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Quasimolecular K X Rays from Heavy-Ion Collisions*

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We report on a search for the production of quasimolecular K x rays with 30- to 90-MeV Br projectiles incident on targets with Z near 35. We disagree in some important aspects with previously published results from a similar experiment, and we show that the evidence for quasimolecular K x-ray emission from the Br + Br system is at present inconclusive.

The possibility, proposed by Greiner and coworkers,[1] of observing fundamental new processes in quantum electrodynamics has motivated a recent search for K x-ray transitions between the transient molecular orbitals (MO) formed during collisions of heavy ions with heavy atoms. An observation of such MO K x-rays was reported recently in a study of x-ray production from 30- to 60-MeV Br + Br collisions.[2] The identification of the K x-ray transitions in the quasiatom with $Z=70$, in this experiment, was based principally on two criteria which have been found to be characteristic features of the spectral distribution and the production cross section of MO x-ray emission in low-energy, light-ion–atom collisions[3]: (1) an enhancement in the x-ray production for symmetric projectile-target combinations, an enhancement predicted on the basis of electron promotion mechanisms[4] for inner-shell vacancy production; (2) a continuous spectrum, decreasing approximately exponentially with increasing energy, whose high-frequency limit can be identified roughly with the united-atom characteristic K x-ray energy. In this Letter we present the results of a search for the production of MO K x rays in quasiatoms with Z near 70. We disagree in some important aspects with the conclusions reached in Ref. 2, and in particular with the two criteria used for identifying the quasimolecular K x rays. We show that the evidence for the detection of K x-ray emission from the molecular orbitals in the Br + Br system is at present inconclusive.

The most convincing demonstrations of radiative transitions between molecular orbitals, and the best tests of the existing theories of MO x-ray emission, have come from studies of low-energy collisions on light-ion–atom systems.[3,5] The interpretation of experiments involving MO K x-ray emission from high-energy collisions of heavier ions with heavy atoms are presently more speculative. One of the principal difficulties in interpreting these measurements is that the available theories of inner-shell vacancy production in high-energy, heavy-ion–atom collisions are not sufficiently developed to permit prediction of the details of the spectral distribution and of the features of the production cross section such that these can be exploited as a guide for identifying MO K x-ray emission. Lacking a detailed theory it is unclear, therefore, whether those theories which are successful in describing MO x-ray production in low-energy collisions of light ions can be extrapolated for identification of MO K x rays from high-energy collisions of heavier ions. The interpretation of the latter measurement is further complicated by the possible similarity between the intensities and the spectral distributions of the MO K x rays and some of the competing backgrounds. Major backgrounds include bremsstrahlung from accelerated nuclei and electrons, and radiative capture of target electrons by the impinging ions.[6] Therefore, the identification of all processes whereby x rays may be produced during ion-atom collisions is a most important consideration in all such measurements.

In this investigation a detailed study of x-ray production was carried out as a function of projectile-target combination and projectile energy in order to isolate MO K x-ray production from some of the important background radiations. Targets of Al, KCl, Ni, KBr, and Zr were bombarded with 30-, 57-, and 90-MeV ^{79}Br beams. Both thick (~10 mg/cm^2) and thin (300–500 μg/cm^2) targets were used. The bromine and chlorine targets consisted of KBr and KCl, respectively, sandwiched between thin layers of Al; all other targets were self-supporting foils. The KCl and Al targets were employed to monitor backgrounds from the aluminum and potassium in the KBr targets. The Ni and Zr targets provided a comparison of asymmetric collisions with the symmetric Br + Br case. All the data were taken with a 5-mm-thick intrinsic Ge counter with a resolution of 250 eV at 6.4 keV; this represents a substantial improvement on the system resolution used in Ref. 2. The intrinsic efficiency of the x-ray detector was found to vary by less than 15% over the region of interest. The x rays were viewed at 90° to the beam direction. Precautions were taken to reduce pulse pileup to negligible proportions.

The results we obtained can be summarized and compared with those of Ref. 2 as follows: (1) A high-energy x-ray continuum, extending between the K x-ray energies of the separated and united atoms, was observed; its intensity and spectral distribution varied with projectile-target combination and projectile energy. However, for Br + Br collisions, the intensity of the high-energy continuum, relative to the characteristic K x rays, was smaller than that reported in Ref. 2 by more than 1 order of magnitude.[7] (2) It was shown that the bremsstrahlung background can contribute significantly to the observed high-energy continuum for particular projectile target combinations. (3) At the bombarding energies 57 and 90 MeV, *no* significant enhancement was observed for the symmetric collision combination of target and projectile over an asymmetric situation of approximately 5 a.u. This observation differs from one of the basic observations used to identify the MO K x rays in Ref. 2. (4) Because of the exponential spectrum of the continuum x rays, the determination of the high-energy limit of the spectrum is largely influenced by competing backgrounds and the statistical accuracy. In consequence, the identification of this limit is imprecise and cannot be used as a signature for a particular united atom. These observations are all evident from selected spectra shown in Fig. 1.

