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Nucleus-Nucleus Bremsstrahlung from Heavy-Ion Collisions*

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We present the first direct observation of nucleus-nucleus bremsstrahlung from heavy-ion collisions, and demonstrate the characteristic forward-backward emission asymmetry predicted for interfering dipole and quadrupole emission components. These studies indicate that both the intensity and angular distribution of nucleus-nucleus bremsstrahlung constitute important considerations in the quasimolecular spectroscopy of heavy collision systems.

The distinctive line and continuum x-ray spectra emitted during heavy-ion collisions have become important sources of information on different aspects of atomic collision phenomena and their associated spectroscopy. Whereas the prominent characteristic line spectra generally reflect the state of the isolated atomic species after the collision, the continuum spectra have been identified with a number of atomic and molecular radiative mechanisms associated, more directly, with the collision complex. One important source of continuum radiations is nucleus-nucleus bremsstrahlung (NNB)[1-4] arising from accelerated motion of the target and projectile produced by their mutual Coulomb interaction. In this paper we present the first direct observation of NNB in heavy-ion collisions under conditions where this component of the continuum spectrum has been effectively isolated from the other x-ray emission processes.

In addition to the intrinsic interest in this bremsstrahlung process involving heavy, highly charged particles, these measurements have been particularly motivated by the recent intense emphasis on investigations of the continuum radiations in connection with the search for the formation of superheavy quasimolecular systems in high-energy heavy-ion collisions. The relevance of NNB to the latter investigations has been pointed out by Davis and Greenberg.[5] Herein we demonstrate the predicted[2,3] coherent interference between the dipole and quadrupole components of NNB, and utilize the distinctive forward-backward emission asymmetry which it generates as a signature for the NNB process. In addition, studies of both symmetric and asymmetric collision systems substantiate absolute-cross-section calculations[6] and justify the approximations employed. The measurements further demonstrate that, for asymmetric systems, NNB can be a dominant contributing factor to the interesting high-energy region of the continuum near the vicinity of the united-atom K–x-ray limit of the combined quasiatom. Depending on the angle of observation, the influence of quadrupole NNB changes the intensity by almost a full order of magnitude compared to predictions based on dipole emission alone. Moreover, our observations also emphasize that even for symmetric collisions of systems with sufficiently high Z, where the dipole component of the bremsstrahlung radiation is absent, quadrupole NNB alone constitutes a large fraction of the x-ray intensity near the united-atom K–x-ray limit, and potentially can obscure the information which may be extracted on the quasimolecular K–x-ray spectroscopy of such systems.

Two principal aspects of NNB distinguish it from the other continuum x radiations. In the photon frequency region above the radiative-electron-capture peak, and particularly above the united atom K–x-ray limit, the NNB intensity distribution decreases much less rapidly with photon frequency than all the competing processes such as radiative electron capture,[7] radiative ionization,[7] secondary electron bremsstrahlung,[4,8] and molecular-orbital x rays,[7] growing in relative magnitude and dominating at the highest photon energies. Therefore with a proper choice of projectile-target combinations, NNB can be effectively differentiated from all these sources of continuum x rays by focusing on the region beyond the united-atom K–x-ray limit.

The other important distinguishing feature, already referred to above, is a characteristic and prominent forward-backward emission asymmetry[3,6] associated with NNB. This forward-backward asymmetry is evident from considering the multipole expansion of NNB radiation in a semiclassical approximation where the ion path is treated clasically.[2,3] Reinhardt, Soff, and Greiner[3] have shown that only the dipole and quadrupole components need be considered, with the higher multipoles contributing negligibly. The cross sections can be written in the following form:

$$\frac{d\sigma}{dE_x d\Omega} \propto \frac{Z_1^2 Z_2^2}{E_x \beta^2}\{D^2 W_{E1}(E,E_x,\theta) + \mu^2\beta^2 Q^2 W_{E2}(E,E_x,\theta) + 2\mu\beta D Q W_{E1E2}(E,E_x,\theta)\}, \quad (1)$$

