OM(8) and OM(7); W(7) moves towards OM(6); W(6) moves toward OM(5) but overshoots it, probably because of the excessively large second-order breakup correction for this particular L value; W(5) moves in a wrong direction; W(4) moves towards OM(4) and OM(3) but overshoots both. Even if the location of the corrected W points is not in perfect correspondence with the OM points for the surface partial waves, the magnitudes of the S_T(W) scattering elements are remarkably close to the corresponding OM values.

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Enhancement of the Excitation Function for the 0^+, 6.049-MeV State of ^{16}O in the Reaction ^{12}C(^{16}O,^{12}C)^{16}O

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Excitation functions for the 0^+, 6.049-MeV and 3^-, 6.130-MeV states were measured separately at $\theta_{c.m.} \sim 15.0°$, in steps of 86 keV from $E_{c.m.}$ = 22.7–33.0 MeV. Enhancement of the cross section by a factor of 2–5 above the constant cross section is clearly observed at 23.60, 24.60, 28.40, and 32.20 MeV, for the lowest three of which the most probable total spins, J^π, are found to be 14^+, 14^+, and 15^-, respectively. These resonance energies are quite different from those for the 3^-, 6.130-MeV state observed at 25.2 and 29.8 MeV.

Recently, there has been a great deal of interest in alpha-particle exchange during heavy-ion reactions. In particular, it is predicted that alpha particles are easily formed in p- and sd-shell nuclei having rather low excitation energies,[1] resulting in enhancement of the cross section for the production of such alpha-cluster states in alpha-transfer reactions. Another way to confirm the occurrence of alpha-particle exchange during such collisions is to search for intermediate resonances which selectively decay to good alpha-cluster states. Michaud and Vogt have proposed the alpha-particle doorway-state model for the ^{12}C + ^{12}C system.[2] However, no strong experimental evidence to support their model has been observed in the ^{12}C + ^{12}C system.[3]

For the ^{12}C + ^{16}O system, several intermediate resonances have also been found above the Coulomb barrier in various exit channels[4] and in fusion.[5] Precise measurements have mainly concentrated on the $E_{c.m.}$ = 19.7 MeV resonance, for which the transition to the 3^-, 6.130-MeV state dominates, thus explaining the failure to identify any alpha-particle doorway state in ^{28}Si.[6] Recently, the ^{12}C + ^{16}O inelastic scattering excitation functions were measured by Malmin and Paul over a wider energy range between 14 and 23 MeV (c.m.).[7] Striking features are found for inelastic scattering to the 0^+ and 3^- states in ^{16}O for which resonance doublets appear to occur both at 20 and 22.5 MeV with widths of ~ 300 keV. In their measurement,[7] the lack of separation of the decay to the 0^+, 6.049-MeV state from that to the 3^-, 6.130-MeV state prevents confirmation of the alpha-particle doorway states in the ^{12}C + ^{16}O system.

In the present work, the excitation functions for the alpha-transfer reaction, ^{12}C(^{16}O,^{12}C)^{16}O*, were investigated at the forward angle, first, by separately measuring the ^{12}C ions to the 0^+, 6.049-MeV and the 3^-, 6.130-MeV states. Four other transitions to the (2^+, 6.919-MeV), (1^-, 7.117-MeV), (4^+, 10.353-MeV), and (4^+, 11.095-MeV) states of ^{16}O were measured at the same time; secondly, the bombarding energies were chosen to be over a wider energy range and to be higher than those used in Ref. 7.

