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Doppler shift of continuum x rays from heavy-ion collisions*

W. E. Meyerhof and T. K. Saylor
Department of Physics, Stanford University, Stanford, California 94305

Robert Anholt
Lawrence Berkeley Laboratory, Berkeley, California 94720

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The continuum K x-ray spectrum from 200-MeV Kr + Zr has been found to undergo a Doppler shift with an effective Doppler velocity equal to $(0.92 \pm 0.03) v_{ci}$, where v_{ci} is equal to the center-of-mass velocity of the intermediate Kr + Zr molecule, corresponding to the incident projectile velocity. If the x rays are indeed generated by quasimolecular processes, the expected Doppler velocity is $0.90 v_{ci}$, taking into account the slowing down of the projectile in the target. The anisotropy of the continuum spectrum in the c.m. system is derived.

It is important to determine the Doppler shift of the continuum x rays from heavy-ion collisions for two reasons. (1) The Doppler velocity characterizes the radiating system independently of the details of the assumed production mechanism. In particular, if the radiation in a certain x-ray energy region is believed to originate from quasimolecular processes,[1,2] the Doppler velocity should be equal to the center-of-mass (c.m.) velocity v_c of the intermediate molecule. (2) In the interpretation of the laboratory (lab.) anisotropy of the continuum spectrum, which has recently been found,[3-6] it is important to know the Doppler velocity in order to compare the anisotropy with the theoretically predicted c.m. anisotropy.[2]

As long as only electric dipole x radiation is emitted, one can show that if the radiation is emitted in a quasimolecular interaction, the anisotropy must vary as $1 + A \sin^2\theta_{\text{c.m.}}$ in the c.m. system, where $\theta_{\text{c.m.}}$ is the angle between the x-ray photon and the incident particle direction.[2] The coefficient A depends on details of the x-ray emission process. Therefore, the intensity of the x-ray spectrum at a given c.m. x-ray energy must be symmetric about 90° c.m. In the lab. system an asymmetry about 90° lab. will appear because the x-ray energy, the x-ray angle, and the x-ray solid angle are each Doppler shifted. Using the lab. asymmetry about 90° lab., one can find the experimental Doppler velocity v_D by an iterative procedure, where the final result must produce symmetry in the c.m. system about 90° c.m.

In order to obtain a large Doppler shift, we chose a high projectile velocity v_1, which, nevertheless, would not be so high as to destroy the validity of the molecular-orbital model. This requires $v_1/v_K \lesssim 0.5$, where v_K is the K-electron Bohr velocity of the higher-Z collision partner.[7] Also, continuum backgrounds, in particular nucleus-nucleus bremsstrahlung,[8,9] had to be minimized, although at high bombarding energies it is not possible to avoid Compton background in the detector due to Coulomb-excited nuclear γ rays.[1]

To meet these conditions, we used a 200-MeV ^{84}Kr beam from the Lawrence Berkeley Laboratory Superhilac to bombard a Zr target just sufficiently thick to stop the beam. For this system $v_1/v_K = 0.27$, and nucleus-nucleus bremsstrahlung[10] is negligibly small compared to the observed spectrum (Fig. 1). The target, 4.5 mg/cm^2 thick, was placed at 22.5° with respect to the beam (see inset, Fig. 1) in order to equalize x-ray absorption effects in the target at the lab. angles at which measurements were made: −45°, −90°, 90°, and 135°. (The minus sign indicates measurements made towards the back of the target.) The wall of the target chamber was $\frac{1}{16}$-in.-thick aluminum. In order to sufficiently reduce the intensity of the lower-energy portion of the spectrum, including the characteristic Kr and Zr K x-ray lines, an additional $\frac{1}{8}$-in.-thick Al absorber was placed in front of the intrinsic Ge detector.