where the factor $D = Z_1/A_1 - Z_2/A_2$ derives from the dipole moment $\vec{d} = \sum_\nu e_\nu \vec{r}_\nu$ when transformed to the center-of-mass system, and similarly $Q = Z_1/A_1^2 + Z_2/A_2^2$ is associated with the quadrupole moment. The quantities $W_{E1}(E, E_x, \theta)$, $W_{E2}(E, E_x, \theta)$, and $W_{E1E2}(E, E_x, \theta)$, respectively, represent the dipole, quadrupole, and dipole-quadrupole interference parts of the angular distribution at bombarding energy E, photon energy E_x, and emission angle θ; μ is the reduced mass and $\beta = v/c$ of the projectile. The quadrupole and dipole components of the intensity are each symmetric about 90°, and the dipole term is exactly zero for $Z_1 = Z_2$. The interfering amplitude from these two multipoles provides the source of the forward-backward asymmetry.

The target-projectile combination and the bombarding conditions were particularly chosen to demonstrate the above features. An illustrative example of spectra obtained in a single data run is shown in Fig. 1 for the system $^{18}O + ^{58}Ni$. In this case the radiations from sources other than NNB are confined to the region below approximately 30 keV. Above this energy, the intensity distribution is dominated by NNB. A calculation of the dipole, quadrupole, and interference-term components are indicated as the dashed, dotted, and dash-dotted lines, respectively. It becomes immediately evident from the 135° data that the dipole NNB intensity is too small to account for the measured intensity, but that an excellent fit to the data is obtained by the inclusion of the *constructive* interference between dipole and quadrupole components, even though the quadrupole contribution at 135° is about a factor of 4 weaker than the dipole term. The significance of the interference term is further emphasized by the ob-

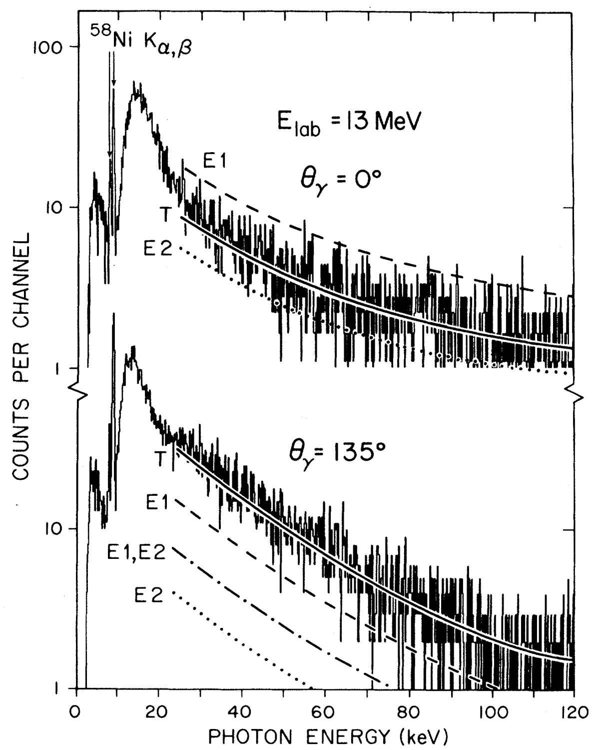

FIG. 1. Sample x-ray spectra for ^{18}O on ^{58}Ni at forward and backward angles obtained with an 0.4-cm^3 intrinsic germanium detector and 0.86-mm Al absorber. Absolute intensity calculations for the $E1$, $E2$, and E_1-$E2$ interference components are shown.

