Coulomb dissociation of $^{19}$C

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Abstract

We aim to re-investigate the structure of the neutron rich exotic nucleus $^{19}$C through studies of its Coulomb breakup reactions, assuming that its excitation is to states in the low energy continuum. The method used retains all finite-range effects associated with the interactions between the breakup fragments and can use realistic wave functions for this possibly halo nucleus. We apply the method to compute the longitudinal momentum distribution of $^{18}$C, exclusive neutron angular distribution and relative energy spectrum of $^{19}$C following Coulomb breakup of $^{19}$C on heavy targets at beam energies below 100 MeV/nucleon. The calculated results are compared with recently available experimental data. In the majority of the few cases, the data favour $^{18}$C($0^+$)$\otimes1s_{1/2}$ as the probable ground state configuration of $^{19}$C, with a one-neutron separation energy of 0.53 MeV. However, it appears that the existing experimental data do not allow to draw a clear conclusion about the ground state configuration of this nucleus.

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I. INTRODUCTION

The neutron rich nucleus $^{19}$C has drawn much attention recently as candidate for having a one-neutron halo structure [1,2]. This can be easily anticipated due to its very small neutron binding energy (of the order of a few hundred keV). However, halo formation not only depends upon the small separation energy of the valence neutron. The spin-parity and the configuration of the single particle state of the valence neutron also play important roles in the formation of the halo. The case in which $^{19}$C has a $J^\pi=1/2^+$ ground state (with a dominant $^{18}$C($0^+$)$\otimes1s_{1/2}$ single particle configuration [3]) favours the halo formation. On the other hand, the case of a $J^\pi=5/2^+$, expected from standard shell model ordering, prevents the halo from being formed due to the large centrifugal barrier associated with a $0d_{5/2}$ orbit. The $J^\pi=5/2^+$ may also result when the dominant single particle configuration in the ground state is $^{18}$C($2^+$)$\otimes1s_{1/2}$. In this case, the binding energy of the valence neutron is effectively increased by the excitation energy of 1.62 MeV of the excited ($2^+$) state of the $^{18}$C core, thereby also hindering the halo formation. A $J^\pi=3/2^+$ is also possible with this configuration for the ground state, as considered in recent model calculations [4].

In order to probe the structure of $^{19}$C, only a few experiments on the dissociation of $^{19}$C have been carried out so far. Some of them are inclusive measurements, in which observables related to either the $^{18}$C core or the valence neutron have been measured following the breakup of $^{19}$C. The longitudinal momentum distribution of $^{18}$C has been measured at incident energy of 88 MeV/nucleon at MSU on Be and Ta targets [1], where a very narrow momentum width of around 42 MeV/c FWHM (full width at half maximum) has been reported. A similar experiment, conducted at GSI at very high incident energy of around 910 MeV/nucleon on a carbon target, shows a rather broad width of 69 $\pm$ 3 MeV/c [5].

The neutron momentum distribution, measured in a core breakup reaction of $^{19}$C at 30 MeV/nucleon energy on Ta target at GANIL, shows a narrow component of 42 $\pm$ 17 MeV/c FWHM [2]. This is in contradiction with the observed broad width of 120 $\pm$ 18 MeV/c FWHM of the neutron angular distribution measured at GANIL in an elastic breakup of $^{19}$C [6].

Very recently the relative energy spectrum of $^{19}$C has been measured in its Coulomb dissociation at 67 MeV/nucleon incident energy on Pb target in a kinematically complete experiment at RIKEN [7]. The RIKEN data, when compared with semi-classical calculations [8], support a dominant $1s_{1/2}$ configuration of $^{19}$C halo wave function. The MSU data, on the other hand, suggest an s-wave neutron around the $2^+$ excited state of $^{18}$C [1]. Recent theoretical calculations on the Coulomb breakup of $^{19}$C [8] indicate the possibility of an s-wave neutron coupled to the $2^+$ excited state of $^{18}$C, or a $d$-wave neutron, or a coherent superposition of these two configurations as far as the recent GANIL neutron angular distribution data are concerned. The total one-neutron removal cross sections in the Coulomb dissociation of $^{19}$C on heavy targets have been calculated in [8]. These cross sections, when compared with experimental data on one-neutron removal cross sections measured at GANIL [3] and MSU [1], show that the configuration of a $1s_{1/2}$ neutron coupled to the $0^+$ $^{18}$C core has non-significant contribution to the ground state structure of $^{19}$C [8]. However, very recent calculations of reaction cross sections of $^{19}$C on a carbon target at relativistic energies [9], when compared with experimental data [10], show the dominance of the $^{18}$C($0^+$)$\otimes1s_{1/2}$ ground state configuration. In view of all these discrepancies, it has not been possible to
draw any definite conclusion on the structure of $^{19}$C.