An $^{16}O^{6+}$ beam was delivered by the 12-UD Pelletron Tandem Accelerator at the University of Tsukuba. The outgoing $^{12}C^{6+}$ particles were momentum analyzed by an ESP-90 magnetic spectrograph[8] and detected with use of two silicon position-sensitive detectors placed in the focal plane. The overall energy resolution obtained for ^{12}C was about 70 keV for a self-supporting carbon target 29 $\mu g/cm^2$ thick, and was sufficient to separate the 0^+ and 3^- state of ^{16}O at reasonable counting rates. The excitation functions for the reaction $^{12}C(^{16}O, {}^{12}C)^{16}O^*$ feeding the four states (0^+, 3^-, 2^+, and 1^-) of ^{16}O were measured at $\theta_{lab} = 7.0°$ ($\theta_{c.m.} \sim 15°$), in steps of 0.2 MeV (86 keV in the c.m. system) from $E_{lab} = 53.0$ MeV to 77.0 MeV ($22.7 \leq E_{c.m.} \leq 33.0$ MeV) and the two 4^+ states from $E_{lab} = 62.0$ MeV to 77.0 MeV ($26.6 \leq E_{c.m.} \leq 33.0$ MeV). The excitation functions to the 0^+ and 3^- states are shown in Fig. 1.

Several interesting points are notable in the observed excitation functions. In the present Letter, the discussion will be confined to those resonances decaying to the 0^+, 6.049-MeV state (i) and to the 3^-, 6.130-MeV state (ii).

(i) *The 0^+, 6.049-MeV state.*—The most striking result is the observation of enhancement in the excitation function to the 0^+, 6.049-MeV state. Two doublets and a single peak are observed near 24.1, 27.6, and 32.2 MeV. Enhancement of the cross section by a factor of 2–5 above the constant (direct) cross section is clearly observed. Provided that this enhancement of the cross section is due to resonances, the resonances should have definite spins and parities. For the determination of the total spin, angular distributions were measured at the four bombarding energies inducated by arrows in Fig. 1. The six angular distributions for the 0^+, 6.049-MeV and the 3^-, 6.130-MeV states are shown in Fig. 2. The square of the Legendre polynomial, $|P_L(\cos\theta)|^2$, with definite spin ($L = J$), is drawn in the figure, with the correction for finite solid angle. From this fitting, the most probable spin values are found to be $J^\pi = 14^+$, 14^+, and 15^- for the resonances at $E_{c.m.} = 23.60$, 24.60, and 28.40, respectively. In addition, the similar analysis used by Shapira *et al.*[9] on the angular distributions for the 3^-, 6.130-MeV and 2^+, 6.919-MeV states supports these spin assignments. The preliminary angular distributions at $E_{c.m.} = 32.2$ MeV indicate the total spin to be $J^\pi = 16^+$. With these values

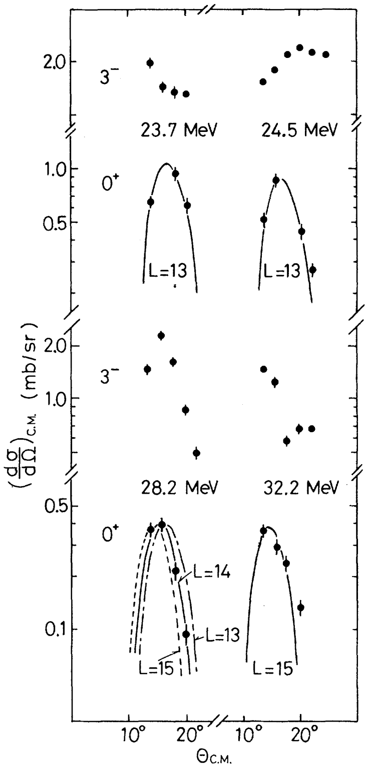

FIG. 1. Excitation functions for the 0^+, 6.049-MeV and the 3^-, 6.130-MeV states of ^{16}O measured at $\theta_{lab} = 7.0°$ ($\theta_{c.m.} \sim 15°$) in the reaction $^{12}C[^{16}O, {}^{12}C(g.s.)]^{16}O^*$. Four arrows show energies at which angular distributions are taken. The full line indicates the result for two-level resonance-formula analysis, and the dotted line indicates that for one-level resonance-formula analysis.

for the total spin, resonance parameters were extracted from the fit to the excitation function by means of the Breit-Wigner resonance formula. Obviously, the fit for the two-level formula is better than that for the one-level formula, since the destructive and constructive interferences in both tails and in the middle of two resonances are well described. This fact confirms that the resonances at $E_{c.m.} = 23.60$ and 24.60 and at $E_{c.m.} = 27.00$ and 28.40 MeV are, respectively, of the same total spin. The fits are shown in Fig. 1 and the resonance parameters thus extracted are summarized in Table I.