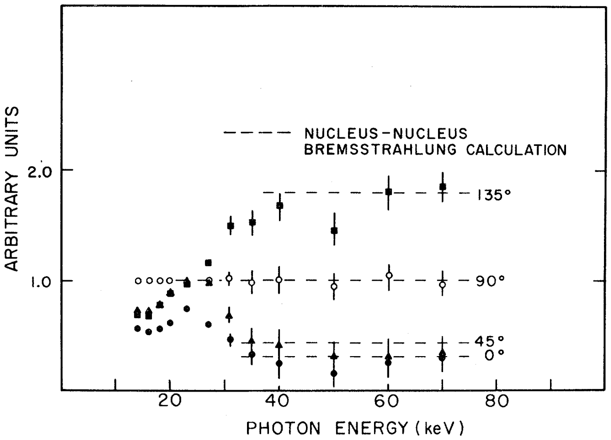

FIG. 2. Variation of the x-ray angular distribution with photon energy: $^{58}Ni + ^{12}C$, $E_{lab} = 60$ MeV. Relative intensities are normalized to the value at 90° of a Legendre polynomial fit of the angular distribution at each photon energy. Observation angles of 135° (solid squares), 90° (open circles), 45° (triangles), and 0° (solid circles) are compared with relative thick-target-yield calculations of NNB.

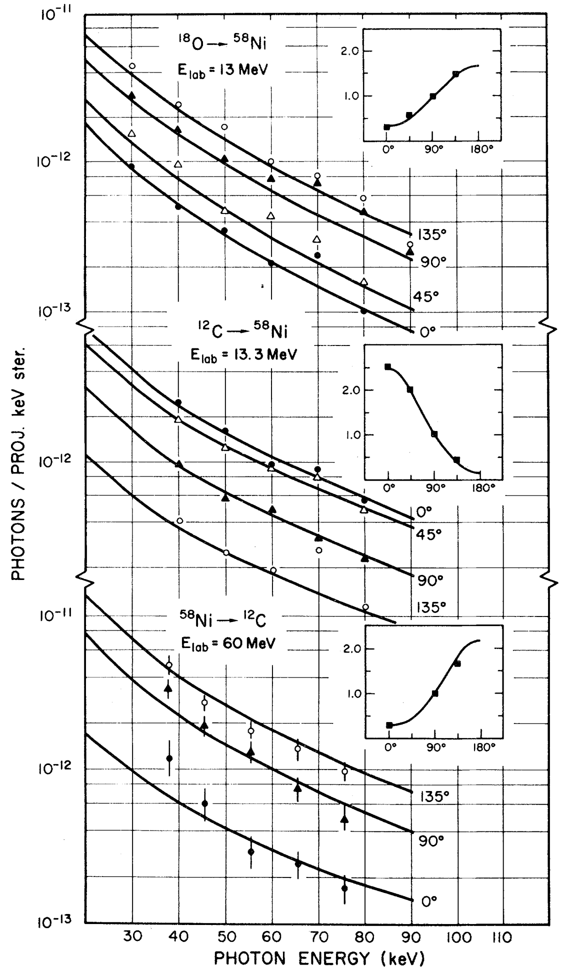

FIG. 3. Comparisons of calculated NNB absolute thick-target yields with x-ray intensities as a function of photon energy at four angles of observation. Each datum point represents an integration over a 10-keV photon energy interval. The statistical errors shown on the bottom graph are typical. The insets (vertical scale relative) show a comparison of the calculated angular distribution (solid lines) with data (squares) for the photon energy interval 40–60 keV.

servation that at 0° pure dipole emission now overestimates the measured intensity, but that in this case again an excellent fit to the data is obtained with *destructive* dipole-quadrupole interference, as predicted by the calculations[3,6] for forward angles. This expected characteristic behavior provides convincing evidence that the radiation is NNB related.

The influence of other sources of radiation is best illustrated by considering the angular distribution as a function of the photon energy, as is shown selectively for the system $^{58}Ni + ^{12}C$ in Fig. 2. The shift to symmetry about 90° for photons below ~25 keV is evident, as well as the transition to excellent agreement with expectations from NNB calculations above 40 keV.