The difficulties in drawing conclusion about the structure of $^{19}$C might arise also due to lack of precise knowledge of the one-neutron separation energy in $^{19}$C. This quantity is very crucial as far as the property of the neutron halo is concerned. The value used in most of the calculations to date is 240 keV. This is the average over previous four measurements of this quantity [11–14]. The recent measurement of the relative energy spectrum of $^{19}$C in its breakup on Pb at RIKEN has led to an indirect determination of the $^{19}$C one-neutron separation energy [7], which is different from that mentioned above (see below).

In this paper, we attempt to re-investigate the structure of $^{19}$C through studies of breakup reactions induced by it in the Coulomb field of a heavy target at beam energies below 100 MeV/nucleon. We compare our results with all the sparsely available differential breakup data and try to throw light on its structure. We follow the theoretical formalism which was first described in [15] for the Coulomb breakup of a light weakly bound two-body composite nucleus $a$ consisting of a charged core $c$ and a neutral valence particle $v$ on target $t$ at energies of a few tens of MeV per nucleon and above. There are two approximations used in this theory - that the dominant projectile breakup configurations excited are in the low-energy continuum and that the valence particle does not interact with the target. The theory is fully quantum mechanical and is also non-perturbative. The method retains all finite-range effects associated with the interactions among the breakup fragments and includes the initial and final state interactions to all orders. It allows the use of realistic wave functions to describe the halo nuclei.

We describe the theoretical formalism in section 2. Structure models are discussed in section 3. Section 4 deals with results and discussions. Finally, we conclude in section 5.

II. FORMALISM

The transition amplitude for the elastic Coulomb breakup reaction $a + t \rightarrow c + v + t$, in the c.m. frame, is given by (Fig.1)

$$T_{\sigma_c \sigma_v; \sigma_a} = \langle \chi(\vec{k}_c, \vec{R}_c)S_{\sigma_c}e^{i\vec{k}_c \cdot \vec{R}_c}S_{\sigma_v}|V_{cv}|\Psi_{\vec{k}_a \sigma_a}^{(+)}(\vec{r}, \vec{R}) \rangle ,$$

(1)

where $S_{\sigma_c}$ and $S_{\sigma_v}$ are the core and valence particle internal wavefunctions with $\sigma_c$ and $\sigma_v$ their spin projections. $\hbar \vec{k}_c$ and $\hbar \vec{k}_v$ are the asymptotic momenta of these fragments, conjugate to $\vec{R}_c$ and $\vec{R}_v$, respectively, and $\chi(\vec{r})$ is an in-going waves Coulomb distorted wave function describing the $c$–$t$ relative motion in the final state. Since it is assumed that $V_{ct} = 0$ the valence particle is described by a plane wave in the final state.

Following the adiabatic approximation of ref. [16], the exact three-body scattering wave function $\Psi_{\vec{k}_a \sigma_a}^{(+)}(\vec{r}, \vec{R})$ separates in the variables $\vec{R}_c$ and $\vec{r}$, namely

$$\Psi_{\vec{k}_a \sigma_a}^{(+)}(\vec{r}, \vec{R}) \approx \Psi_{\vec{k}_a \sigma_a}^{AD}(\vec{r}, \vec{R}) = \Phi_{\sigma_a}(\vec{r})e^{i\vec{k}_a \cdot \vec{r}} \chi^{(+)}(\vec{k}_a, \vec{R}_c) .$$

(2)

Here $\chi^{(+)}$ is a Coulomb distorted wave representing projectile’s motion in the incident channel, evaluated at the core coordinate $\vec{R}_c$ and $\gamma = m_v/(m_c + m_v)$.