Each measured spectrum had a Compton background due to Coulomb excited γ rays from ^{84}Kr (0.88 MeV) and approximately ten times weaker, Zr (0.91 and 0.93 MeV). By normalizing the Compton distribution of the 0.85-MeV γ ray from radioactive ^{54}Mn to the Compton distribution from 200-MeV Kr + Zr, the latter was extrapolated under the continuum x-ray spectrum and was subtracted. At 70-keV x-ray energy the Compton and x-ray intensities were approximately equal, so that above 70-keV large systematic errors could affect our results.

All spectra were corrected for target and absorber attenuation, for the detection efficiency, and for deadtime effects. Furthermore, since

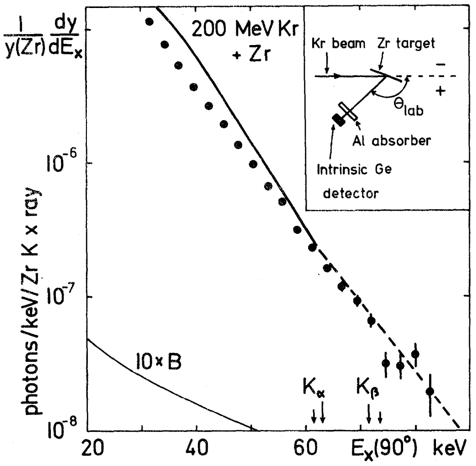

FIG. 1. Continuum x-ray spectrum from 200-MeV Kr + Zr collisions at $\theta_{lab} = 90°$. Only the part of the spectrum lying above the region normally assigned to radiative electron capture is shown. Compton background due to Kr and Zr Coulomb excited nuclear γ rays has been subtracted. Heavy solid and dashed lines represent absolute quasistatic (Ref. 1) and normalized line-broadened (Ref. 12) theoretical spectra, respectively. The curve labeled $10 \times B$ represents computed nucleus-nucleus bremsstrahlung spectrum (Ref. 10) multiplied by 10. Arrows give united-atom $K\alpha$ and $K\beta$ energies. Inset shows experimental arrangement.

the beam spot on the target was considerably spread out, each spectrum was normalized to the intensity of the Zr $K\beta$ line which had previously been shown to be isotropic to within a few percent.[5] The Zr $K\alpha$ line could not be used for this purpose, because at forward angles the Doppler shifted Kr $K\beta$ line moved under it.

Figure 1 shows a typical continuum spectrum (here normalized to the total Zr $K\alpha + K\beta$ x-ray intensity for the purpose of comparison with theory) at $\theta_{lab} = 90°$, lying above the region normally assigned to radiative electron capture.[11] The quasistatic theory proposed in Ref. 1 gives the solid line; the yield due to the one-collision process[1] is an order of magnitude more intense than the two-collision yield over most of the spectrum. Macek and Briggs have proposed a schematic model for the effect of line broadening[12]; the predicted curve, normalized to the quasistatic calculation near the united-atom $K\alpha$ x-ray energy, is shown as the dashed line in Fig. 1. The relatively good agreement between the theory of Ref. 1 and experiment is pleasing, considering the absence of adjustable parameters.

To indicate that the asymmetry measurement was not appreciably affected by systematic errors, we show in Fig. 2(a) the ratio R of the normalized −90° lab. to 90° lab. spectra as a function of lab x-ray energy. In Fig. 2(b) we give the ratio R of the −45° lab. to 135° lab. spectra. The asymmetry lies around 40%, so that even if the Zr $K\beta$ line is asymmetric by a few percent or if small systematic errors are present [Fig. 2(a)], this would not have an appreciable effect on the final results. Figure 2(c) gives the derived Doppler velocity v_D in units of the c.m. velocity v_{ci} of the intermediate molecule computed with the incident projectile velocity. In view of the possibility of systematic errors near the upper end of the spectra, no significance should be attached to the slight drop of v_D/v_{ci} near $E_X = 64$ keV. Greenberg[13] has pointed out that a small overall decrease in v_D might be expected if the two-collision production mechanism dominates (which is not the case here). For then, after the first collision in which the projectile receives a K vacancy, the projectile no longer travels along incident beam direction and x rays generated in the second collision have a Doppler shift determined by the direction and energy of the scattered projectile rather than the incident projectile.

