methods.[7,12] Also shown in Fig. 2(a) is a solid line corresponding to the best fit of an exponential cross section to the data. The derived function has the form

$$Q = Q_0 \exp[(E - E_1)/E_0], \quad E > E_1,$$
$$Q = 0, \quad E < E_1, \tag{1}$$

where E_1, E_0, and Q_0 are constants. Equation (1) is plotted in Fig. 2(b), where a definite threshold corresponding to $E_1 = 0.1$ eV is indicated. A variety of other less accurate representations involving polynomials or combinations of polynomials with exponentials all suggest a sharp threshold in the vicinity of 0.1 eV.

The existence of a threshold for excitation transfer in an exothermic atom-atom reaction indicates the presence of a distinct repulsive barrier. The barrier appears to be nonobligatory[1,2] only in the sense that it is not essential for a smooth transition from the equilibrium He 2^3S potential curve to the final Ne $4s'[\frac{1}{2}]_1^0$, $4s'[\frac{1}{2}]_0^0$ potential curves. Since there is no known long-range resonance force acting between He 2^3S atoms and ground-state neon atoms, tentative indications are that the potential barrier is caused by intermediate- and short-range valence forces. More extensive studies concerning the physical origin of the repulsive forces are currently in progress.

*Work supported by the U. S. Atomic Energy Commission under Contract No. AT(11-1)-3073.

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Observation of a K X-Ray Band Emitted by the Transient C-C System Formed at keV Energies*

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(Received 14 December 1972)

The yield and high-energy limit (from 1.1 to 1.5 keV) of a K x-ray band emitted by the transient C-C collision system are reported for 19- to 240-keV carbon ions incident on graphite. This K x-ray band is interpreted as characteristic of the C-C system when the nuclear separation approaches the united-atom limit. A small yield of a similar band produced by other light ions in graphite has been observed; this can be accounted for in part by integrating the C-C yield over the appropriate energy distribution of recoil carbon atoms.

In this Letter, we report the observation of x rays that are produced in collisions of carbon ions with solid carbon. The x rays have a maximum energy comparable to K x rays in a united-atom limit. With increasing carbon ion energy, a large increase was observed in both the yield of x rays and the maximum energy of the x-ray band when the distance of closest approach in these collisions was less than the united-atom K-shell radius. In addition, a small yield of x rays was observed when graphite was bombarded with helium and lithium ions at 100 keV. An integration of the yield from symmetric C-C collisions over the energy distribution of recoil carbon atoms fully accounts for the observed yield with these light ions. However, with 100-keV boron ions incident upon graphite only 10% of the yield can be attributed to recoil events.

The observation of noncharacteristic x-ray bands in collisions of energetic heavy ions with solids has been reported recently by a number of authors.[1-3] These bands have been interpreted as the de-excitation of projectile L-shell vacancies that are promoted[4] in energy during an atomic collision. In this Letter we report similar results for K-shell promotion. In addition, the importance of recoiling target atoms in the yield of characteristic x rays in atomic collisions has been calculated by Taulbjerg and Sigmund,[5] and Saris[6] has pointed out that recoil events will be important in the production of quasimolecular x rays because of the larger yield produced in symmetric compared with asymmetric collision systems.

In the collisions of carbon ions in graphite at energies from 19 to 240 keV, x rays with energies greater than 500 eV have been detected in an 80-mm^2 Si(Li) detector with a resolution at 1 keV of 150 eV full width at half-maximum. A broad x-ray band having a maximum energy of from 1.1 to 1.5 keV was observed, and we attribute these x rays to decay of the transient C-C collision system. Characteristic x rays from surface contaminants cannot account for the band because of the broad spectral shape, and because analysis of x rays emitted by the pure graphite targets under proton bombardment limited the targets to less than a monolayer of sodium, silicon, and sulphur contaminants.

