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The $^{12}C(\alpha,\gamma)^{16}O$ reaction: Effects of nuclear excitation on the breakup of a ^{16}O beam

V. Tatischeff, J. Kiener, P. Aguer, and A. Lefebvre
Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, IN2P3-CNRS,
Bâtiment 104-108, 91405 Campus Orsay, France

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We present some preliminary calculations on cross sections for the breakup of ^{16}O around 100 MeV/nucleon with emphasis on the effect of nuclear breakup on the angular distributions. Underlying the results of these calculations, the possibilities and problems of extracting the astrophysical S factor for the $^{12}C(\alpha,\gamma)^{16}O$ reaction at very low energies are discussed. Some considerations on the experimental conditions for a ^{16}O breakup experiment aiming at this astrophysical information are given.

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I. INTRODUCTION

The Coulomb breakup approach has been proposed as a possible way to improve the knowledge on the astrophysically very important $^{12}C(\alpha,\gamma)^{16}O$ radiative capture reaction. With that method, because of the generally larger cross sections compared to the direct reaction ones, one hopes to approach the energy region of thermonuclear burning around 300 keV. Any improvement of experimental data would be of great importance in this case, because of the difficulties encountered when extrapolating the capture cross section from the measured data above ≈ 1 MeV down to astrophysical energies. The theoretical extrapolation is particularly difficult due to the superposition of $E1$ and $E2$ capture; moreover, both capture processes below 1 MeV are the result of interference of subthreshold resonances (1^-, 7.117 MeV and 2^+, 6.917 MeV) of unknown α-spectroscopic factor with a resonance at higher energies for $E1$ (1^-, 9.552 MeV) and the direct capture process for $E2$ (see Fig. 1). This complex situation, together with a capture cross sections at the interesting energies in the subfemtobarn range, is the main reason why the thermonuclear reaction rate for $^{12}C(\alpha,\gamma)^{16}O$ is still poorly known, despite enormous experimental and theoretical efforts.

In sight of planned breakup measurement of ^{16}O, we investigate in detail the conditions and possibilities of obtaining astrophysically useful informations from those experiments. It has already been pointed out [1] that relatively high energies around 100 MeV/nucleon for the ^{16}O projectile are required to produce a virtual photon spectrum extending to sufficiently high energies to reach the high-lying $\alpha+^{12}C$ threshold at 7.16 MeV. At this bombarding energy, the $E2$ excitation prevails over the $E1$ excitation (as shown by Shoppa and Koonin [2]), giving access mainly to the $E2$ capture cross section, which is believed to contribute to about 50% to the thermonuclear reaction rate. The restriction to the $E2$ branch has, however, renewed the interest in Coulomb breakup after recent measurements of the β-delayed α decay of ^{16}N [3, 4], adding new precise data for the $^{12}C(\alpha,\gamma)^{16}O$ reaction, but restricted to the $E1$ branch.

The main complication of the breakup approach here is the possibility of nuclear breakup, resulting from grazing collisions and interfering with Coulomb breakup from trajectories with larger impact parameter. Nuclear contributions are expected to be particularly strong in the ^{16}O case, because of the $E2$ nature of the breakup and the high $\alpha+^{12}C$ threshold. Nevertheless, it has been shown [5] that an extraction of the $E2$ Coulomb part may be possible when fitting simultaneously the measured elastic and inelastic angular distributions using, for example, the coupled channel codes ECIS [6]. Here, the differential inelastic cross sections $d\sigma/d\Omega_{a^*}$ for excita-

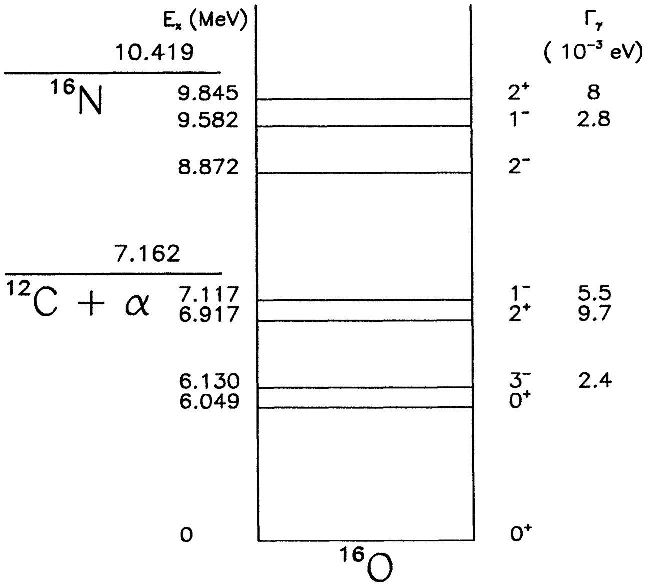

FIG. 1. Level scheme of the ^{16}O nucleus around the α-^{12}C threshold.