The average value of v_D/v_{ci} obtained from Fig. 2(c) is 0.92 ± 0.03. Using the expected velocity

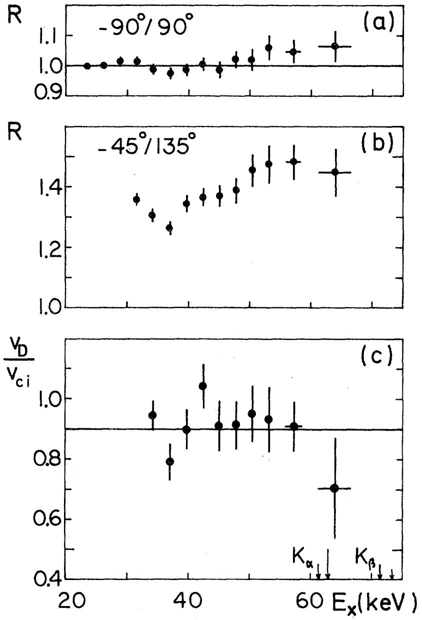

FIG. 2. (a) Ratio of normalized spectra at −90° and 90° lab. vs lab. x-ray energy. (b) Ratio of normalized spectra at −45° and 135° lab. vs lab. x-ray energy. (c) Doppler velocity in units of c.m. velocity of Kr + Zr quasimolecule computed with the incident projectile energy, vs c.m. x-ray energy. Slowing down of projectile in target gives a predicted value of $v_D/v_{ci} = 0.90$ shown by the horizontal line.

(v_1) dependence[1] of the one-collision production mechanism ($\sim v_1^{7.6}$) which depends mainly on the cross section for $1s\sigma$ vacancy production,[7] we have shown that the slowing down of the projectile in the target should produce an effective Doppler velocity given by $v_D/v_{ci} = 0.90$. Therefore, the observed Doppler shift is in agreement with that expected for radiation emitted by Kr + Zr quasimolecules. If the radiation were emitted from the projectile, one would expect v_D to be approximately twice as large as found. For radiation from the target, v_D would be approximately zero.

Having found the experimental Doppler velocity, one can now compute the anisotropy coefficient A of the c.m. differential cross section. The dependence of A on c.m. x-ray energy is shown in Fig. 3 by the open symbols. We have also reanalyzed our previous measurements[5] of 200-MeV Kr + Zr spectra measured at $\theta_{\text{lab}} = -10°$ and $-80°$ with a 8.3-mg/cm^2-thick Zr target placed at 45° to the beam. Using $v_D/v_{ci} = 0.92$ we find the results shown as solid symbols in Fig. 3, which have better statistical accuracy than the open symbols. The consistency between the two sets of data indicates that within experimental error v_D has been correctly determined. The peaking of the anisotropy coefficient A near the united atom limit has been found in other collision systems[3,4,6] and has been interpreted in terms of Coriolis-induced radiative transitions.[2] We believe the interpretation of the x-ray energy dependence of A must await reformulations of the theory[2] which incorporate line-broadening effects *ab initio*,[14] since the magnitude of A is very sensitive to the latter.[5] Without a complete theory, the relative importance of spontaneous and induced radiative transitions[2] cannot be judged.

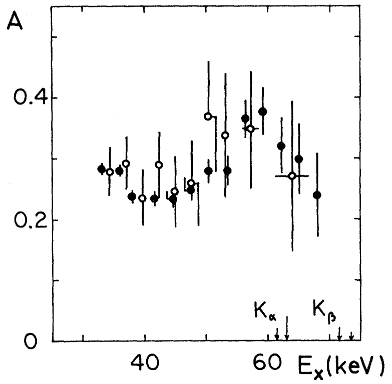

FIG. 3. Anisotropy coefficient A, assuming differential x-ray production cross section varies as $1 + A \sin^2\theta_{\text{c.m.}}$, vs c.m. x-ray energy. Open circles from −45°, −90°, 90°, and 135° measurements; solid circles from previous −10° and −80° measurements (Ref. 5).

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