The ^{12}C(^{16}O,γ^{28}Si) radiative capture reaction at sub-barrier energies

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The heavy-ion radiative capture ^{12}C(^{16}O,γ^{28}Si) was measured at the sub-Coulomb barrier bombarding energy $E_{\rm lab} = 15.7$ MeV, which corresponds to the lowest important resonance observed in the ^{12}C+ ^{16}O fusion excitation function. Thanks to combination of the bismuth germanate (BGO) γ-ray array and the 0° DRAGON electromagnetic spectrometer at TRIUMF, the γ-decay spectrum from the entrance channel down to the ground state of ^{28}Si was measured. Comparisons of the experimental spectrum to γ spectrum extracted from Monte Carlo simulations of the complete setup suggest a $J^\pi = 2^+$ spin-parity assignment to the entrance channel and yield the radiative capture cross section $\sigma_{RC} = 0.22 \pm 0.04$ μb. Combining this present spin assignment with previous data on radiative capture, a $J(J+1)$ systematics was constructed, and it indicated a moment of inertia commensurate with the ^{12}C+^{16}O grazing angular momentum. Strong dipole transitions are observed from the entrance channel to $T = 1$ states around 11.5 MeV and are found to result from enhanced $M1_{IV}$ transitions to states exhausting a large part of the $M1$ sum rule built on the ground state of ^{28}Si. This specific decay was also reported at bombarding energies close to the Coulomb barrier in our previous study of the ^{12}C(^{12}C,γ^{24}Mg) heavy-ion radiative capture reaction. Similarities between both systems are investigated.

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Following the pioneering work of Sandorfi *et al.* in the 1980s on heavy-ion radiative capture [1,2], we had studied in previous works the ^{12}C(^{12}C,γ^{24}Mg) [3,4] and ^{12}C(^{16}O,γ^{28}Si) [5] reactions at energies above the Coulomb barrier (CB). In particular, for the ^{12}C+^{16}O system, we reported results for three energies, $E_{\rm c.m.} = 8.5$, 8.8, and 9 MeV, above the CB which is located at $V_B \sim 7.9$ MeV [5]. The 0° DRAGON electromagnetic spectrometer [6,7] and its associated bismuth germanate (BGO) γ array at TRIUMF were used to measure the complete γ-decay spectrum of the produced ^{28}Si compound nucleus (CN) [5]. Comparisons of the experimental γ spectra with Monte Carlo simulations indicated that the angular momenta introduced in the system were rather large, i.e., a mixing of $l = 5$–$6\,\hbar$ with a relatively pure spin value of $6\hbar$ at the bombarding energy of $E_{\rm lab} = 21$ MeV ($E_{\rm c.m.} = 9$ MeV). This paper will discuss results of a new ^{12}C(^{16}O,γ^{28}Si) experiment at the sub-Coulomb barrier bombarding energy using the same experimental setup as in our previous study.

The present ^{12}C(^{16}O,γ^{28}Si) heavy-ion radiative capture experiment was performed at a bombarding energy at the center of the target of $E_{\rm lab} = 15.7$ MeV ($E_{\rm c.m.} = 6.6$ MeV), corresponding to the lowest energy resonance observed in the ^{12}C+^{16}O fusion excitation function correlated in p and α evaporation channels [8]. This choice of energy was motivated by the fact that a sub-barrier study should lead to fewer open γ-decay channels and thus give better access to the resonance decay properties. As a consequence, the corresponding γ-decay spectrum is more structured and presents strong γ rays

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to states in the excitation energy region $E^* \sim 11$–12 MeV. The purpose of this article is to provide some insight to the origin of these strong γ rays.

