

Spin Alignment & Density Matrix Measurement in $^{28}\text{Si}+^{12}\text{C}$ Orbiting Reaction

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Abstract. Gamma-ray angular correlations have been measured for the strongly damped reactions $^{12}\text{C}(^{28}\text{Si},^{12}\text{C})^{28}\text{Si}$ between $\theta_{\text{cm}} = (120^\circ - 160^\circ)$ for $E_{\text{cm}} = 43.5$ and 48 MeV. We find that the density matrices for the $^{12}\text{C}(2_1^+)$ and ^{28}Si states are almost diagonal with respect to the direction of motion of the outgoing particle. The measured density matrices and spin alignments are consistent with the picture of formation of a long-lived dinuclear complex undergoing orbiting, bending and wriggling motions, but not with those obtained from statistical compound nucleus or sticking model calculations.

It has been suggested that strongly damped reaction products at backward angles from the $^{28}\text{Si}+^{12}\text{C}$,¹ $^{20}\text{Ne}+^{12}\text{C}$,² and $^{16}\text{O}+^{27}\text{Al}$ ³ reactions result from the formation of long-lived orbiting complexes. Observations of entrance channel effect⁴ in $^{28}\text{Si}+^{12}\text{C}$, $^{24}\text{Mg}+^{16}\text{O}$ and selective population⁵ of natural parity states in $^{24}\text{Mg}+^{12}\text{C}$ reactions corroborate this suggestion by pointing to the noncompound nature of these reactions. The population of magnetic substates of $^{12}\text{C}(2_1^+)$ and ^{28}Si states for the $^{12}\text{C}(^{28}\text{Si},^{12}\text{C})^{28}\text{Si}$ orbiting reaction at $\theta_{\text{cm}} = 180^\circ$ was measured before. The selective population⁶ of $m=0$ magnetic substate with respect to the beam axis agrees qualitatively with a simple dinuclear sticking model.^{1,6} However, the observed division⁶ of excitation energy disagrees with the sticking model prediction. Measurements⁷ of the $^{32}\text{S}+^{24}\text{Mg}$ system suggest that asymmetric fission could also yield large cross-sections of ^{12}C and similar products.

To further clarify the mechanism involved in these reactions and the nature of the intermediate state involved, we have performed a new particle- γ ray coincidence measurement to determine how the structure of the orbiting complex influences the density matrices of $^{12}\text{C}(2_1^+)$ and ^{28}Si states and their spin alignment parameters as a function of emission angle. Using reverse kinematics, we have measured for the first time the complete angular correlation of 4.44 MeV and 1.78 MeV γ rays in coincidence with carbon particles detected at $\theta_{\text{lab}} = 10^\circ, 15^\circ$ and 25° and have deduced density matrices.

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A natural carbon target ($150\mu\text{g}/\text{cm}^2$) was bombarded by 145 MeV and 160 MeV ^{28}Si beams from the ORNL HHIRF tandem accelerator. Three ΔE - E solid-state telescopes placed in a horizontal plane at 10° , 15° and 25° were used to identify carbon particles. The experiment was performed in the ORNL Spin Spectrometer using 70 NaI detectors which covered more than 95% of the total solid angle. A lead plate about 0.25" thick was placed in front of each NaI detector to absorb low energy γ rays. The relative efficiencies of the NaI detectors as a function of energy were obtained by measurement with γ ray sources and by bombardment of a carbon target with a proton beam and the use of the known differential γ -ray cross section⁸ for production of 4.44 MeV γ rays.

Fig. 1 shows examples of NaI spectra in coincidence with carbon particles detected at $\theta_{\text{lab}} = 15^\circ$ at $E_{\text{cm}} = 43.5$ MeV for $-22 < Q < -10$ MeV. We observe Doppler-shifted 1.34 MeV and 2.75 MeV γ -ray lines from the $(2_1^+ - 0_1^+)$ and $(4_1^+ - 2_1^+)$ transitions in ^{28}Si and 4.44 MeV γ rays from ^{12}C at all angles. The large Doppler shift of the 4.44 MeV γ rays indicates that they are mostly coming from the $(2_1^+ - 0_1^+)$ transition from the fast moving ^{12}C .