tion of the projectile into a resonance above the breakup threshold or $d^2\sigma/d\Omega_{a^*}dE_{\mathrm{c.m.}}$ for excitation directly into the continuum with relative energy $E_{\mathrm{c.m.}}$ between the fragments have to be extracted from the experimentally obtained double (triple) differential breakup cross section $d^{2(3)}\sigma/d\Omega_{a^*}d\Omega_{bc}(dE_{\mathrm{c.m.}})$, where $d\sigma/d\Omega_{bc}$ reflects the fragment angular distribution in the system of their center of mass.

Baur and Weber [7] developed the semiclassical theory for those particle-particle correlations in first-order Coulomb excitation theory, including the effect of possible interferences between different multipolarities. Up to now, for nearly all cases of breakup studies with astrophysical application, Coulomb breakup prevailed over nuclear breakup, being furthermore in all cases a pure $E1$ or $E2$ transition and a first-order Coulomb excitation theory was suitable for the extraction of radiative capture cross sections. We want to study the influence of nuclear interaction on the fragment angular distributions for the selected case of the breakup of ^{16}O at $\approx$ 100 MeV/nucleon, where nuclear breakup is supposed to be of considerable importance and should be taken into account explicitly.

As a conclusion, we present some considerations on an experiment, able to furnish data for the extraction of the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ capture cross section at astrophysically interesting energies.

II. BREAKUP CROSS SECTIONS

The reduced electromagnetic excitation probabilities $B(E\lambda)$, which are used for the calculation of the Coulomb excitation cross section, are directly related to this astrophysical S factor:

$$\frac{dB_{(E\lambda)}}{dE_{\mathrm{c.m.}}} = \frac{\mu}{\pi^2\hbar^2}\,\frac{(2I_a+1)(2I_b+1)}{(2I_i+1)}\,\frac{\lambda(2\lambda+1)!!^2}{8\pi(\lambda+1)} \times \left(\frac{\hbar c}{E_\gamma}\right)^{2\lambda+1} e^{-2\pi\eta}\, S^{E\lambda}_{(E_{\mathrm{c.m.}})}. \qquad (1)$$

In the case of a resonance, the $B(E\lambda)$ value is simply obtained by an integration of that equation over the resonance peak. For particle unstable excited states where $\Gamma_\gamma \ll \Gamma_{\mathrm{tot}}$ that expression leads to

$$B(E\lambda,\mathrm{res}) = \frac{(2I_f+1)}{(2I_i+1)}\,\frac{\lambda(2\lambda+1)!!^2}{8\pi(\lambda+1)}\,\left(\frac{\hbar c}{E_\gamma}\right)^{2\lambda+1}\Gamma_\gamma. \qquad (2)$$

I_a and I_b are the angular momenta of the target and projectile, and I_f is the angular momentum of the excited level in the compound nucleus formed in the direct reaction $a + b \to c$. E_λ is the energy of the gamma ray of multipolarity λ deexciting nucleus c to the ground state I_i, and η is the Sommerfeld parameter.

A. Inelastic scattering cross sections

For the coupled-channel calculations, these $B(E\lambda)$ are related by known relations to the Coulomb deformation parameter [8]:

$$\beta^C_\lambda = \frac{4\pi}{3}\,\frac{1}{ZeR^\lambda_C}\,\sqrt{B(E\lambda)}. \qquad (3)$$

The reduced transition probability is a function of the radial moment of the charge density averaged over the nuclear charge distribution. That presciption is an assumption which may not hold strictly, but appeared to be well adapted for heavy-ion inelastic scattering [9].

For the following estimations of breakup cross sections, an astrophysical S factor $S_{E2}(E_{\mathrm{c.m.}})$, taken from the curve published in [10], has been used. Figure 2 shows some angular distributions obtained with the coupled-channel program ECIS79 [6]. In Fig. 2(a) the inelastic cross section for exciting ^{16}O to the 2^+-subthreshold state at 6.92 MeV is plotted. There the nuclear deformation β^N_2 has been taken following the prescription of Ref. [8]: $\beta^N_2 R_N = \beta^C_2 R_C$. The same calculation is shown in Fig. 2(b) for excitation of ^{16}O into the continuum at 8.56 MeV, 1.4 MeV above the α-^{12}C threshold. For this a $B(E2)$ value is taken obtained by an integration of Eq. (1) from $E_{\mathrm{c.m.}} = 1.35 - 1.45$ MeV. For both cases the optical potential parameters of [12], obtained by elastic scattering of ^{16}O on ^{208}Pb at 94 MeV/nucleon, have been used.