The projectile ground state wave function is given by
\[ \Phi_{a\sigma}(r) = \sum_{l\mu jm\sigma\sigma'} \langle s_c \sigma_c' jm | s_a \sigma_a \rangle \langle l \mu s_v \sigma_v' jm \rangle \Phi_{\mu}^a(r) S_{\sigma'} S_{\sigma}, \] (3)

where \( \Phi_{\mu}^a(r) = i^l u_l(r) Y_{\mu}(\hat{r}) \), the \( u_l \) are radial wavefunctions, and the \( Y_{\mu} \) are the spherical harmonics. Since the only distorting interaction \( V_a \) is assumed to be central, the integrations over spin variables can be carried out in Eq. (17). The required approximate transition amplitude can then be expressed as

\[ T_{\sigma \sigma'; \sigma}^{AD} = \sum_{l\mu jm} \langle s_c \sigma_c jm | s_a \sigma_a \rangle \langle l \mu s_v \sigma_v jm \rangle \beta_{\mu}^{AD}, \] (4)

where the reduced transition amplitude \( \beta_{\mu}^{AD} \) is

\[ \beta_{\mu}^{AD} = \langle \chi(\cdot)(k_c, R_c) e^{i\mathbf{k}_a \cdot \mathbf{R}_a} | V_{\mu} | \Phi_{\mu}^a(r) e^{i\gamma} \mathbf{k}_a \cdot \mathbf{R}_c \chi(\cdot)(k_a, R_c) \rangle. \] (5)

Since \( R_v = \alpha R_c + r \) (Fig.1), where \( \alpha = m_t/\left(m_t + m_v\right) \), then without further approximation the entire adiabatic amplitude now separates exactly in the coordinates \( R_c \) and \( r \), as

\[ \beta_{\mu}^{AD} = \langle \phi \rangle \langle \chi(\cdot)(k_c, R_c) e^{i\mathbf{k}_a \cdot \mathbf{R}_c} \chi(\cdot)(k_a, R_c) \rangle \] (6)

The momentum \( q_v \) appearing in the first term is \( q_v = k_v - \gamma k_a \).

Here the structure information about the projectile is contained only in the first term, the vertex function, denoted by \( D(q_v) = D_l(q_v) Y_{\mu}(\hat{q}_v) \), where

\[ D_l(q) = 4\pi \int_0^{\infty} dr r^2 \tilde{j}_l(qr) V_{ce}(r) u_l(r). \] (7)

The second factor is associated with the dynamics of the reaction only, which is expressible in terms of the bremsstrahlung integral [17].

The triple differential cross section for the elastic breakup reaction is

\[ \frac{d^3\sigma}{dE_c d\Omega_c d\Omega_v} = \frac{2\pi}{h v_a} \left\{ \frac{1}{2s_a + 1} \sum_{\sigma \sigma' \sigma} |T_{\sigma \sigma' \sigma}^{AD}|^2 \right\} \rho(E_c, \Omega_c, \Omega_v), \] (8)

or, upon carrying out the spin projection summations,

\[ \frac{d^3\sigma}{dE_c d\Omega_c d\Omega_v} = \frac{2\pi}{h v_a} \left\{ \sum_{l\mu} \frac{1}{(2l + 1)} |\beta_{l\mu}^{AD}|^2 \right\} \rho(E_c, \Omega_c, \Omega_v). \] (9)

Here \( v_a \) is the \( a-t \) relative velocity in the entrance channel. The phase space factor \( \rho(E_c, \Omega_c, \Omega_v) \) appropriate to the three-body final state is [18,19]

\[ \rho(E_c, \Omega_c, \Omega_v) = \frac{h^{-6} m_t m_c m_v p_c p_v}{m_v + m_t - m_v p_v \cdot (P - p_c)/p_v^2} \] (10)

where, for the differential cross section in the laboratory frame, \( P, p_c \) and \( p_v \) are the total, core, and valence particle momenta in the laboratory system.
The neutron angular distribution is obtained by integrating the above triple differential cross section with respect to solid angle and energy of the core fragment. The core three dimensional momentum distribution \( \frac{d^3\sigma}{dp_x,dp_y,dp_z,c} \) is related to its energy distribution cross section by

\[
\frac{d^3\sigma}{dp_x,dp_y,dp_z,c} = \frac{1}{m_c \sqrt{2m_cE_c}} \frac{d^2\sigma}{dE_c d\Omega_c}
\]

\( \frac{d^2\sigma}{dE_c d\Omega_c} \) can be readily obtained from the triple differential cross section above (Eq. (8)) by integration with respect to the solid angle of the valence particle. Starting from the three dimensional momentum distribution, the parallel momentum distribution of the heavy charged fragment \( c \) can be obtained by integration over the transverse momentum components. To calculate the \( c-v \) relative energy spectrum \( d\sigma/dE_{cv} \) from the above triple differential cross section, we follow ref. [8]. Since the excitation energy \( E_{ex} \) is equal to \( E_{cv} + \epsilon_0 \), where \( \epsilon_0 \) is the one-neutron separation energy, the relative energy spectrum is also equal to the excitation energy spectrum \( d\sigma/dE_{ex} \).

