ_N (mb)	σ_{th} ($\sigma_C + \sigma_N$) (mb)	$C^2S \cdot \sigma_{th}$ (mb)	σ_{exp} (mb)
0^+	0.0	2	0.03	148	38	75	113	261	8	113±26
2^+	1.77	0	0.16	110	57	106	163	273	44	
		2	1.44	32	22	52	74	106	153	
		sum		142	79	158	237	379	197	162±56
2,3^+4^+	4.1	0	0.22	32	31	69	100	132	29	
		2	0.76	10	15	40	55	65	49	
		sum		42	46	109	155	197	78	75±25

partial cross section (CPC). However, for the excited states, the NPC dominates the CPC. This can be understood from the fact that Coulomb breakup cross sections decrease strongly as the value of SE increases, while nuclear breakup cross sections have a weaker SE dependence. Furthermore, as expected the cross sections to $\ell = 0$ states are larger in comparison with those with $\ell = 2$.

The sum of the NPC and CPC is in reasonable agreement with the data for the excited states. However, for the ground state, the theoretical partial cross section is more than an order of magnitude smaller than the corresponding experimental value. Similar observation was also made in the analysis of the experimental data on a ^{9}Be target [11]. A J^π assignment of either $\frac{1}{2}^+$ or $\frac{5}{2}^+$ to the ground state of ^{17}C could enhance the partial cross sections to the ground state of ^{16}C, as it brings in the $\ell = 0$ component to this transition. However, presence of this component has been ruled out in [11] from the measurements of the corresponding parallel momentum distribution, which is found to be broad and similar to the distribution of a $\ell = 2$ state. This excluded the $J^\pi = \frac{1}{2}^+$ assignment to the ^{17}C ground state. At the same time, with $J^\pi = \frac{5}{2}^+$, the calculated partial cross sections were found to be in disagreement with the data [11]. It has been concluded [11] that only with the assignment $J^\pi = \frac{3}{2}^+$ for the ground state of ^{17}C, the trend of the experimental partial cross sections for the excited states can be explained.

In our case the situation is similar. Of course, here the data for the parallel momentum distribution corresponding to the ground state of ^{16}C, have larger statistical errors (see Fig. 2), which may not allow an unambiguous assignment of the ℓ-value to this state. However, with the J^π value of $\frac{1}{2}^+$ for the ground state of ^{17}C and the corresponding spectroscopic factors [16], the pure Coulomb partial cross sections are found to be 690 mb, 40 mb and 89 mb corresponding to the states with excitation energies of 0.0 MeV, 1.7 MeV and 4.1 MeV, respectively. Looking at the data, these cross sections, on their own, rule out this assignment of the spin-parity to the ^{17}C ground state. Consideration of the nuclear partial cross sections will worsen the comparison with the data even further. On the other hand, with $J^\pi = \frac{5}{2}^+$, the theoretical partial cross section for the transition to the ground state ($\sim$ 170 mb) is closer to the data. However, the cross section to the group of states at 4.1 MeV is predicted to be larger than that to the 1.77 MeV 2^+ state, which is in disagreement with the pattern of the experimental data. Therefore, our calculations too suggest that the most suitable spin-parity assignment for the ground state of ^{17}C is $\frac{3}{2}^+$.

Thus, the discrepancy between theoretical and experimental cross sections for the transition to the ground state of ^{16}C can not be resolved by a different spin-parity assignment to the ^{17}C ground state. Furthermore, the theories of the Coulomb and nuclear breakup reactions used here are quite robust; they have been used earlier to explain successfully the Coulomb and nuclear dominated data as discussed above. Although it is desirable to calculate both these cross sections on an equal footing within the same quantum mechanical theory, which would also include the Coulomb-nuclear interference terms, yet this is unlikely to explain the observed one order of magnitude difference between the data and the calculations for the ^{16}C ground state transition. To solve this problem, a couple of possibilities are discussed in Ref. [11]. They essentially, try to invoke mechanisms which go beyond the simple direct one-neutron removal process assumed in the present analysis. If the $\frac{5}{2}^+$ state lies very close to the $\frac{3}{2}^+$ ground state of ^{17}C, then the coupled channel calculations for the breakup process may help in resolving this discrepancy. However, such calculations, which are difficult to perform at these high energies, have not yet been carried out.

The parallel momentum distributions (PMD) of each of the ^{16}C core states, are shown in Fig. 2. In this figure we have shown only the pure Coulomb calculations. As stated earlier, the data have large statistical errors for the ground state transition. Even then, it appears to be a broad distribution which supports a *d*-wave relative motion for the core(g.s.)-neutron relative motion. For the excited states, the momentum distribution data can only be understood by a combination of the *s*-wave and *d*-wave distributions, which have narrow and broad widths respectively. However, the difference in relative contributions of these components for the excited states at 1.77 MeV and 4.1 MeV should be noted. This can be attributed to the relative difference in the spectroscopic factors for $\ell = 0$ and 2 configurations in two cases. The fact that with values of C^2S (as given table I) the shapes of the experimental PMDs are described rather well by the theory, provides further support to the assignment of a spin-parity of $\frac{3}{2}^+$ to the ^{17}C ground state, as these spectroscopic factors are based upon this assumption. This conclusion is unlikely to be affected by the inclusion of the nuclear breakup in the calculations, as the shapes of the corresponding PMDs are not different from those of the Coulomb ones shown in this figure.