Nuclear excitation evidently accounts for more than half of the inelastic cross section at projectile energies around 100 MeV/nucleon, which will rather complicate

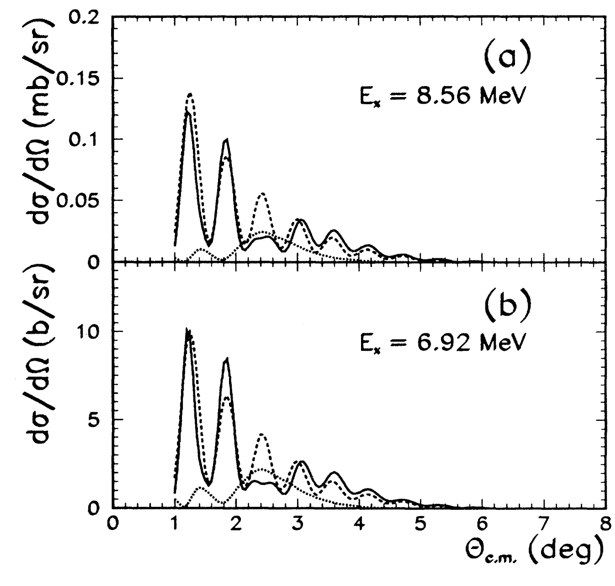

FIG. 2. Angular distributions of the inelastic cross section for the reaction $^{208}\mathrm{Pb}(^{16}\mathrm{O},^{16}\mathrm{O}^*)^{208}\mathrm{Pb}_{\mathrm{g.s.}}$ for two excitation energies at 6.92 and 8.56 MeV. The ^{16}O beam energy is 94 MeV/nucleon, and the computations are carried out with the ECIS code. A $B(E2)$ value is obtained by integration of Eq. (1) from $E_{\mathrm{c.m.}}$=1.35 to 1.45 MeV. The dashed line shows pure nuclear excitation ($\beta^C_2 = 0$), the dotted line pure Coulomb excitation ($\beta^N_2 = 0$), and the full line represents the full calculation with both nuclear and Coulomb excitation interfering. Note the difference of the cross section scale between (a) and (b).

the extraction of the capture cross section. That result is in good agreement with coupled channels calculations for excitation of the 2^+ state in ^{16}O [13], but in some contradiction with Ref. [14], where a much more optimistic calculation for the Coulomb to nuclear cross-section ratio in the same angular region is published. However, even with a less favorable ratio as in our estimations, the Coulomb amplitudes may be extracted by measuring precisely the angular distribution at scattering angles between 2° and 3°, where the effect of nuclear Coulomb interference shows up quite clearly. Comparing Figs. 2(a) and 2(b), the similarity between the angular distributions is obvious, and one may be inclined to say that an experimental determination of that angular distribution should give a strong constraint for the determination of the optical potential parameters to apply to the nuclear breakup. This similarity should, however, be established by more sophisticated theoretical analysis of experimental data, before firmer conclusions can be made.

B. Fragment angular distributions

An explicit expression for the triple differential cross section of Coulomb breakup $d^3\sigma/d\Omega_{bc}\underline{d}\Omega_{\alpha^*}dE_{\text{c.m.}}$ is given by Baur and Weber [7]. For the ^{16}O breakup at 100 MeV/nucleon, they obtained very strong interference effects between pure Coulomb $E1$ and $E2$ breakup assuming an astrophysical S factor S_{E2}, 1/10 of the S_{E1} at their relative energy (1.5 MeV). The observed asymmetries in the fragment angular distributions could even help to extract the $E1$ and $E2$ amplitudes. However, keeping in mind the importance of nuclear $E2$ breakup, we made preliminary calculations of the nuclear breakup effects on the fragment angular distribution.