The interchange of projectile and target also provides us with a further demonstration of the signature represented by the effect of the interference term. It is clear from Eq. (1) that making this interchange, as well as selectively changing the ratios Z/A for the projectile and target, can change the sign of the interference term. The examples chosen in Fig. 3 provide a convincing demonstration of this effect, while the comparisons of calculated absolute thick-target yields[6] with experimental yields at four angles show excellent agreement with photon energies above ~40 keV.

Examples of heavier systems investigated are shown in Fig. 4. From these studies it becomes evident that for asymmetric systems the higher-energy part of the spectrum essentially can be accounted for by NNB. For symmetric systems, although the quadrupole component of NNB is negligible for a combined Z of 56,[9] it alone is a very significant contributor to the continuum spectrum near the united-atom K-x-ray limit, for a quasiatom with $Z = 82$. Since the NNB grows as $\sim Z^4$ for symmetric collisions, and molecular-orbital (MO) radiation decreases rapidly with increasing Z, it is important to note that the NNB

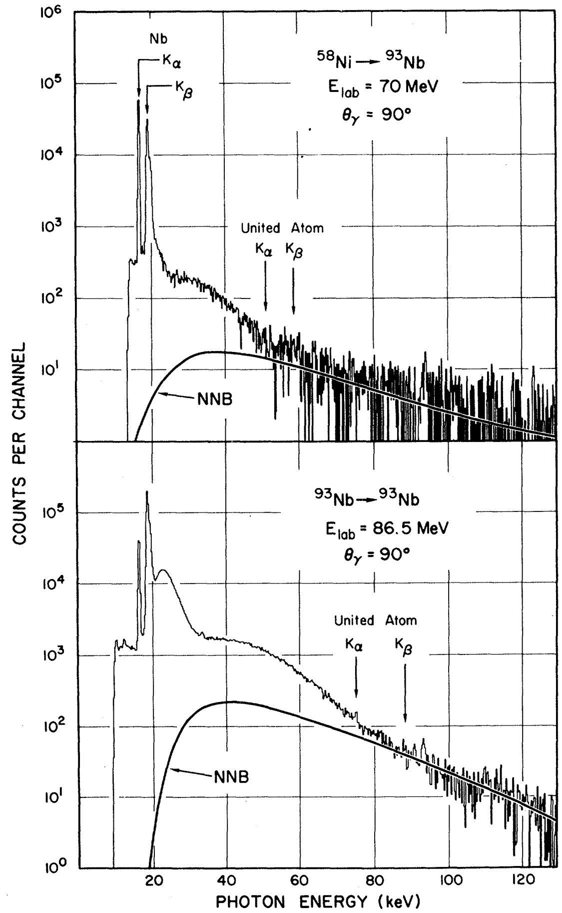

FIG. 4. Sample x-ray spectra for both symmetric and asymmetric systems with Z_1 and $Z_2 \geq 28$. NNB calculations, folded with detector efficiency and absorber effects, are shown as solid lines.

contribution has to be evaluated carefully in recent quasimolecular x-ray studies for united atoms with $Z \geq 100$.[10]

In summary, by isolating the NNB emissions from other competing continuum radiations, it has been demonstrated that semiclassical calculations, using a multipole expansion, reproduce the measured NNB cross sections and correctly predict the significant effects reflecting interference between the dominant dipole and quadrupole radiation components. With recent experiments[9,11] indicating that the peaked photon energy dependence of the emission anisotropy near the united-atom limit offers one of the more promising features for the development of a quasimolecular spectroscopy, it is especially relevant to point out the potential influence of the angular distribution of a prominent NNB intensity near the united-atom limit, especially for heavy systems, $Z_1 + Z_2 \geq 100$, where the NNB cross section can be comparable to or exceed the MO production cross section.

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