Although the use of different x-ray filters accentuates different aspects of the spectra, the general features of all spectra in Fig. 1 are alike. The distinctive hump in the vicinity of the characteristic x-ray lines has been associated in part with radiative capture, and with contributions from bremsstrahlung of tightly bound electrons.[6] The centroid of this distribution decreases in energy with a decrease in target atomic number. The principal feature of interest to the present discussion, however, is the high-energy continuum, extending from the vicinity of the hump up to approximately 50 keV, which was assigned by Meyerhof *et al.*[2] as being of quasimolecular origin. A calculation of nucleus-nucleus bremsstrahlung (solid curves in Fig. 1), averaged appropriately over the isotopic composition of each target, indicates that this type of bremsstrahlung contributes significantly to the observed high-energy continua for the KBr and Ni targets. It accounts almost entirely for a similar high-energy continuum observed with KCl and Al targets. We note, also, that its calculated shape is not very different from that of the observed spectra.
From a comparison of symmetric and asymmetric collision cases (Ni, KBr, and Zr), after subtraction was made for (a) nucleus-nucleus bremsstrahlung, (b) ambient room backgrounds, and (c) beam-induced background reflecting nuclear Coulomb excitation, it is apparent that the high-energy continuum is not very different in the three cases. A more detailed comparison of the spectra in the region between 20 and 50 keV [Figs. 1(d)–1(f)], after they have been corrected for the effects of absorber foils and for the slight variation of counter efficiency with x-ray energy, shows a distinct difference in the shapes of the high-energy continuum for the different targets, and a shift of the high-energy limit to larger values with increasing target Z. However, as mentioned above, the determination of the high-energy limits is only approximate due to the exponen-

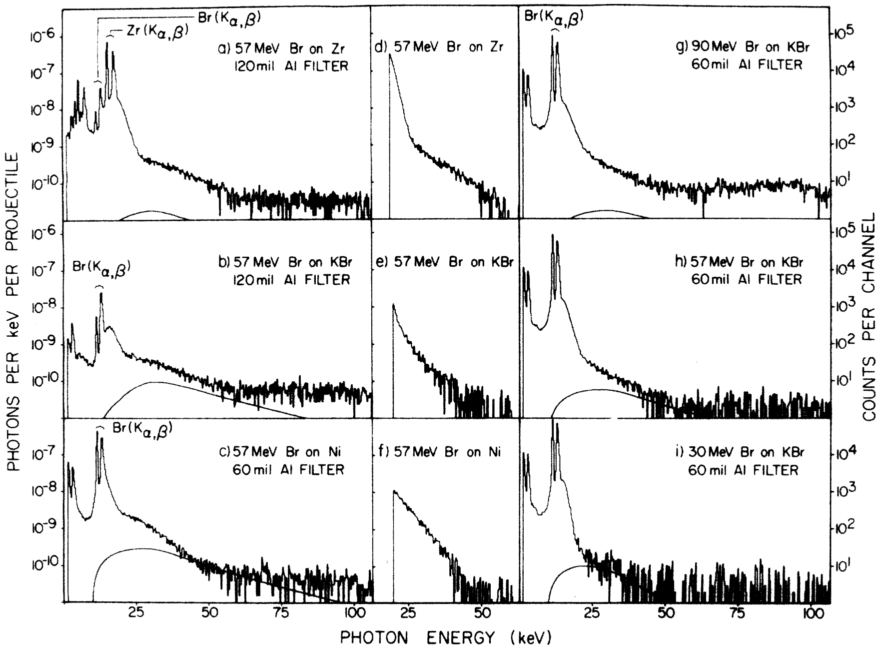

FIG. 1. X-ray spectra from various targets bombarded by Br ions as explained in text. For (a)–(f) use the left-hand scale, which is in absolute units; compare the symmetric Br + Br system with the asymmetric Br + Ni and Br + Zr systems. For (g)–(i) use the right-hand scale, which is normalized to the same yield of Br K x rays; these parts demonstrate the variation in the yield of the high-energy x-ray continuum with projectile energy.

tial character of the spectra and uncertainties in the normalization of the calculated nucleus-nucleus bremsstrahlung. Figures 1(g)–1(i), and additional data not shown, also show that there is an obvious increase of continuum x-ray yield, above the nuclear bremsstrahlung, relative to the K x-ray yield of the lower-Z partner as the projectile energy is raised.

Finally we note that the similarity of the results we obtained with thick and thin targets rules out the possibility that ion implantation can account for the close resemblance of all the spectra. The comparison of thin- and thick-target yields was also used to explore the possibility that very high equilibrium charge-state stripping in solids may unduly influence K-vacancy lifetimes which would be reflected as large differences in the MO x-ray production from thick and thin targets. No significant differences were found.

Although the data do not exclude the possibility that part of the high-energy continuum x rays observed may originate from quasimolecular x-ray production, it is clear that their identification, in the cases studied herein, cannot be based conclusively on an enhancement in yield for symmetric collisions nor on the approximate guide provided by the high-frequency spectral limit. It is evident that background processes play an important role in the interpretation of the data in experiments such as this one which accentuate the low-frequency components of the spectrum. The lack of a definite theory for the spectral shape further enhances the inconclusiveness of the interpretation, since there may exist yet unknown background processes.