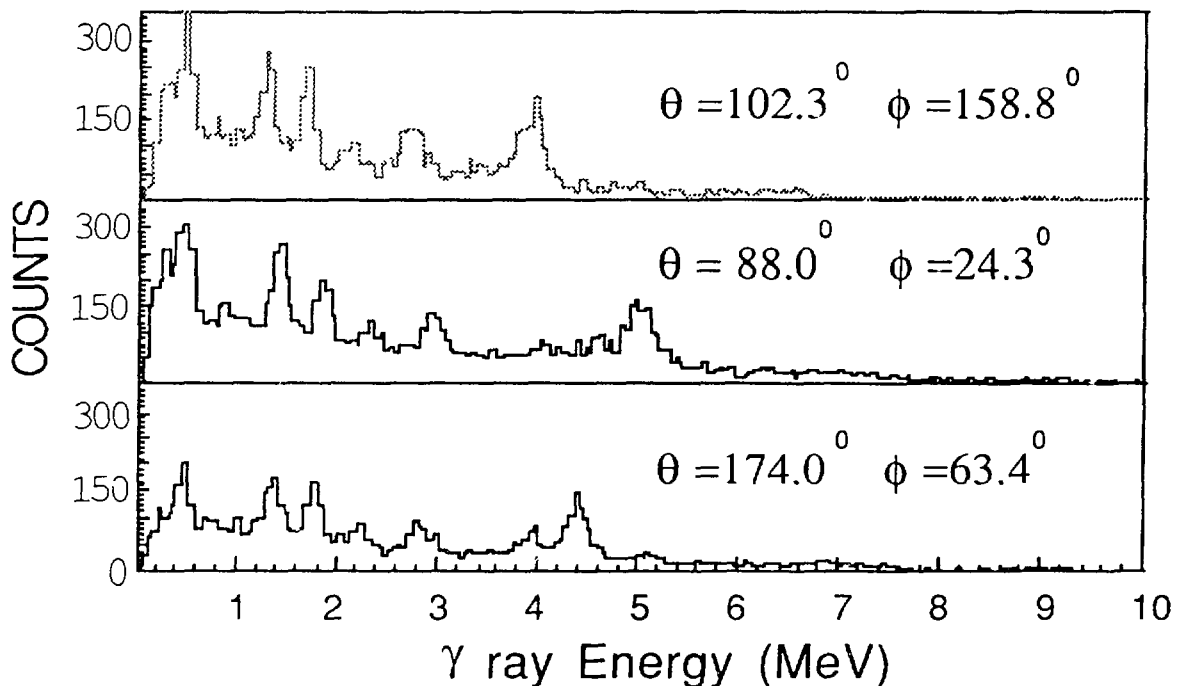


Fig. 1. Coincidence NaI spectra for the reaction $^{28}\text{Si}+^{12}\text{C}$ at $E_{\text{cm}} = 43.5$ MeV and $-22 < Q < -10$ MeV at $\theta_{\text{lab}} = 15^\circ$, $\phi_{\text{lab}} = 0^\circ$. Polar and azimuthal angles of NaI detectors are measured in a coordinate frame whose Z-axis is normal to the reaction plane and X-axis is along the beam direction.

The observations of comparable yields at $\theta = 174^\circ$, 88° and 192.3° for both 4.44 and 1.78 MeV γ rays imply rather poor spin alignments for both $^{12}\text{C}(2_1^+)$ and $^{28}\text{Si}(2_1^+)$ states, in disagreement with the simple dinuclear sticking model.^{1,6} A complete study of γ ray angular correlation has been done. The γ -ray angular correlation function can be written as⁹

$$W(\theta, \phi) = \sum_{kq} [4\pi / (2k+1)]^{1/2} t_{kq}(J) R_k Y_{kq}(\theta, \phi) \quad (1)$$

where θ , ϕ are polar and azimuthal angles of the direction of emission of the γ rays, Y_{kq} is the spherical harmonics function, R_k is the radiation parameter, t_{kq} is the polarization tensor and J is the spin of the emitting nucleus. We choose a coordinate frame whose Z -axis is along the direction of motion of the nucleus emitting γ rays and Y -axis is normal to the reaction plane and consider γ -ray emission from the $(2^+ - 0^+)$ transition. Then considering symmetry properties of polarization tensor and the conservation of parity we find nine independent elements of the polarization tensor (t_{00} , t_{20} , t_{21} , t_{22} , t_{40} , t_{41} , t_{42} , t_{43} , t_{44}). The elements of the density matrix ρ are given by the expression⁹

$$\rho_{mm'} = \sum_{kq} t_{kq}(J) \langle J, J, m', -m | kq \rangle (-1)^{J-m} \quad (2)$$