Sample x-ray spectra obtained with three different energies of carbon ions incident upon graphite are shown in Fig. 1(a). These spectra are relatively symmetric, but in our interpretation the x rays originate in a continuous spectrum of undetermined distribution, and hence selective absorption in the 0.025-mm Be window greatly accentuates the high-energy end of the x-ray band. The observed x-ray spectra were shifted to higher energy with increasing ion energy, and to normalize the number of x-ray counts taken in different runs, the E^{-3} energy dependence of the absorption coefficient[7] was used to reconstruct the spectra as shown in Fig. 1(b). Because the lowest-energy x rays give no significant information pertaining to the spectral distribution but just reflect the exponential factor used to correct for absorption, only the part of the spectra above 800 eV is shown in the reconstruction. The error bars shown in Fig. 1(b) indicate the statistical uncertainty of the data, but possible systematic errors from the absorption correction that apply to all spectra have not been indicated.

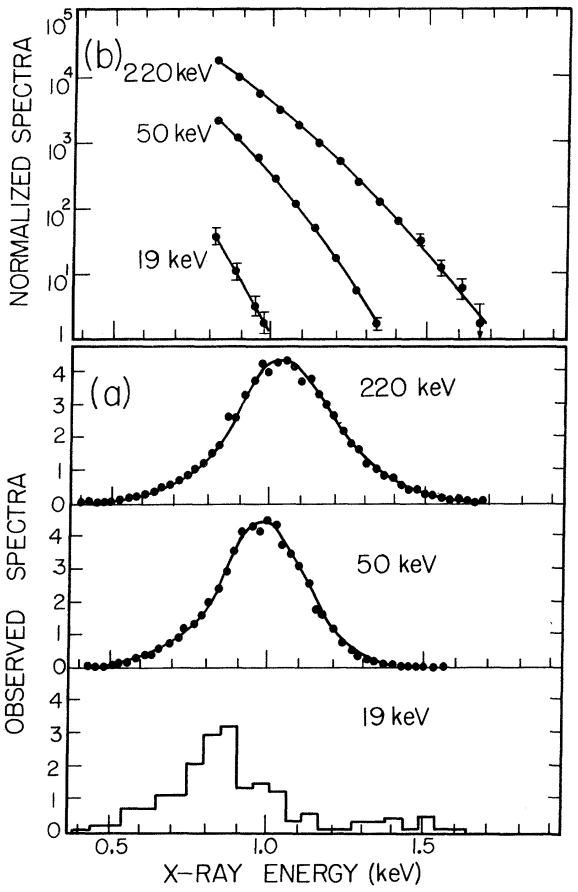

FIG. 1. (a) X-ray spectra observed when graphite was bombarded with 220-, 50-, and 19-keV carbon ions. (b) X-ray spectra reconstructed from the data using theoretical absorption coefficients and normalized to the same intensity scale.

The x-ray energy calibration of the detector system was determined in this energy interval from the characteristic K x rays of sodium, magnesium, and silicon produced by 100-keV proton bombardment.

On the basis of energetics, we interpret that the observed x-ray band originates with the de-excitation of a K-shell vacancy in a projectile carbon ion during a collision with a target carbon atom. The energy of the system containing such a vacancy is lowered during the collision because of the presence of the target nucleus within the K shell of the ion. The maximum energy of the x-ray band corresponds to transitions that occur near the distance of closest approach in the collision, and hence the K-shell energy level for the transient carbon-carbon system is mapped by the high-energy limit of the

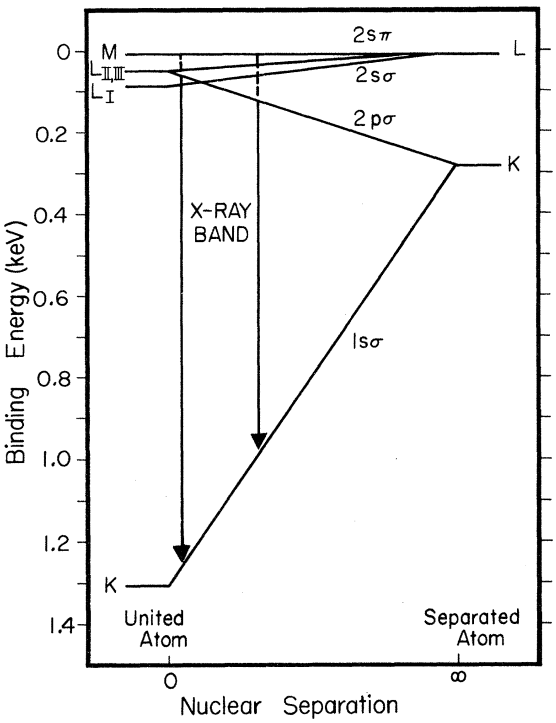

FIG. 2. Electronic energy level diagram for the C-C collision system with the transitions of the observed x-ray band illustrated.