A ^{16}O beam with intensity $I = 50$ pnA, accelerated to 16.8 MeV by the ISAC-I accelerator at TRIUMF was impinging on thin self-supporting 99.9% enriched ^{12}C foils of 50 μg/cm^2. Beam intensity was limited to keep the detection dead time under 20%. This was monitored during all experiment using the ratio between presented and accepted trigger in the BGO γ-ray array. The DRAGON spectrometer was employed to separate radiative capture residues from the primary beam and the fusion-evaporation residues. The ^{28}Si recoils with a charge state $q = 8^+$ were detected at the focal plane by a double-sided silicon strip detector (DSSD). The selected recoils have $A/q = 28/8$ which interferes the least with the ^{16}O beam and the strongly produced ^{27}Al (p-channel) and ^{24}Mg (α-channel) evaporation residues. Unambiguous identification of the ^{28}Si compound nucleus (CN) was performed using the recoil time-of-flight measured between the BGO array and the DSSD, together with the energy of the recoils recorded at the focal plane. The energy calibration of the BGO array was performed in several steps, in order to obtain a good alignment of the detectors. A Cm^{13}C source was first used to align them at 6.0 MeV and give us a first calibration. The lines of fusion-evaporation channels were then used to correct the calibration run by run. Combining all these steps, we were able to reach a resolution for the total array of ~8% after Doppler correction for the ^{28}Si $2_1^+ \rightarrow 0^+$ transition. This low resolution does not allow us to extract the decay pattern of the entrance channel without comparison of the experimental γ spectrum with complete simulations of the setup.

Possible ^{13}C contamination of the enriched ^{12}C target was investigated using a 50 μg/cm^2 ^{13}C target. Such contamination could lead to extra production of ^{28}Si via the ^{13}C(^{16}O,n) fusion-evaporation reaction. Using identical DRAGON settings, the yields of ^{28}Si produced with this ^{13}C target are comparable to what was obtained with the ^{12}C target. However, the γ spectrum from the ^{13}C(^{16}O,n) fusion reaction mainly contributes to the low-energy part of the spectrum, i.e., at $E_0 \leqslant 7$ MeV, whereas specific features of the radiative capture decay spectrum occur at higher energies, i.e., $E_0 \geqslant 11$ MeV, as will be discussed later.

Figure 1 presents the spectrum (full line) of the highest energy γ ray recorded for each event after Doppler correction and add-back procedure between the nearest-neighbors BGOs. This procedure uses the highest energy hit and checks if hits are present in the nearest neighbors. Any energy deposited in the neighbors is considered to belong to the initial high-energy BGO. The energy is subtracted from the neighbors and added back into the high-energy BGO. The same add-back procedure is used for the experimental and simulated data. At low energy ($E_0 \leqslant 7$ MeV), transitions between low-lying states of ^{28}Si are observed, which confirm the ^{28}Si CN detection at the focal plane. This spectrum was obtained in a 4-day beam time with an intensity kept to 50 pnA to limit the dead time of the BGO array data acquisition system. The general shape of the spectrum is similar to what was observed at higher bombarding energies, except for the rather strong structure at $E_0 \sim 11.5$ MeV. Above 15 MeV, the observed γ rays are consistent with the feeding

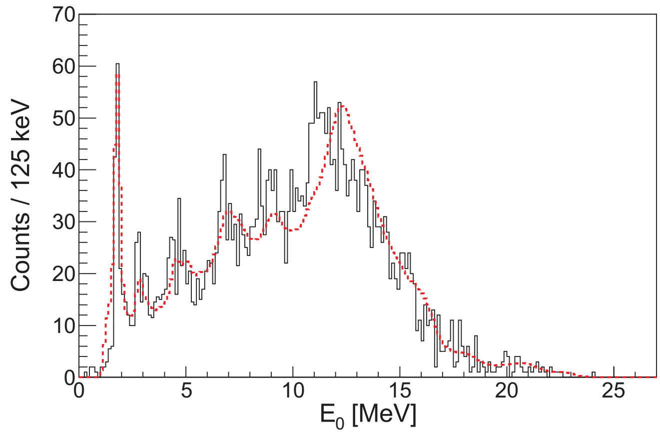

FIG. 1. (Color online) ^{12}C(^{16}O,γ^{28}Si) experimental spectrum of the highest energy γ ray detected per event after Doppler correction and add-back procedure (E_0) in coincidence with ^{28}Si CN detected at DRAGON focal plan, in full line. The (red) dashed line corresponds to a Monte Carlo simulation of the complete setup when the hypothesis of a statistical spin distribution for the entrance channel is made.

of ^{28}Si states which belong to the prolate band based on the 0^+ state at 6.7 MeV and the oblate ground state band.