By comparing the 640–720-keV total widths to the 300-keV values for the resonances in the yield for the 3^- state, and by taking into account the fact that the 0^+, 6.049-MeV state in ^{16}O has a 4p-4h intrinsic configuration, these states can be assumed to be doorway states for alpha exchange. The observation of these intermediate resonances

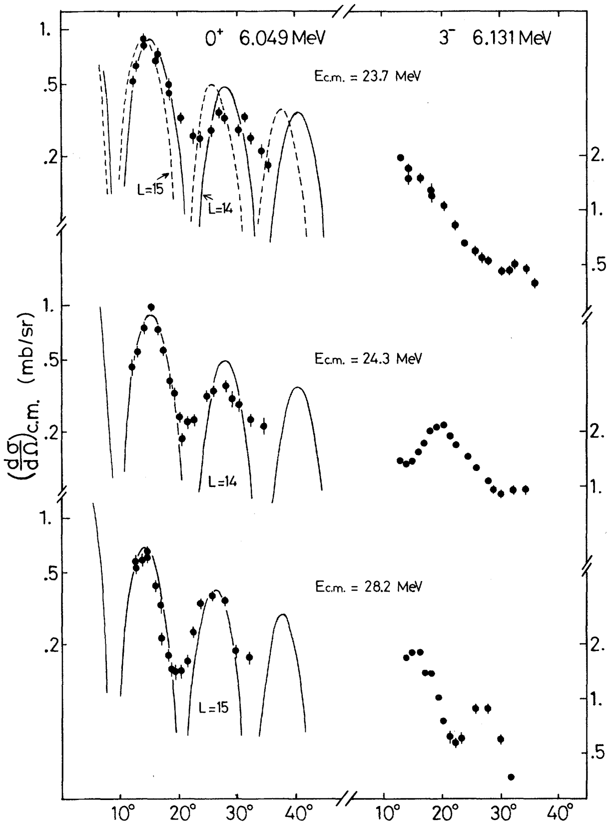

FIG. 2. Angular distributions for the 0^+, 6.049-MeV and the 3^-, 6.130-MeV states at $E_{\mathrm{c.m.}}=23.7$, 24.3, and 28.2 MeV. The square of the Legendre polynomial with difinite spin ($L=J$) is drawn for the 0^+, 6.049-MeV state.

decaying to the 0^+, 6.049-MeV state gives the first experimental evidence of the alpha exchange process predicted by Michaud and Vogt.[2] This enhancement of the yield for alpha exchange occurs at energies for which the relative angular momenta match.

TABLE I. Resonance energies, total spins, total widths, and products of elastic and inelastic partial widths. Resonance parameters were extracted from the fit shown in Fig. 1.

E_R (MeV)	J^π	Γ (keV)	$\Gamma_C\Gamma_{C'}$ [a] (keV)
23.60	14^+	640	1640
24.60	14^+	640	1680
27.00	(15^-)	680	480
28.40	15^-	680	1130
32.20	(16^+)	720	750

[a]See Ref. 2.

The trajectory in $E_{\mathrm{c.m.}}$ versus $J(J+1)$ is shown in Fig. 3, where resonances having larger and smaller $\Gamma_C\Gamma_{C'}$ are connected by a line. From this figure, one may deduce that two rotational bands with different moments of inertia, $\hbar^2/2\mathcal{I}=123$ and 113 keV, cross over near the resonance with $J^\pi=14^+$, or two bands with J-dependent moments of inertia approach each other and then separate.