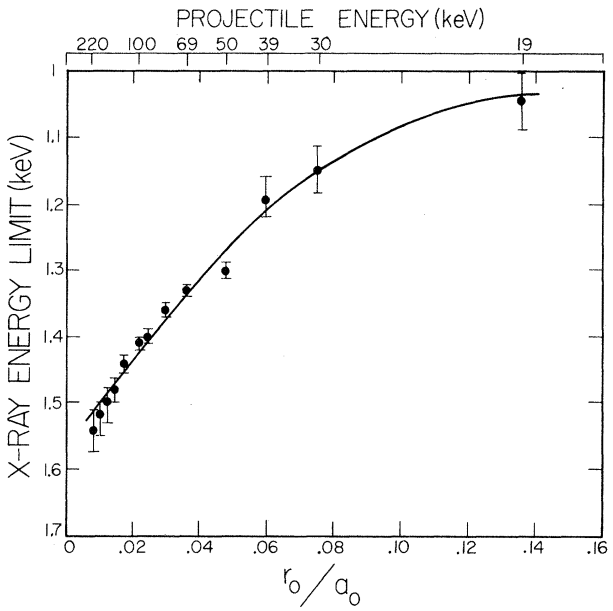

FIG. 3. High-energy limit of the x-ray band plotted against distance of closest approach in atomic units. The distance of closest approach was calculated using a screened Coulomb potential (Ref. 9). The carbon ion energy is shown on the top scale.

spectrum observed at each incident energy. This limit to the band was determined systematically from the observed spectra as that energy at which a smooth curve through the data had fallen to 3 times the average background. The average background ranged from 0.2 to 2 counts per channel in different runs and is assumed to originate from cosmic rays and radiation from radioactive contaminants in the apparatus. A random error of from 10 to 50 eV is inherent in this definition of the maximum energy of the spectrum, and a systematic error giving up to 100 eV too high a limit is possible since the detector resolution has been ignored in using this technique.

A correlation diagram relevant to the carbon-carbon atomic system is shown in Fig. 2, with the united-atom limit represented by the atomic energy levels of magnesium. The rapidly falling K levels of the system are expected to occur for distances of closest approach (r_0) less than the carbon K-shell radius of about 0.27 atomic units (a_0) and comparable to the magnesium K-shell radius of $0.13a_0$.[8] In Fig. 3 the maximum energy of the observed band is plotted as a function of the distance of closest approach that has been calculated using a screened Coulomb potential.[9] For convenience, the carbon-ion energy scale is shown at the top of Fig. 3. Clearly, the united-atom $K\alpha$ energy limit of 1.25 keV has been surpassed in these carbon-carbon collisions. Possibly, this reflects the existence of numerous L-shell vacancies in this highly distorted system. The portion of the K-shell energy structure given by the experimental data plotted in Fig. 3 represents the band of transitions indicated on the correlation diagram in Fig. 2.