The DRAGON spectrometer is a state-of-the-art recoil spectrometer built to study reactions of astrophysical interest such as radiative capture of light particles in inverse kinematics. In these conditions, the recoiling nuclei are emitted close to 0° with respect to the beam axis. Its acceptance (~20 mrad [6]) is thus adapted for such reactions. We took advantage of the DRAGON high selectivity in a heavy-ion radiative capture reaction with a rather symmetrical entrance channel for which the recoil cone can be larger than the acceptance cone. As an example, in the extreme case where a γ ray is emitted directly from the entrance resonance to the ground state ($E_0 \sim 23$ MeV) at 90° with respect to the beam axis, the ^{28}Si maximum recoil cone opening is 34 mrad.

As mentioned earlier, in order to extract quantitative results, complete Monte Carlo simulations of the BGO array coupled to the DRAGON spectrometer were performed. The response function of the detection setup was extracted, taking into account the transport of the recoils through the spectrometer, as well as the influence of the cascade and the electromagnetic nature (dipole or quadrupole) of the γ-ray transitions which constrain the acceptance of the spectrometer. Details on the simulation procedure can be found in [5,9,10] and we will only recall here the main steps. The 68 bound and quasi-bound states of ^{28}Si reported in the literature [11,12], distributed up to an excitation energy of 13 MeV were included in the GEANT3 simulations [13]. The branching ratios from the entrance channel to these states are estimated using the average transition strengths observed in the $A = 26$–30 region [14] and are given in Ref. [15]. The subsequent γ decays of the populated states are known from the literature [12].

The γ-decay scheme was calculated using different hypotheses to describe the entrance channel. A statistical spin distribution derived from the coupled-channel CCFULL code [16] was first employed. Details of the couplings and potential used are given in Ref. [10]. The parameters were adjusted to reproduce the ^{12}C+^{16}O excitation function [17]. Partial waves that contribute to the radiative capture cross section have $l \leqslant 3\hbar$ as expected from a reaction occurring below the CB. The corresponding calculated spectrum is reported in Fig. 1 (red curve). While this scenario of statistical formation of the ^{28}Si (CN) reproduces the global trend of the γ spectrum, the structure at $E_0 \sim 11.5$ MeV is not correctly described. There is thus an effect beyond the statistical description of this radiative capture reaction.

This effect was investigated by the means of simulations involving a unique entrance spin. As expected from the calculated spin distribution, the global behavior of the experimental γ spectrum is best reproduced for small partial waves ($l \leqslant 3\hbar$). Indeed, the best agreement for the high E_0 part of the spectrum, where the contamination coming from other reaction channels is not present, is obtained for a 2^+ entrance channel. However, as in the spin distribution scenario, none of the unique spin simulations are able to reproduce the strong structure observed at $E_0 \sim 11.5$ MeV.

This region could correspond to the direct feeding of states around $E^* \sim 12$ MeV starting from the $T = 0$ entrance channel at $E^* \sim 23.5$ MeV. In particular, two $T = 1$ states, the 1^+ and 2^+ states at 11.45 MeV and 11.43 MeV respectively, could be fed by $L = 1$ allowed transitions in ^{28}Si. A better agreement with experimental data was thus obtained with the 2^+ entrance state by increasing the $M1_{IV}$ transition strength to these $T = 1$ states in the simulations. Figure 2 displays the calculated strength function, i.e. branching ratio versus excitation energy for the 2^+ case, together with the corresponding calculated γ spectrum. A χ^2 per degree of freedom of 0.96 was obtained with this simulation, which should be compared to the 0.82 with the simulation presented on Fig. 1. The strength enhancement introduced in the calculation allows us to extract the value $B(M1)$ ($2^+ \rightarrow 1^+$ and 2^+, $T = 1$) $\sim 2.1\mu_N^2$, which is comparable to the $B(M1)\downarrow \sim 1.5\mu_N^2$ of the ^{28}Si transition from the ground state 0^+ to the 1^+ state at 11.45 MeV as measured in (e,e) experiments [18]. It has been shown that this particular state exhausts the major part of the total magnetic dipole strengths built on the ground state (g.s.), i.e., $\sim 70\%$ of the $B(M1)$ sum rule. The $B(M1)$ values extracted in our data from the resonant state to the $T = 1$ states ($\sim$1.25 W.u.) are among the strongest measured in this mass region [12]. In addition, this enhanced feeding of the 1^+, $T = 1$ state does not support the hypothesis of a 3^- entrance resonance for the above reasons.