We adopted the prescription of [7], with the major difference of using for the excitation amplitudes not the semiclassical ones, but the inelastic scattering amplitudes $f^{\lambda}_{M_i}(\Theta,\Phi)$ obtained by coupled-channels calculations. For the ^{16}O breakup, where all involved particles are spinless, the Φ dependence disappears and the expression for the breakup cross section is rather simple:

$$d^2\sigma/d\Omega_{^{16}\text{O}^*}d\Omega_{\alpha\text{-}^{12}\text{C}} = \left|\sum_{\lambda,M_i} f^{\lambda}_{M_i}(\Theta)Y^{*}_{\lambda M_i}(\theta_{\alpha\text{-}^{12}\text{C}},\phi_{\alpha\text{-}^{12}\text{C}})\right|^2 . \quad (4)$$

The $\theta_{\alpha\text{-}^{12}\text{C}}$ and $\phi_{\alpha\text{-}^{12}\text{C}}$ angles are the angles for one fragment in the frame of the excited ^{16}O and are displayed in Fig. 3. Θ is the deviation angle of the excited ^{16}O before the breakup. We checked that the coupled-channels calculations without nuclear excitation give about the same result as semiclassical theories of Coulomb excitation for the magnitude and the form of the double differential cross section. The angular distributions in Fig. 4 have been calculated at $E_{\text{c.m.}} = 1.5$ MeV with a ratio of the astrophysical S factors $S_{E2}/S_{E1} = 1/10$. With that ratio in the astrophysical factor, the $E2$ breakup cross section is still about 4 times larger than the $E1$ one. The $E2$-$E1$ phase difference $\Delta\phi = 50°$ has been obtained from the analysis of angular distributions for ^{12}C(α,γ)^{16}O [15].

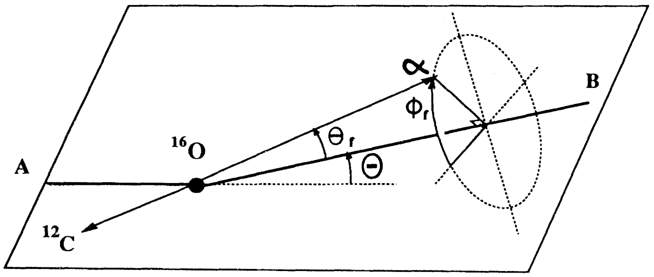

FIG. 3. Sketch of the angles used in the computation. The excited ^{16}O would follow the trajectory A-^{16}O-B if it did not break. Θ is the scattering angle, and θ_f and ϕ_f are the polar coordinates of the breakup vector in the frame of the scattered ^{16}O. The symbol f stands for the subscript α-^{12}C in the text.

Angular distributions resulting from pure Coulomb breakup are displayed in Fig. 4. In Fig. 4(b), the strong asymmetries for $\phi_{\alpha\text{-}^{12}\text{C}}$ equal to 0° and 180° at $\Theta_{\text{c.m.}} = 3°$ which are the result of $E1$-$E2$ interference are observed as they were observed in Ref. [7] at $\Theta_{\text{c.m.}} = 2.5°$. This is to compare with the angular distribution resulting from $E2$ Coulomb breakup alone in Fig. 4(a). Figures 4(c) and 4(d) show the result of the full coupled channels calculation including $E1$-$E2$ contributions and both nuclear *and* Coulomb interaction at two slightly different fragment center-of-mass scattering angles. These very