It is particularly difficult to reconcile the lack of enhancement in symmetric collisions with a simple interpretation of an electric-promotion model, such as the two-step one suggested by Saris *et al.*[8] Single-step mechanisms have also been proposed.[2,9] It is clear that if what we were observing are truly quasimolecular K x rays, then we have to have large contributions from additional mechanisms. These may include two-step processes involving recoils as suggested by the Br + Ni data, since the Ni K-vacancy production exceeds the Br K-vacancy production by nearly an order of magnitude. The Zr data suggest significant contributions from K-vacancy sharing mechanisms as proposed by Meyerhof.[10]

It is evident that the relative importance of contributions from these and other mechanisms to MO K x-ray production in the high-energy collisions of heavy ions with heavy atoms must be worked out in detail before any final interpretation of the data can be made. This present Letter is directed at pointing out these uncertainties in the interpretation of the available data, and the need for such detailed calculations. Experiments which selectively emphasize the high-energy part of the spectrum would clearly make the identification of MO x rays more reliable.[5] Such measurements are in progress at our laboratory.

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[1] B. Müller, H. Peitz, J. Rafelski, and W. Greiner, Phys. Rev. Lett. 28, 1235 (1972), and Z. Phys. 257, 183 (1972).

[2] W. E. Meyerhof *et al.*, Phys. Rev. Lett. 30, 1279 (1973).

[3] J. R. MacDonald, M. D. Brown, and T. Chiao, Phys. Rev. Lett. 30, 471 (1973); also see other references given in this paper.

[4] U. Fano and W. Lichten, Phys. Rev. Lett. 14, 627 (1965); M. Barat and W. Lichten, Phys. Rev. A 6, 211 (1972).

[5] W. Lichten, to be published.

[6] P. Kienle *et al.*, Phys. Rev. Lett. 31, 1099 (1973).

[7] Because of the use of incorrect absorption factors, the yields reported in Ref. 2 have been lowered [W. E. Meyerhof, private communication; W. E. Meyerhof *et al.*, Phys. Rev. Lett. 32, 502(E) (1974)].

[8] F. W. Saris, W. F. van der Weg, H. Tawara, and R. Laubert, Phys. Rev. Lett. 28, 717 (1972).

[9] P. H. Mokler, H. J. Stein, and P. Armbruster, Phys. Rev. Lett. 29, 827 (1972).

[10] W. E. Meyerhof, Phys. Rev. Lett. 31, 1341 (1973), and private communication.

Calculation of Total Cross Sections for the Ionization of Atomic Hydrogen by Electron Impact Using the Glauber Approximation

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Total cross sections for the ionization of atomic hydrogen by electron impact are calculated using the Glauber approximation. These cross sections are compared with the results obtained by the Born approximation and with experimental results.

Calculations of atomic ionization by electron impact have found useful applications in analyzing the effects of radiation on a variety of materials. Most of these calculations[1] are based on the Born approximation for direct Coulomb ionization established by Bethe.[2] In this paper we apply the more rigorous Glauber approximation[3] to the ionization of atomic hydrogen by electron impact to compute the total cross section as a function of the energy of the incident electron.

The Glauber approximation has been derived[3-5] in a number of ways. Conceptually, it corresponds to a "rigorous" distorted-wave Born approximation which approximately includes multiple scattering and is approximately unitary. It is a member of the class of eikonal approximations where straight lines have been chosen as trajectories. With an appropriate choice of the projectile trajectory, the Glauber approximation reduces to the Born approximation at high energies.

There have been a number of applications[5] of the Glauber approximation to scattering processes in atomic physics involving transitions from bound atomic states to bound atomic states. In the case of atomic hydrogen, the mathematical technique introduced by Franco[6] and refined by Thomas and Gerjuoy[7] for bound-state transitions has been used by McGuire *et al.*[8] to derive expressions for excitation to continuum states, i.e., ionization.

For ionization from the ground state of hydrogen by electron impact, this scattering amplitude[8] is given by

$$f(q,\vec{\mathrm{k}}) = \left(\frac{8}{k}\right)^{1/2} \frac{ik_0}{(1-e^{-2\pi/k})^{1/2}} \sum_{l=0}^{\infty} \frac{(-2ik)^l}{(2l+1)!} \exp(-i\delta_l)\Big[\prod_{j=1}^{l}(j^2+k^{-2})\Big]^{1/2} \times \sum_{m=-l}^{l} Y_{lm}{}^*(\hat{k}) \sum_{n=0}^{\infty} A_n(l,k)(-k)^n \left.\frac{d^{n+1}I_{lm}}{d\lambda^{n+1}}\right|_{\lambda=1} = \sum_{l=0}^{\infty}\sum_{m=-l}^{l} f_{lm}(q,k)Y_{lm}{}^*(\hat{k}); \qquad (1)$$