Some anomalies in the excitation functions for the 2^+, 6.919-MeV and the 4^+, 10.353-MeV states (members of a deformed rotational band in ^{16}O) are also observed at excitation energies corresponding to those for the 0^+, 6.049-MeV state. More fragmentation of the magnitude of the resonance superposed on the continuous cross section appears to occur than for the 0^+, 6.049-MeV state.[11]

(ii) *The 3^-, 6.130-MeV state.*—Strong enhancement of the excitation function for the 3^-, 6.130-MeV state is observed at 25.2 and 29.8 MeV at energies different form those seen for the 0^+, 6.049-MeV state. The doublet near 25.2 MeV appears to be similar to the doublets at 20.0 and 22.5 MeV at $\theta_{\mathrm{c.m.}}=33°$ observed in Ref. 7. At higher energies, more fragmentation of the magnitude of the resonance is observed, although the magnitude of the resonance anomaly is localized within an energy region narrow relative to the energy interval between resonances.

Of several anomalies in the excitation function

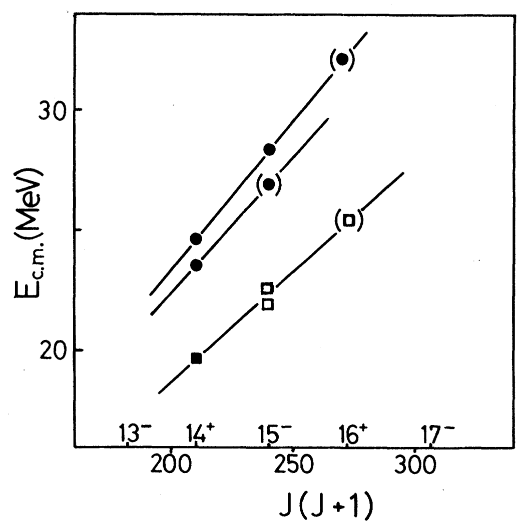

FIG. 3. Trajectory in $E_{\mathrm{c.m.}}$ vs $J(J+1)$. For the 0^+, 6.049-MeV state, the points are connected for the resonance energies with larger and smaller $\Gamma_C\Gamma_{C'}$. For the 3^-, 6.130-MeV state, the squares are shown, with the full square from Ref. 6, and open squares from Refs. 9 and 10.

for the ground state,[12] some anomalies appear to correspond to those in the excitation function for the 3^- state. This implies that the ^{12}C(g.s.) + ^{16}O (3^-, 6.130-MeV) inelastic channel can couple to the ^{12}C(g.s.) + ^{16}O(g.s.) elastic channel.

In fact, Matsuse *et al.* have performed coupled-channel calculations based on the band-crossing model.[13] They assumed that a rotational band composed of a potential resonance with $L = J - 3$ in the ^{16}O(3^-) inelastic channel crosses a rotational band of a potential resonance in the elastic channel at a total spin, J^π, of 14^+ and an $E_{\mathrm{c.m.}}$ of 19.7 MeV. The resonance energies and the resonance widths are fairly well reproduced in the energy region below 27 MeV.[14] For the excitation function of the 3^-, 6.130-MeV state, it is plausible that nuclear-molecular states are formed at c.m. energies of 20.0, 22.5, 25.2, and 29.8 MeV, with total spins, J^π, of 14^+, 15^-, 16^+, and 17^-, respectively. Recently, the spins of resonances at 22- and 25-MeV c.m. energies are assigned to be $J^\pi = 15^-$ (Ref. 9) and $J^\pi \geqslant 16^+$ (Ref. 10). Angular distributions taken by us at $E_{\mathrm{c.m.}} = 25.3$ MeV are also compatible with the statement that the spin around the 25-MeV c.m. energy resonance is $J^\pi \geqslant 16^+$.[10] These new data are plotted in Fig. 3 with the 14^+, 19.7-MeV resonance.[6] Thus, the rotational band associated with the ^{16}O(3^-) inelastic channel must be considered to form a different rotational band from that associated with the ^{16}O(0^+, 6.049 MeV) inelastic channel.