### III. STRUCTURE MODELS

We have considered the following configurations for the valence neutron in \( ^{19}\text{C} \): (a) a \( 1s_{1/2} \) state bound to a \( 0^+ \) \( ^{18}\text{C} \) core by 0.24 MeV, (b) a \( 1s_{1/2} \) state bound to a \( 2^+ \) \( ^{18}\text{C} \) core by 1.86 MeV and (c) a \( 0d_{5/2} \) state bound to a \( 0^+ \) \( ^{18}\text{C} \) core by 0.240 MeV. Recently, another option for the ground state structure of \( ^{19}\text{C} \) has been proposed [7]. We consider it as option (d). In this case, the ground state is a moderately dominant \( 1s_{1/2} \) neutron configuration (with a spectroscopic factor \( S = 0.67 \)) which is bound to a \( 0^+ \) core with 0.53 MeV. The binding potentials in all cases are taken to be of Woods-Saxon type with the radius and diffuseness parameters as 1.15 fm and 0.5 fm respectively. Their depths have been calculated to reproduce the respective binding energies. The rms sizes with the above options are 3.45 fm, 3.00 fm, 2.96 fm and 3.20 fm respectively. The rms size used for the \( ^{18}\text{C} \) core is 2.9 fm [20]. These different wave functions of \( ^{19}\text{C} \) give rise to different vertex functions (Eq. (7)) and consequently, different Coulomb breakup cross sections [8].

### IV. RESULTS AND DISCUSSIONS

In the very recent kinematically complete measurement of the Coulomb dissociation of \( ^{19}\text{C} \) on Pb at 67 MeV/A at RIKEN [9], the breakup fragments have been detected within a narrow forward cone of opening angle of 2.5°. The grazing angle is 2.6°. The excitation (relative) energy spectrum has been constructed and the dipole strength distribution deduced therefrom. The excitation energy spectrum and the extracted dipole strength distribution have strong peaks at excitation energy of almost 800 keV, then it dumbs to almost zero at \( E_{ex} = 2 \) MeV. The peak height of the excitation (relative) energy spectrum is \( \approx 1 \) barn/MeV. A neutron separation energy of 530 keV has been derived indirectly and independently by the analysis of the angular distribution of the \( ^{19}\text{C} \) centre of mass system. The shape of the relative energy spectrum \( \frac{d\sigma}{dE_{rel}} \) as a function of \( E_{rel} \), as calculated by these authors, has been
found in good agreement with that resulting from a ground state spin-parity assignment of $1/2^+$, corresponding to a $1s_{1/2} \otimes ^{18}\text{C}(0^+)$ configuration. The spectral amplitude has been used to extract the ground state spectroscopic factor. This has come out to be 0.67. The total Coulomb breakup cross section has been estimated to be $1.2 \pm 0.11$ b. We have calculated the relative energy spectra of $^{19}\text{C}$ on Pb up to $E_{\text{rel}} = 4$ MeV at the same beam energy using the above four configurations (Fig.2). The angular integration for the centre of mass of the $^{18}\text{C} + n$ system has been done up to $2.5^\circ$. The spectrum in the case (d) only has peak position agreeing with that of the experimental data, the peak height being slightly smaller than that of the experimental data. The relative energy spectra, calculated with other three wave functions, have got significantly different magnitudes and different peak positions (Fig.2). But the shape of the spectrum in the case (d) is somewhat different from that of the experimental one for $E_{\text{rel}} > 0.4$ MeV. The calculated spectrum is smaller than the experimental one in this range. The total Coulomb breakup cross section of 0.75 b, computed in this case, is also less than the value quoted above. It is to be noted that we have not used the spectroscopic factor of 0.67 to get this cross section (and the relative energy spectrum). Rather we have used $S = 1$. It is evident that use of $S = 0.67$ results in even smaller relative energy spectrum and total Coulomb part of one-neutron removal cross section. It is worth mentioning that the sensitivity of the extracted spectroscopic factor of 0.67 to the geometry of the assumed (Woods-Saxon) $^{18}\text{C} + n$ binding potential was not clarified in the calculations in [7]. The parameters of the potential were also not specified in [4]. Also, the relative energy spectrum in pure Coulomb dissociation was obtained by subtracting the nuclear breakup contribution, calculated approximately by the authors of ref. [7], from the experimental relative energy spectrum. An accurate estimate of this nuclear breakup contribution as well as Coulomb-nuclear interference is necessary for arriving at any definite conclusion from comparison with the extracted Coulomb breakup contribution. We infer that the configuration proposed for $^{19}\text{C}$ in [7] is supported by our calculations only to some extent.