The BGO array associated to the DRAGON spectrometer is designed for the measurement of total γ-decay widths of resonances of nuclear astrophysics interest. Such measurements are made possible by the compact configuration of the 30 BGO detectors close to the target [7]. As a consequence, this configuration is not optimal for angular distribution measurements, which we have nevertheless tried to determine. Simulation of an isotropic distribution was performed to take into account the solid angle of each BGO detector and the possible bias induced by the coincidence requested between the γ-ray array and the focal plane detector. The BGO array response function can thus be determined.

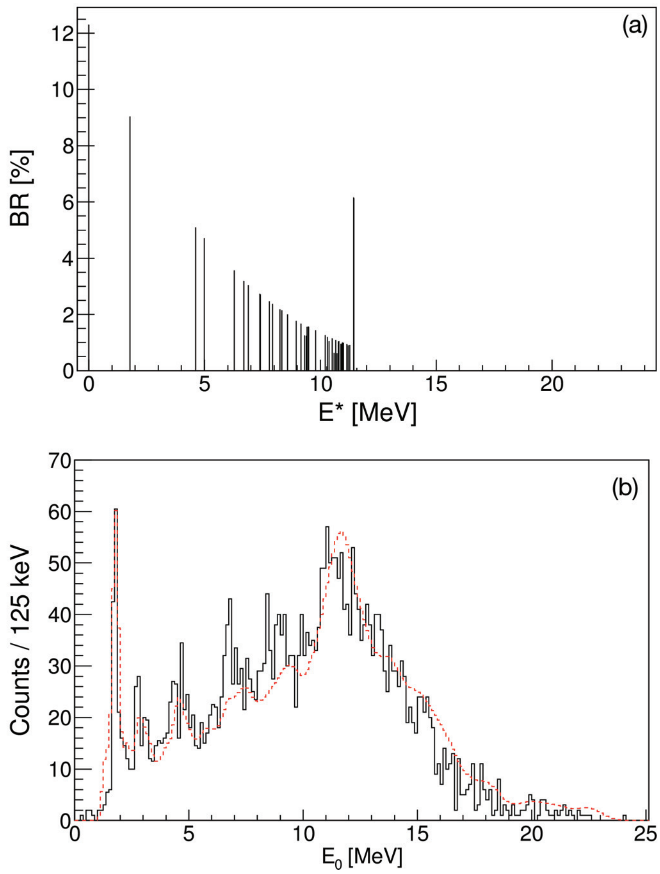

FIG. 2. (Color online) Decay scheme of the ^{12}C(^{16}O,γ^{28}Si) entrance channel. (a) Branching ratio versus excitation energy E^* for the 2^+ entrance state. The enhancement of the $M1_{IV}$ transitions to the 1^+ and 2^+ states at 11.45 MeV and 11.43 MeV is shown. (b) The corresponding GEANT3 γ-ray spectrum is shown in part (in red) together with the experimental data (black).

The experimental γ-ray angular distribution has been extracted and is given in Fig. 3 for the $10 \leqslant E_0 \leqslant 13$ MeV region. This region contains the decay of the resonance to the 1^+ state and the subsequent decay of the 1^+, $T = 1$ state to the ground state. The extracted angular distribution will thus correspond to the sum of the angular distribution of the transition from the entrance channel to the $T = 1$ state and the transition $L = 1$ 1^+, $T = 1 \rightarrow$ g.s. Different cascades were investigated and ruled out: the $1^- \rightarrow 1^+ \rightarrow 0^+$ cascade because its calculated angular distribution presents a minimum at 90 degrees, which is not seen in the experimental distribution. In the case of a 0^+ entrance channel, the angular distribution would be isotropic and, finally, as said a 3^- can also be rejected due to the strong feeding of the $T = 1$ states. This leaves us with a $L = 1$ $2^+ \rightarrow 1^+ \rightarrow 0^+$ cascade decay; the corresponding calculated angular distribution is also represented in Fig. 3. It is worth noting that in this case the two steps of the cascade have not only the same energy but also the same angular distribution. It is thus not necessary to determine the relative intensity of the two steps to compare the theoretical distribution and the experimental one, which strongly reduced