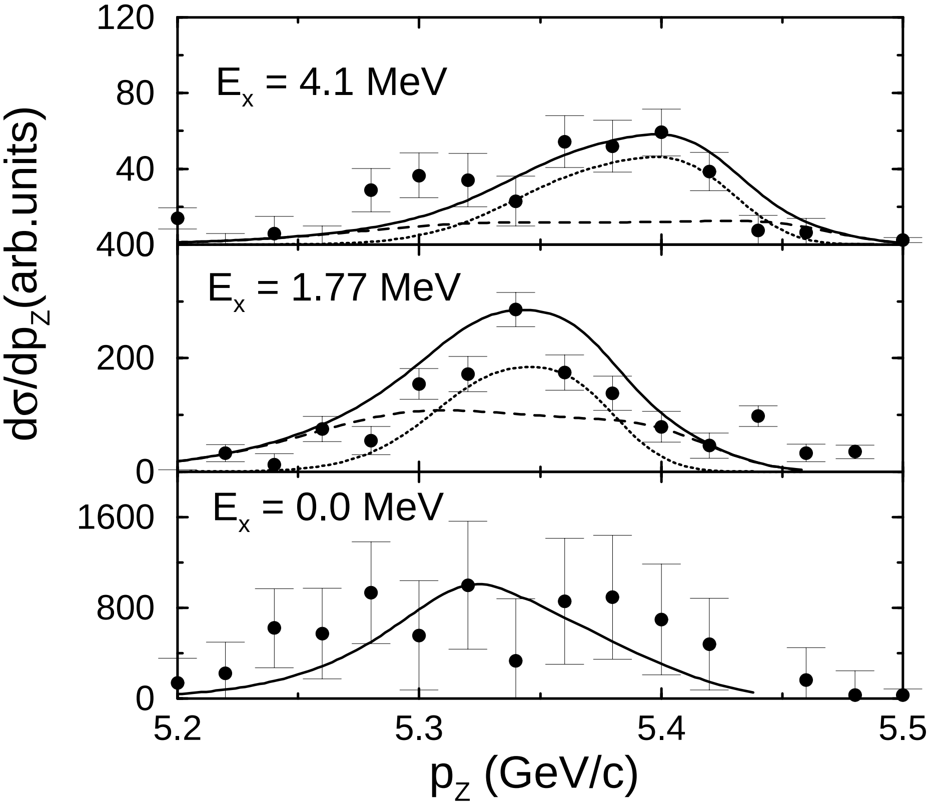

FIG. 2. Comparison of the pure Coulomb breakup calculations and the experimental data for the partial parallel momentum distributions of the ^{16}C core states with the excitation energy (E_x) as indicated. The dotted and dashed lines represent the results of the calculations performed with *s*-wave and *d*-wave configurations for the core - valence neutron system respectively, while the solid line represents their sum.

In summary, we investigated the role of the Coulomb and nuclear breakup mechanisms in the one-neutron removal reaction ^{197}Au(^{17}C,^{16}Cγ)X studied at the beam energy of 61

MeV/nucleon. Partial cross sections and parallel momentum distributions were measured for the ground as well as excited bound states of the core fragment ^{16}C, by detecting the core residues in coincidence with the γ rays emitted in the decay of the excited core states. Substantial partial cross sections were found for the excited core states, which is in contrast to the results seen in the case of the similar measurement performed with the one-neutron halo nucleus ^{14}B on this target.

An important observation of our study is that while for the excitation of the core ground state the nuclear partial cross sections are of the similar magnitude as the Coulomb ones, they dominate the calculated cross sections for transitions to the excited states. The sum of these two cross sections, weighted by the spectroscopic factors taken from Ref. [16] (which is based on a $\frac{3}{2}^+$ spin-parity assignment for the ground state of ^{17}C), is able to provide a good description of the experimental data for the partial cross sections for transitions to the excited states of the core. The dominance of the nuclear breakup effects in these data (taken on a heavy target), is reminiscent of the similar observations made [17] in the case of the breakup of stable nuclei. This supports the fact that ^{17}C is not a halo nucleus even though it has a small one-neutron separation energy. However, the theory is unable to describe the data for the transition to the core ground state. Similar observations were made earlier in the measurement of this reaction on a ^{9}Be target. This situation can not be remedied by a different spin-parity assignment for the ^{17}C ground state.

The shapes of the parallel momentum distributions are described well by the theory. For the excited states an admixture of the s-wave and d-wave configurations with spectroscopic factors as given above is necessary to explain the shapes of the observed PMDs. Our work underlines the need for a proper quantum mechanical calculation of the nuclear and Coulomb-nuclear interference breakup terms.

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Figure Captions

Fig.1 Doppler-corrected γ-ray spectrum measured in ^{197}Au(^{17}C, ^{16}Cγ)X. The black curve is a fit to the spectrum using a single exponential curve for the background and Monte-Carlo simulated response functions (dashed curves) for each of the γ-ray transitions. The spectrum was fitted using the procedure described in [11].

Fig.2 Comparison of the pure Coulomb breakup calculations and the experimental data for the partial parallel momentum distributions of the ^{16}C core states with the excitation energy (E_x) as indicated. The dotted and dashed lines represent the results of the calculations performed with *s*-wave and *d*-wave configurations for the core - valence neutron system respectively, while the solid line represents their sum.