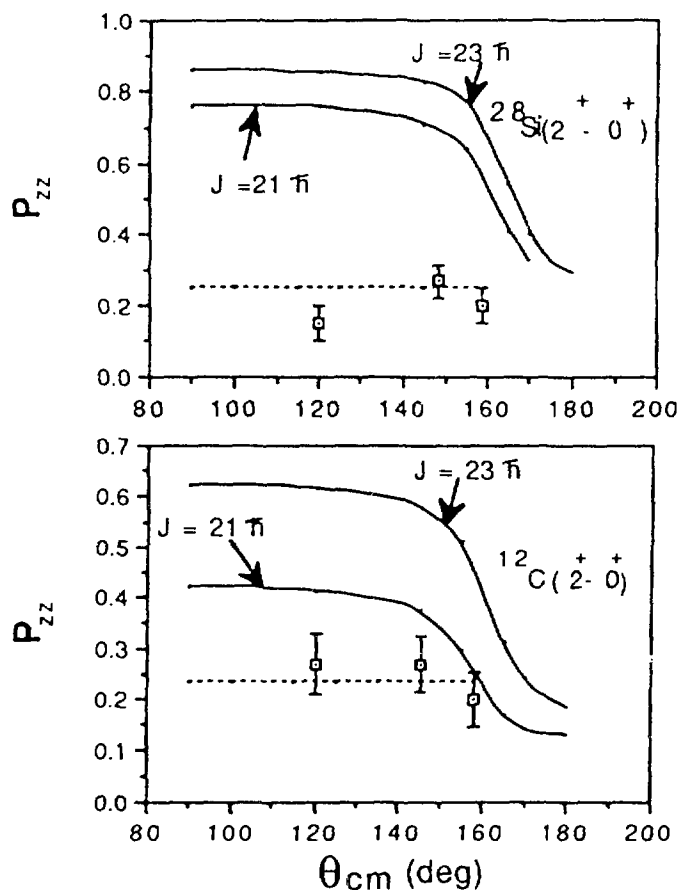
We used the 4.44 MeV and 1.78 MeV γ -ray yields from 70 detectors of the Spin Spectrometer to determine the nine elements of each of the corresponding polarization tensors by fitting them with eq. (1), after taking into account finite solid-angle effects of NaI detectors and Doppler shifts. The attenuation¹⁰ due to the hyperfine interaction has been estimated to be (2-3)% and we do not correct for it. Subsequently, the elements of the density matrices of $^{12}\text{C}(2_1^+)$ and $^{28}\text{Si}(2_1^+)$ states were determined by using eq. (2). Then they were rotated to a coordinate frame whose Z -axis is along the normal to the reaction plane defined by the beam axis and the direction of motion of the scattered carbon particle. The spin alignment parameter with respect to the Z -axis is defined¹¹ as

$$P_{ZZ} = \frac{3 \sum_m^2 \rho_{mm} - J(J+1)}{J(2J-1)} .$$

In Fig. 2, we show P_{ZZ} (Z -axis normal to the reaction plane) of $^{12}\text{C}(2_1^+)$ state in $(-22 < Q < -10)$ MeV and the $^{28}\text{Si}(2_1^+)$ state in $(-10 < Q < 0)$ MeV as a function of emission angle of the carbon particle at $E_{\text{cm}} = 43.5$ MeV. In $-22 < Q < -10$ MeV, the possibility that $^{12}\text{C}(2^+)$ is excited by $^{28}\text{Si} + ^{12}\text{C} \rightarrow ^{24}\text{Mg}^* + ^{12}\text{C}(2^+) + ^4\text{He}$ is extremely small because of kinematical and phase-space reasons. The spin alignments of the $^{28}\text{Si}(2_1^+)$ state and the original parent states of ^{28}Si should be about the same, because in $(-10 < Q < 0)$ MeV, ^{28}Si is predominantly ($\sim 90\%$) excited to 6^+ , 4^+ and 2^+ states and they decay by stretched E2 cascades. Error estimates were obtained by adding