The longitudinal or parallel momentum distribution (PMD) of the heavy charged fragments in the breakup of the neutron halo nuclei is known to give information on the halo structure [1,8,21–24]. The transverse momentum distributions, on the other hand, are substantially affected by the reaction mechanism [8,23,24]. For breakup of nuclei with very small separation energies of the valence neutron(s) and on high Z targets, the PMDs are expected to have a large contribution from Coulomb breakup [1,8]. We have calculated the parallel momentum distribution $\frac{d\sigma}{dp_\parallel}$ as a function $p_\parallel$ of $^{18}\text{C}$ following breakup of $^{19}\text{C}$ on a Ta target at 88 MeV/nucleon beam energy. This has been recently measured at MSU [1]. Calculations with the first three options on the $^{19}\text{C}$ wave function have been reported earlier [25]. We use these results here and present them along with the result of calculation with option (d). The widths and absolute magnitudes of the PMDs are quite different in the four cases (Fig.3). The widths (FWHM) are 27, 71, 83 and 41 MeV/c respectively for the options (a), (b), (c) and (d) cited above for the $^{19}\text{C}$ ground state wave function. The MSU data do not have the absolute magnitudes of the momentum distributions. The published width of $41 \pm 3$ MeV/c, deduced from these data, favours option (d), although these data have limited statistics (Fig.4). This is in contradiction to the observation of Ridikas et al. [4], who investigated $^{19}\text{C}$ in a core-plus-neutron coupling model with a deformed Woods-Saxon potential for the neutron-core interaction. They obtained a reasonable fit to the $^{18}\text{C}$
PMD when $J^\pi = 3/2^+, 5/2^+$ was assumed, and when the wave function had an appreciable amount of s-motion coupled to the $2^+$ state of $^{18}\text{C}$. But this calculation used a one-neutron separation energy of 0.24 MeV. With a different choice of separation energy of 0.5 MeV and with $^{18}\text{C}(0^+) \otimes 1s_{1/2}$ ground state configuration, they were able to reproduce such a narrow width. This one-neutron separation energy is close to that used in option (d) of our calculations, the ground state configuration is the same as that in (d). It is to be noted that the theoretical calculations in [4] were concerned with the breakup of $^{19}\text{C}$ on a light target (Be), for which Coulomb breakup is not the dominant reaction mechanism.

Using the options (a), (b) and (c) above for $^{19}\text{C}$ ground state wave function and following the same theoretical formalism used here, Coulomb breakup calculations on the recent measurement [3] of the neutron angular distribution following $^{19}\text{C}$ elastic breakup on Ta at 30 MeV/nucleon were reported earlier [8]. This observable also gives a direct indication of the ground state structure. We have repeated the calculations with the wave function (d) for $^{19}\text{C}$. The magnitude of this cross section at forward angles is expected to have a significant contribution from the Coulomb breakup mechanism calculated here. Fig.5 shows the calculated angular distributions ($\frac{d\sigma}{d\Omega_n}$ as a function of $\theta_n$) with the above four configurations of $^{19}\text{C}$. The data in [6], reproduced in Fig.5, show a broad neutron distribution with a FWHM of 120± 18 MeV/c. The cross section magnitude is seen to be $\approx 1.5$ b/sr at forward angles. Of our Coulomb breakup calculations with the above four options for the ground state configuration of $^{19}\text{C}$, only the model in which the ground state is described as an s-wave neutron coupled to a core excited state comes close, both in magnitude and shape, to the data. In this case, we have calculated the cross section for detection of the $^{18}\text{C}$ core in the excited $(2^+)$ state. A coherent superposition of $^{18}\text{C}(0^+) \otimes 1s_{1/2}$ and $^{18}\text{C}(2^+) \otimes 1s_{1/2}$ configurations is also allowed, for a $5/2^+$ ground state, and would lead to an incoherent superposition of the lower two curves in Fig.5.