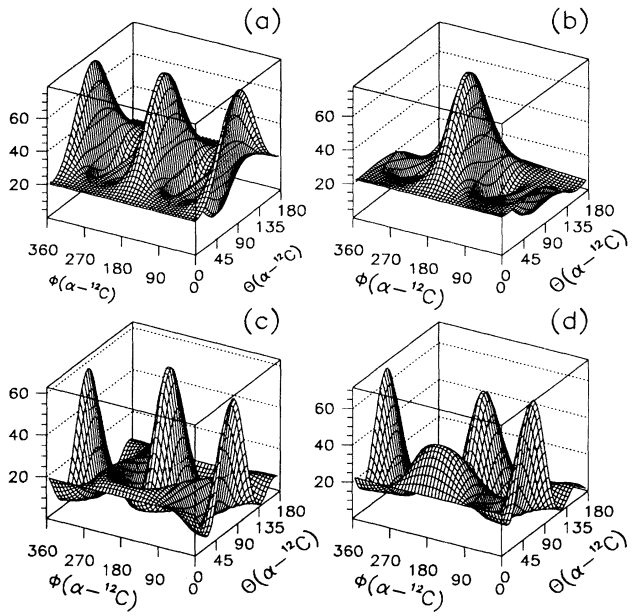

FIG. 4. Double differential cross section $d^2\sigma/d\Omega_{^{16}\text{O}}d\Omega_{\alpha\text{-}^{12}\text{C}}$ (arbitrary units) as a function of the polar breakup angle $\Theta_{\alpha\text{-}^{12}\text{C}}$ for the reaction ^{208}Pb(^{16}O,^{16}O* $\rightarrow \alpha+^{12}$C)^{208}Pb$_{\text{g.s.}}$ at $E_{^{16}\text{O}}$=100 MeV/nucleon and $E_{\alpha\text{-}^{12}\text{C}}$= 1.5 MeV from coupled-channels calculations with $\Theta_{^{16}\text{O}^*}$=3°. (a) Pure Coulomb $E2$ breakup. (b) Pure Coulomb $E1$ + $E2$ breakup interfering. (c) Calculations including nuclear Coulomb $E1$-$E2$ breakup at $\Theta_{^{16}\text{O}^*}$=3°. (d) Same as (c) with $\Theta_{^{16}\text{O}^*}$=2.7°. The units on the x and y axes are in degrees.

characteristic patterns underline clearly the importance of nuclear Coulomb interference in this angular region and the need of precise angular distribution data for the extraction of the Coulomb part and hence the $B(E2)$ values and maybe the $B(E1)$ values.

III. CONSIDERATIONS FOR A ^{16}O BREAKUP EXPERIMENT AT 100 MeV/NUCLEON

It seems obvious that the angular region between 1° and 5°, where the cross section is maximal and the interference effects show up, is to be chosen for the experiment. This can only be done by detecting both breakup fragments in the focal plane of a magnetic spectrometer, where the elastically scattered ^{16}O are eliminated by magnetic selection, as it has already been done by Utsunomiya *et al.* [11] and Kiener *et al.* [5]. Three major points have to be regarded. (i) The relative energy resolution $\Delta E_{\text{c.m.}}$ should be good enough to allow an extraction of a steeply decreasing cross section at low energies. (ii) The emission angles of the two fragments should be determined with an accuracy allowing an identification of the trends observed in the angular distribution of Fig. 4. This point goes hand in hand with the first demand; of course, a good angular resolution is also required for the relative energy resolution. (iii) Recalling the extremely low cross sections expected [see Fig. 2(a)], statistics will be a major problem.

At $E_{\text{c.m.}} = 1$ MeV and $E_{^{16}\text{O}} = 1600$ MeV the fragment angular distribution is concentrated in a narrow cone of $\approx 3°$ in the laboratory. It is thus of primordial importance to determine the emission angles of both fragments with a precision significantly better than 1°, in order not to wash out the interference effects displayed in Fig. 4. The angular resolution in the actual spectrometers are at the limit of that demand, and fine structures may already be missed, although the differences between Figs. 4(b) and 4(c) could surely be detected. Great care in any case should be employed to obtain the best angular resolution by limiting especially the beam emittance and the spot size on the target, which could worsen the angular resolution of spectrometers.

On the other hand, the narrow angular cone is advantageous for the coincidence detection efficiency. With a solid angle of 5 msr, an efficiency of 30% can be obtained at $E_{\text{c.m.}} = 1$ MeV. This means that in 30% of the cases, when the fragment center of mass is inside the acceptance of the spectrometer, both fragments can be detected in the focal plane.

It is evident that the breakup experiments should come along with elastic and inelastic scattering measurements for a good optical potential parameter set. In particular, the inelastic scattering on the first 2^+ state at 6.92 MeV in ^{16}O is certainly of great interest but difficult to measure due to energy broadening of in-flight γ emission.

IV. CONCLUSION

The breakup method may improve our knowledge of the $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ reaction cross section. The major problem is the importance of the nuclear excitation contribution, specifically when accuracy is needed. The importance of very precise measurements of angular distributions is underlined by preliminary calculations of inelastic cross sections and fragment angular distributions. Especially the very characteristic shapes of the angular distributions due to Coulomb nuclear and $E1$-$E2$ interference may help to finally extract the different contributions from the measured data. Some demands on a breakup experiment, aiming at those precise angular distributions, have been investigated, and it is shown that it can be hoped to obtain useful results with existing equipments. If the extraction of the radiative capture cross section from those measurements turns out to be possible, long-time runs with a more efficient detection setup can be imagined to reach much lower relative energies than those actually measured. The already existing data obtained from direct measurements should provide a strong constraint, and a check of the validity of the breakup method applied to the $^{12}\text{C} + \alpha$ reaction rate determination.

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