in quadrature the error in determining the area under the peak and the error in the relative gamma detector efficiencies. As a check, we also determined the magnetic substate population ρ_{11} of $^{28}\text{Si}(2^+)$ state for $(-3 < Q < -0.6)$ MeV using a coordinate frame whose Z-axis is normal to the reaction plane and find that ρ_{11} is consistent with zero within the statistical uncertainties as required by the conservation of parity and rotational invariance. We obtained similar values and variation of P_{zz} as a function of emission angle for both bombarding energies. The value of P_{zz} for $^{12}\text{C}(2_1^+)$ drops to about 0.1 ± 0.05 for $-40 < Q < -22$ MeV for both bombarding energies.

In Fig. 2, the solid curves are the predictions of a compound-nuclear statistical model. We assume that ^{12}C and ^{28}Si form a compound nucleus



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Fig. 2. The spin alignment parameter of 1.78 MeV γ rays for $-10 < Q < 0$ MeV and of 4.44 MeV γ rays for $-22 < Q < -10$ MeV at $E_{cm} = 43.5$ MeV. The full curves and dashed lines are statistical and dinuclear orbiting model calculations respectively as explained in the text.

and consider emission of ^{12}C from the compound nucleus. Let J , S_{Si} , S_{C} , S , ℓ be total angular momentum, silicon spin, carbon spin, channel spin and orbital angular momentum, respectively. Let m_J , m_{Si} , m_{C} , m_{S} and m_{ℓ} be their respective magnetic substates with respect to the normal to the scattering plane. Although the compound nucleus will be formed with a broad spin distribution, the contribution to the carbon yield comes predominantly from a few partial waves near the critical angular momentum ($J_{\text{crit}} = 23\hbar$ at $E_{\text{cm}} = 43.5$ MeV). We obtain the following expression for density matrix using Hauser-Feshbach formalism,¹² for a specific value of J and S_{Si} . When the carbon particle is detected at an angle θ_{cm} with respect to the beam axis, then the elements of the density matrix for the $^{12}\text{C}(2^+)$ state in a coordinate frame whose Z-axis is normal to the scattering plane and X-axis is along the beam direction is given by

$$\rho_{m_{\text{C}}m_{\text{C}'}} = \sum_S \sum_{\ell} \sum_{m_{\text{Si}}} \sum_{m_J} \sum_{m_{\ell}} \langle S_{\text{C}}, S_{\text{Si}}, m_{\text{C}}, m_{\text{Si}} | S, m_{\text{S}} \rangle \langle S, \ell, m_{\text{S}}, m_{\ell} | J, m_J \rangle$$

$$\langle S_{\text{Si}}, S_{\text{C}}, m_{\text{Si}}, m_{\text{C}'} | S, m_{\text{S}'} \rangle \langle S, \ell, m_{\text{S}'}, m_{\ell}' | J, m_{\text{J}'} \rangle T_{\ell}(\epsilon) \exp[2\{a(E_{\text{cm}} - V_{\text{C}} - E_{\text{rot}})\}^{1/2}]$$

$$Y_{\ell, m_{\ell}}(\frac{\pi}{2}, \theta_{\text{cm}}) Y_{\ell, m_{\ell}'}^*(\frac{\pi}{2}, \theta_{\text{cm}}) Y_{J, m_J}(\frac{\pi}{2}, 0) Y_{J, m_{\text{J}'}}(\frac{\pi}{2}, 0) \quad (3)$$

Here a is the level density parameter, V_{C} is the Coulomb energy, E_{cm} is the incident centre-of-mass energy and E_{rot} is the total rotational energy. T_{ℓ} is the transmission coefficient of ^{12}C for orbital angular momentum ℓ and exit channel kinetic energy ϵ . We obtained values of T_{ℓ} by using an optical model potential.¹³ The normalization was obtained by multiplying the calculated density matrix by $(\text{tr } \rho)^{-1}$. A similar expression was used for ^{28}Si states also.