In summary, the coupling between the ^{12}C(g.s.) + ^{16}O(0^+, 6.049 MeV) and ^{12}C(g.s.) + ^{16}O(3^-, 6.130 MeV) inelastic channels appears to be weak, since the energies of resonances decaying to the 0^+, 6.049-MeV state do not correlate with those decaying to the 3^- state. However, the ^{12}C(g.s.) + ^{16}O(3^-) inelastic channel appears to be rather strongly coupled to the ^{12}C(g.s.) + ^{16}O(g.s.) elastic channel. As seen in Fig. 3, the alpha-particle exchange cross section via the alpha-particle doorway states in ^{28}Si appears to be enhanced at energies corresponding to $(\hbar^2/2\mathscr{I})J(J+1)$ and the maximum yield is attained at the energy for which the two bands cross over or pass with the minimum energy separation.

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Laser-Induced Two-Photon Blackbody Radiation in the Vacuum Ultraviolet

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We report experimental measurements on a new type of vacuum-ultraviolet radiation source. It is shown that the maximum source brightness, within its narrow linewidth, is that of a blackbody at the temperature T of a metastable storage level. The laser-induced emission at 569 Å from a He glow discharge corresponded to a metastable temperature of 22 700°K and was over 100 times brighter than the 584-Å He resonance line.

We report the first experimental observation of a vacuum-ultraviolet (VUV) or soft-x-ray source based on a new physical concept: that of a two-photon blackbody radiator.[1] Laser-induced spontaneous emission from atoms stored in a metastable level is used to produce a source with several unique properties: narrow linewidth, tunability, linear polarization, the potential for picosecond operation, and high peak spectral brightness. We experimentally demonstrate that the maximum brightness of this source, within its narrow linewidth, is that of a blackbody at the temperature T of the metastable level.

In these experiments, a glow discharge was used to store population in the $2s\,^1S$ level of He at 601 Å ($\cong 166\,272$ cm^{-1}) (Fig. 1). An incident mode-locked Nd:YAlG (yttrium aluminum garnet) pumping laser of wavelength 1.064 μm ($\cong 9395$ cm^{-1}) was focused into the discharge and narrow-band VUV radiation was observed at both the upper (anti-Stokes) sideband at 569 Å and at the lower sideband, 637 Å. The peak spectral brightness of the laser-induced emission was found to be over 100 times greater than that of the 584-Å He resonance line.

We note that laser-induced two-photon and anti-Stokes scattering in the VUV has previously been observed by Bräunlich and Lambropoulos.[2] In their experiments, a collimated atomic beam of deuterium metastables was used to generate upper- and lower-sideband radiation at 1090 and 1373 Å. Since both the metastable- and ground-state densities were very low, the emitted radiation was very weak, the medium was optically thin at the radiated frequencies, and the equilibrium considerations which we stress in this Letter do not apply.

The properties of this radiation source may be

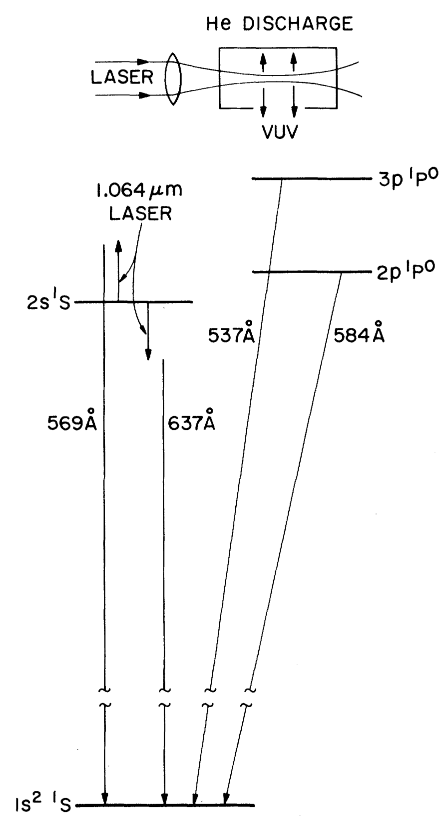

FIG. 1. Energy-level diagram for laser-induced emission in He.