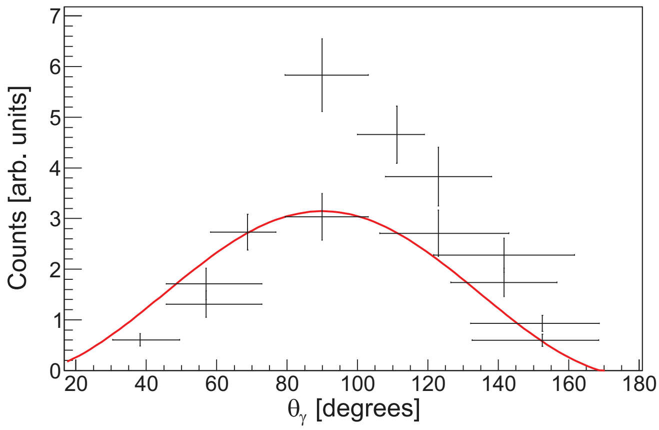

FIG. 3. (Color online) Experimental γ-ray angular distribution of the $10 \leqslant E_0 \leqslant 13$ MeV region of the ^{28}Si CN γ decay. The (red) curve corresponds to an angular distribution of a $2^+ \rightarrow 1^+ \rightarrow 0^+$ cascade decay scenario.

the number of adjusted parameters to scale the theoretical distribution to our data. The rather good agreement between the theoretical and the experimental distributions is consistent with the hypothesis of a 2^+, $T = 0$ entrance channel.

Combining the spin assignment made in the present paper and the ones made at higher bombarding energies [5,15], a $J(J+1)$ systematics for the heavy-ion radiative capture reaction was constructed and is presented in Fig. 4 with (red) triangles. The obtained spin systematics, together with spin attributions from resonant scattering and breakup experiments (blue crosses) [19] seem to form a rotational band. To give a better idea, the spins of the g.s. oblate band (filled circles) and the prolate band (filled squares) are reported in black. For the

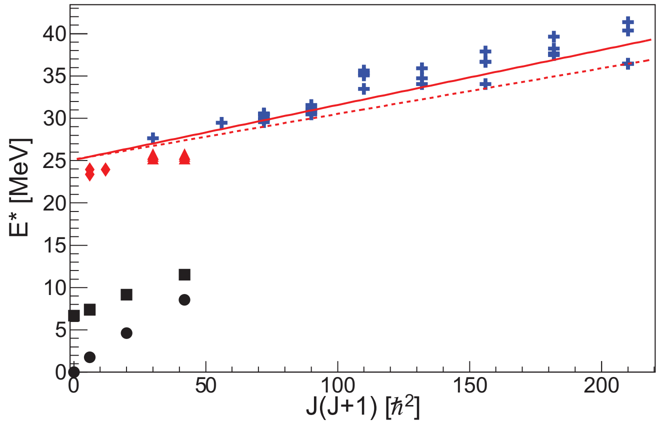

FIG. 4. (Color online) Spin systematics of the oblate g.s. band (filled circles), the prolate band built on 0_3^+ (filled squares) of ^{28}Si, together with the scattering resonances reported in ^{12}C+^{16}O from the compilation work of Ref. [19] (blue crosses), and the resonances explored by the radiative capture reactions in [5] (red triangles) and this work (red diamonds). The (red) full line corresponds to a linear fit of the scattering resonances and our radiative capture results. The (red) dashed line corresponds to the $J(J+1)$ variation in the case of a grazing angular momentum.