The two curves in Fig. 2 were calculated for $J=21\hbar$, $23\hbar$ and $S_{\text{Si}}=8\hbar$ for ^{12}C and $S_{\text{Si}}=6\hbar$ for ^{28}Si . The total rotational energy E_{rot} was calculated by assuming a prolate ellipsoidal shape¹⁴ for the excited ^{28}Si and a spherical ^{12}C nucleus touching each other, so that the major axis of ^{28}Si is along the line joining the centres of two nuclei. The statistical model code CASCADE¹⁵ predicts that most of the contributions to the carbon yield come from $J>23\hbar$ at $E_{\text{cm}} = 43.5$ MeV. So a weighted average over different values of J will significantly increase P_{ZZ} and disagreement with data. A weighted average over a distribution of S_{Si} as obtained from CASCADE code¹⁵ increases P_{ZZ} by approximately 10%. We conclude that the statistical model calculation predicts much higher alignment than observed. Variation of the level density parameter and the shape of the nuclei within reasonable limits do not change this conclusion. Calculations were done for $E_{\text{cm}} = 43.5$ MeV and 48 MeV. The results are similar. The simple sticking model prediction ($P_{\text{ZZ}} = 1$, independent of angle), disagrees even more.

We now discuss the off-diagonal elements of the density matrices. For this purpose, we choose a coordinate frame whose Z-axis is along the direction of motion of the nucleus emitting γ rays and Y-axis is normal to the reaction plane. Let Z_{Si} and Z_{C} denote the directions of motion of ^{28}Si and ^{12}C nuclei respectively. In Table I, we show the deduced density matrix of $^{12}\text{C}(2^+)$ state for $\theta_{\text{cm}} = 145^\circ$ in the range $(-22 < Q < -10)$ MeV at $E_{\text{cm}} = 43.5$ MeV. We find that the density matrix is almost diagonal with respect to the direction of motion of the particle. This means that the spin orientation of the $^{12}\text{C}(2_1^+)$ state is cylindrically symmetric with respect to its direction of motion.

Table I also shows the deduced density matrix of $^{28}\text{Si}(2_1^+)$ state for $\theta_{\text{cm}} =$

Table I

Density matrices for $^{12}\text{C}(2_1^+)$ and $^{28}\text{Si}(2_1^+)$ states

Observation		$^{12}\text{C}(2_1^+)$	$^{12}\text{C}(2_1^+)$
$^{12}\text{C}(2_1^+)^1$	$^{28}\text{Si}(2_1^+)^2$	Theory ³	Theory ⁴
$\rho_{00} = 0.27 \pm 0.02$	0.29 ± 0.019	0.31	0.29
$\rho_{11} = 0.28 \pm 0.013$	0.23 ± 0.011	0.235	0.24
$\rho_{22} = 0.08 \pm 0.02$	0.13 ± 0.014	0.11	0.11
$\rho_{01} = 0.014 \pm 0.012$	0.005 ± 0.017	0.012	0
$\rho_{02} = -0.019 \pm 0.011$	$-0.028 \pm .01$	-0.102	-0.013
$\rho_{12} = 0.018 \pm .013$	$-0.027 \pm .011$	0.022	0
$\rho_{1-1} = -0.017 \pm .015$	$-0.05 \pm .01$	-0.132	-0.041
$\rho_{1-2} = 0.007 \pm .01$	$-0.007 \pm .009$	0.0062	0
$\rho_{2-2} = 0.004 \pm .012$	$0.012 \pm .011$	0.0095	0.0015

¹ Z_C as Z-axis, $-22 < Q < -10$ MeV, $\theta_{\text{cm}} = 145^\circ$.² Z_{Si} as Z-axis, $-10 < Q < 0$ MeV, $\theta_{\text{cm}} = 148^\circ$.³Statistical Model, Z_C as Z-axis, $-22 < Q < -10$ MeV.⁴Dinuclear model (orbiting, bending and wriggling modes) Z_C as Z-axis.