The yield of x rays in this band is determined by the following factors: the cross section for the production of a K-shell vacancy in the projectile or recoil atom, the differential cross section for subsequent close encounters that lower the energy levels, the collision time, and the transition probability for the decay of the transient system. Although the total yield of x rays is uncertain because of the unknown spectral distribution at low energies, thick-target yields of x rays with energy greater than 820 eV have been estimated and are shown in Fig. 4. The low-energy cutoff was chosen because it permitted a comparison in all spectra of the number of x rays with energy greater than those observed near the centroid in the lowest-yield spectrum taken with 19-keV carbon ions. Since the absorption cor-

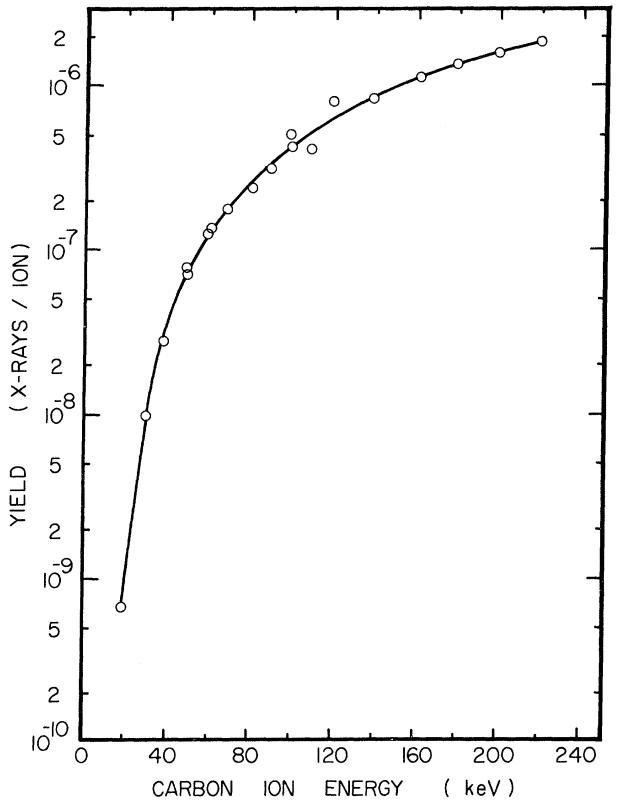

FIG. 4. The yield of x rays having energies above 820 eV plotted against the carbon ion energy.

rections have been made similarly to the data of all spectra, the relative error in the yield of these highest-energy x rays is small even though the absolute error in the yield may be more than an order of magntiude.

The rapid rise in yield of x rays (with energies greater than 820 eV) seen in Fig. 4 is associated with the rapid increase in nuclear penetration from 20 to 60 keV, while the more gradual rise at higher energy indicates that the yield is following the rise in K-shell ionization reported in C-C collisions.[10] These yields are 5×10^{-4} times the carbon K x-ray yields at 20 keV and rise to a constant 5×10^{-3} times the characteristic yield above 100 keV. Such a small branching ratio for the decay of a K-shell vacancy during a collision is consistent with the fact that the collision time (approximately 10^{-17} sec) is much less than the vacancy lifetime in the united-atom limit (approximately 10^{-14} sec).

In collisions of 100-keV B, Li, and He ions with the graphite targets, x rays with energies near 1 keV have been observed with progressively decreasing yields of 1.3×10^{-8}, 2.3×10^{-10}, and less than 10^{-11} x rays per ion, respectively. The contribution to these yields from energetic carbon atoms recoiling in graphite has been calculated by integrating the following equation:

$$Y(E)=N\int_0^R dx\int_{Q_0}^{Q_m}[d\sigma(E,Q)/dQ]\,y(Q)\,dQ,$$

where $y(Q)$ is the C-C yield at energy Q from Fig. 4, $d\sigma/dQ$ is the Rutherford differential cross section for energy transfer Q to a recoiling atom, Q_m is the maximum energy transfer, Q_0 is an appropriate lower limit, N is the number of target atoms per cubic centimeter, and R is the range of the primary ion. The results of this integration gave 1.7×10^{-9}, 2.1×10^{-10}, and 10^{-11} x rays per ion for B, Li, and He ions, respectively. Hence, the yield with He and Li on carbon is attributed completely to recoil events; however, only 13% of the boron yield can be accounted for in this manner. One would expect that the remainder of the yield was produced by a primary asymetric collision system.

We wish to acknowledge stimulating discussions with Frans Saris concerning many aspects of the molecular model used to describe energetic atomic collisions.

*Work partially supported by the U. S. Atomic Energy Commission under Contract No. AT(11-1)-2130.

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