TABLE I. ^{12}C+^{16}O RC cross sections obtained in our experimental campaigns at TRIUMF and ratios to the total fusion cross section. See text for more details.

$E_{\rm c.m.}$ (MeV)	σ_{RC} (μb)	$\sigma_{RC}/\sigma_{\rm Fus}$ (10^{-5})
9	23.4 ± 5.7	9.63
8.8	16.3 ± 4.0	7.62
8.5	11.6 ± 2.8	6.82
7.2	0.88 ± 0.18	2.75
6.6	0.22 ± 0.04	2.77

upper band, the linear fit of the $J(J+1)$ systematics indicates a rotational band with moment of inertia $\hbar^2/2J \sim 64 \pm 4$ keV, which is commensurate with the grazing angular momentum of the ^{12}C+^{16}O system ($\hbar^2/2J \sim 55$ keV) [20]. This suggest that the deformation of the entrance channel can be represented as a ^{12}C-^{16}O molecule. The head of this band would be located at an excitation energy very close to 23 MeV. Such a molecular configuration is in very good agreement with the antisymmetrized molecular dynamic model (AMD) for ^{28}Si which predicts strong ^{12}C+^{16}O molecular configuration at low energy for the prolate band and also at higher energy close to $E^* \sim 23$ MeV [21].

In all ^{12}C(^{16}O,γ^{28}Si) radiative capture (RC) experiments performed by our group, RC cross sections have been extracted taking into account the ^{28}Si charge state distribution [5,10].

These results are given in Table I along with the present measurement at $E_{\rm c.m.} = 6.6$ MeV. In this table are listed the capture cross sections (σ_{RC}) as well as the ratio to the total fusion cross section ($\sigma_{RC}/\sigma_{\rm Fus}$). Interestingly enough, the ratio to total fusion cross section is decreasing above the CB ($V_B \sim 7.9$ MeV) but seems to stay constant below. Such a trend could be confirmed by measuring at lower beam energies, experiments which of course would be much more time consuming.

The present study of the ^{12}C(^{16}O,γ^{28}Si) radiative capture reaction below the CB shows striking similarities with previous results obtained for the ^{12}C+^{12}C radiative capture reaction close to the CB. In the ^{12}C+^{12}C system, narrow resonances correlated in several reaction channels have been observed around the Coulomb barrier ($V_B \sim 6.0$ MeV) by Almqvist *et al.* [22]. Close to V_B, at $E_{\rm c.m.} = 6.0$ and 6.8 MeV, a spin $J^\pi = 2^+$ has been assigned to the resonances and their γ-decay pattern shows feeding not only of the ^{24}Mg prolate ground state band, but also an enhanced feeding of $T = 1$ states, especially to 1^+ states at 9.97, 10.71 MeV and the 2^+ state at 10.06 MeV [3,4]. In the case of ^{24}Mg, the two 1^+ states concerned exhaust more than 90% of the total $B(M1)$ strength measured in (e,e') scattering [23].

In the two heavy ion radiative capture reactions, 2^+ resonances are found and an enhanced feeding of low-spin ($J^\pi = 1^+$ and 2^+) $T = 1$ states located in an excitation energy region from 10 to 12 MeV has been observed. In both cases, this enhanced feeding has been attributed to strong isovector $M1$ transitions. Both reactions populate self-conjugate compound nuclei in which isospin selection rules strongly reduce the dipole transition strength for $\Delta T = 0$ transitions. It could thus be very interesting to study the decay of a non-self-conjugate nucleus populated by a similar radiative capture reaction, for example the ^{12}C+^{14}C system, known to show resonances close to the CB and to lead to a low number of open channels [24].

In both cases, ^{12}C+^{12}C and ^{12}C+^{16}O, the use of a next generation γ detector based on $LaBr_3$ scintillators, for example, would allow us to measure the decay with better resolution and extract precisely the complete decay strength distribution to the low-lying positive and negative parity bands as well as to the low-spin $T = 1$ states [25]. This would perhaps give us a better understanding of why a 2^+ resonance decays by strong $M1_{IV}$ transitions in both ^{12}C+^{12}C and ^{12}C+^{16}O low-energy radiative capture reactions.

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