148° in the range ($-10 < Q < 0$) MeV at $E_{\text{cm}} = 43.5$ MeV. The orientation of the $^{28}\text{Si}(2_1^+)$ state is also found to be approximately cylindrically symmetric with respect to its direction of motion. Since the $^{28}\text{Si}(2_1^+)$ state is mostly populated by stretched E2 transitions in ($-10 < Q < 0$) MeV region, the orientations of the parent ^{28}Si states are also approximately cylindrically symmetric with respect to the direction of motion of ^{28}Si ion. Similar behavior of the density matrix was found at other scattering angles. Using eq. 3, we find that the statistical model predicts that the density matrix will be almost diagonal with respect to the normal to the reaction plane. We then rotate the calculated density matrix to a coordinate frame where Z_C is the Z-axis and Y-axis is normal to the reaction plane, and find that the density matrix has significant off-diagonal terms (ρ_{02} , ρ_{1-1}) as shown in the third column of Table I, in disagreement with our observations. Calculations shown in Table I have been performed for $J = 23\hbar$. We also find large off-diagonal elements $\rho_{02} = -0.068$, $\rho_{1-1} = -0.085$ for $^{12}\text{C}(2^+)$ state even for $J = 21\hbar$.

Let us consider a simple picture of two nuclei connected by a narrow neck living long compared to the damping time of their relative motion. The twisting¹⁶ motion between them will be small because of the assumption¹⁷ of a narrow neck. If we assume bending and wriggling modes dominate

because of the structure of the orbiting complex and sum incoherently over different orientations of the spin angular momentum vectors lying randomly in a plane perpendicular to the body-fixed symmetry axis, then the density matrix of $^{12}\text{C}(2_1^+)$ with respect to the body-fixed symmetry axis is given by

$$\begin{aligned} \rho_{00} &= 0.375, \rho_{11} = \rho_{-1-1} = 0.25, \rho_{22} = \rho_{-2-2} = 0.0625 \\ \rho_{01} &= \rho_{02} = \rho_{12} = \rho_{1-1} = \rho_{2-2} = \rho_{1-2} = 0 \end{aligned} \quad (4)$$

In the body-fixed frame, the dinuclear system breaks along the symmetry axis. Here the Coulomb energy $V_C = 18.1$ MeV and orbital energy $V_\ell = \ell(\ell+1)/2I_R = 6.2$ MeV for $\ell=12\hbar$, where I_R is the moment of inertia of the relative motion. So in a space-fixed frame, the trajectory of emitted ^{12}C will be rotated by $\pm \tan^{-1}(\sqrt{V_\ell/V_C}) = \pm 30^\circ$ with respect to the body-fixed symmetry axis. We rotate the density matrix (eq. 4) by $\pm 30^\circ$ and take an average. The results, shown in the last column of Table I, are in better agreement with the experimental data than are the statistical model calculations as shown by the small off-diagonal (ρ_{02}, ρ_{1-1}) elements. A similar analysis for the ^{28}Si state also predicts approximate symmetry of ^{28}Si states with respect to the direction of motion of ^{28}Si . We also obtain alignment parameters of 0.24 and 0.25 (as shown by dashed line in Fig. 2), with respect to the normal to the reaction plane for $^{12}\text{C}(2^+)$ and ^{28}Si states, in agreement with our observation. In the higher Q-value bin ($-35 < Q < -22$) MeV, P_{zz} is very small ($0.1 \pm .05$). This can be understood because the angular-momentum misalignment along the body-fixed symmetry axis (twisting mode) increases and therefore the alignment parameter is reduced. Also, some of the carbon particles in this bin can come from decay of ^{16}O and so will be less aligned. Although our simple classical dinuclear model is not quantitatively valid near $\theta_{\text{cm}} = 180^\circ$, it qualitatively agrees with observed γ -ray angular correlation⁶ at $\theta_{\text{cm}} = 180^\circ$.

In summary, we have done the first measurements of density matrices of ^{12}C and ^{28}Si states produced in the $^{28}\text{Si}+^{12}\text{C}$ reaction. Our observation is consistent with the picture of a long-lived dinuclear system connected by such a narrow neck that bending and wriggling motions are the dominant spin carrying modes.

We found that a Hauser-Feshbach compound Nucleus calculation fails to account for the data. However, it can not be ruled out that the observations of entrance channel effect,⁴ selective population⁵ of natural parity states, γ -ray angular correlation⁶ at $\theta_{\text{cm}} = 180^\circ$ and the observed spin alignments and density matrices distribution may result from the complicated dynamical processes of fusion and fission of the compound nucleus.

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