V. CONCLUSIONS

In conclusion, we have studied Coulomb dissociation of the neutron rich exotic nucleus $^{19}\text{C}$ and compared our calculations with the existing experimental results in order to probe its possible halo structure. The calculations are performed within an approximate quantum mechanical theoretical model of elastic Coulomb breakup, which makes the following assumptions: (i) only the charged core interacts with the target via a point Coulomb interaction and (ii) that the important excitations of the projectile are to the low-energy continuum, and so can be treated adiabatically. The method permits a fully finite-range treatment of the projectile vertex and includes initial and final state interactions to all orders. The comparison between the calculated and experimentally measured parallel momentum distributions of the breakup fragment $^{18}\text{C}$ and the relative energy spectra of $^{19}\text{C}$ gives some support to a dominant $^{18}\text{C}(0^+) \otimes 1s_{1/2}$ ground state configuration with $1/2^+$ spin-parity and therefore, to a neutron halo structure. These calculations use a one-neutron separation energy of 0.53 MeV. But this configuration is in contradiction with $^{18}\text{C}(0^+) \otimes 0d_{5/2}$ or $^{18}\text{C}(2^+) \otimes 1s_{1/2}$ or a superposition of these two ground state configurations (with $J^\pi = 5/2^+$) necessary to account for the neutron angular distribution (at forward angles) measured at GANIL, which results from the elastic breakup of $^{19}\text{C}$. The one-neutron binding energy of 1.86 MeV/0.24
MeV is also different in this case. We see that in the majority of the available few cases, the data favour $^{18}\text{C}(0^+)\otimes 1s_{1/2}$ as the probable ground state configuration of $^{19}\text{C}$, with a one-neutron separation energy of 0.53 MeV. In view of the insufficiently available data, we feel that more good quality experimental measurements will prove useful in arriving at a more definite conclusion.

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FIGURES

FIG. 1. Coordinate system adopted for the core, valence particle and target three-body system.

FIG. 2. Calculated relative energy spectra in the Coulomb dissociation of $^{19}$C on a Pb target at 67 MeV/nucleon. The dotted, short dashed and long dashed curves are results of multiplication by 0.16, 10 and 10 respectively of the actual calculations. The experimental data have been taken from [7].

FIG. 3. Calculated parallel momentum distributions of $^{18}$C from Coulomb breakup of $^{19}$C on Ta at 88 MeV/nucleon. The short dashed and long dashed curves result when actual calculations in these two cases have been multiplied by a factor of 55. We have not used $S = 0.67$ in case of the solid curve, as the experimental data (not shown here) do not have absolute magnitudes.

FIG. 4. Calculated parallel momentum distribution of $^{18}$C from Coulomb breakup of $^{19}$C on Ta at 88 MeV/nucleon with option (d) (see text). The peak of the calculation has been normalized to that of the data (in arbitrary units), taken from [1]. The centroid of the data has been shifted to compare the widths.

FIG. 5. Calculated neutron angular distributions from Coulomb breakup of $^{19}$C on Ta at 30 MeV/nucleon. The experimental data have been taken from [2]. The solid curve has been obtained with $S = 0.67$. 


$^{19}$C + Ta at 88 MeV/nucleon

$d\sigma/dp_z$ (mb. c/MeV)

- s–state BE=0.24 MeV
- s–state BE=1.86 MeV
- d–state BE=0.24 MeV
- s–state BE=0.53 MeV

($\times 55$)
$^{19}$C + Ta at 88 MeV/nucleon
$\frac{d\sigma}{dE_{\text{rel}}} (\text{b/MeV})$

- $s$-state $BE=0.53$ MeV
- $s$-state $BE=0.24$ MeV
- $d$-state $BE=0.24$ MeV
- $s$-state $BE=1.86$ MeV

$^{19}\text{C} + \text{Pb}$ at 67 MeV/nucleon

$\times 10$

$\times 0.16$
$d\sigma/d\Omega_n$  (b/sr)

- $s$-state BE=0.24 MeV
- $d$-state BE=0.24 MeV
- $s$-state BE=1.86 MeV
- $s$-state BE=0.53 MeV

$^{19}$C + Ta, 30 MeV/nucleon

$\theta_n$ (degrees)