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High-energy gamma emission in heavy-ion collisions at 9-14 MeV/nucleon

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We have measured the cross sections for high-energy photon production in $^{12,13}C+^{92,100}Mo$ reactions at incident beam energies of 9-14 MeV/nucleon. The bombarding energy dependence, angular distribution, and projectile-target mass dependence of the photon yields at high energy, $E_\gamma \geq 30$ MeV, have been examined. Our measurements are consistent with production of these photons via nucleon-nucleon bremsstrahlung, the production mechanism dominant in heavy-ion collisions for $E/A \geq 20$ MeV/nucleon.

Although there has been extensive experimental[1-10] and theoretical[11-24] study of hard photon production in heavy-ion collisions for incident energies $E/A \geq 20$ MeV/nucleon, very little is known[25-29] about high-energy photon production at energies of 5-20 MeV/nucleon. Below $E/A \sim 5$ MeV/nucleon, the high-energy gamma emission process is dominated by the statistical decay of the giant dipole resonance built on excited nuclear states.[30,31] Above $E/A \sim 20$ MeV/nucleon, hard photon production in individual nucleon-nucleon collisions appears to dominate the high-energy gamma emission.[32] At intermediate energies, other production mechanisms, such as collective bremsstrahlung,[12,22] may become important. At $E/A \sim 10$ MeV/nucleon it has been suggested[28] that corrections to nucleon-nucleon bremsstrahlung due to differences in neutron and proton Fermi distributions or due to reaction Q values may be significant. In order to delineate the production mechanism for $E/A = 5-20$ MeV/nucleon, it is crucial to measure not only the γ-ray energy dependence of the high-energy photon cross section, but also the dependence on bombarding energy, projectile-target mass, and angle.

We present here results of a study of high-energy photon production in $^{12,13}C+^{92,100}Mo$ reactions at 9-14 MeV/nucleon. The observed yields for $E_\gamma \geq 30$ MeV are much larger than can be accounted for by statistical decay of the compound system. The results of our measurements of the angular distribution, energy dependence, and projectile-target mass dependence of the cross section are generally consistent with photon production via nucleon-nucleon bremsstrahlung.

Beams of $^{12,13}C$ ions of energies of 9-14 MeV/nucleon, produced in the University of Washington tandem-linac facility, were incident upon self-supporting, isotopically enriched foils of ^{92}Mo and ^{100}Mo of thicknesses 2-5 mg/cm^2. The target thicknesses and the absence of target impurities were measured in separate experiments. Gamma rays were detected in a 25-cm diameter by 37-cm long NaI scintillator equipped with a plastic anticoincidence shield and with passive lead, paraffin and ^{6}LiH shielding. Along with the energy deposited in the detector, the time-of-flight relative to the linac radio frequency for a 0.9-m flight path was recorded for each event. The time resolution for $E_\gamma > 15$ MeV was 1.0 nsec full width at half maximum providing excellent separation of neutron and gamma induced events. The gain of the NaI detector was measured using discrete lines from 2 to 22 MeV from the $p+^{11}B$ reaction at E_p=7.25 MeV and was stabilized during the run using a stabilized light emitting diode pulsing system. The detector response, including energy dependent line shape and efficiency, has been measured directly.

The high-energy photon yield measured at a laboratory angle of 90° from the reaction $^{12}C+^{92}Mo$ at 11 MeV/nucleon is shown in Fig. 1. The contribution to the spectrum from the statistical decay of the compound system has been calculated with a modified version of the code CASCADE,[33] including decay via the giant dipole and quadrupole resonances built on excited states. This contribution is shown as the solid curve in Fig. 1. The parameters for a Lorentzian form for the giant dipole resonance have been taken as 16.4 MeV, 12 MeV, and 1 classical dipole sum rule for the resonance energy, width, and strength, respectively. Above E_γ=25 MeV the measured yield exceeds that which can be accounted for by statistical decay. As can be seen in Fig. 1, above 30 MeV the statistical contribution to the high-energy photon yield becomes quite small compared to the data. If, in the statistical decay calculation, the photoabsorption cross section is taken as the observed form of the cross section for creation of a compound nucleus excited with the full energy of the absorbed photon[34] instead of a simple Lorentzian form for the giant dipole resonance, the effect is to increase the statistical decay yield by ~10-15% at E_γ=30 MeV. However, the effect is insufficient to account for the difference in the measured yield and the statistical calculation.

Figure 2 shows a comparision of the integrated photon yields for $\theta_{\rm lab} = 90°$ and $E_\gamma \geq 30$ MeV from the ^{12}C+^{92}Mo and ^{12}C+^{100}Mo reactions as a function of bombarding energy. One observes first, a very rapid increase in cross section with energy and second, that the yield for the ^{100}Mo target is consistently larger than that for the ^{92}Mo target at the same bombarding energy per nucleon. The weighted average ratio of the yields is $R = 1.55\pm0.12$ for ^{12}C+^{100}Mo compared to ^{12}C+^{92}Mo. The dashed curve in Fig. 2 represents the calculated contribution to the high energy photon yield of ^{12}C+^{100}Mo due to the statistical decay of the compound system and is negligible compared to the data. At high photon energy the statistical decay yield from ^{12}C+^{92}Mo is ~15-30 % lower than that from ^{12}C+^{100}Mo due principally to the lower Q-value for the reaction.

For bombarding energies above approximately 20 MeV/nucleon the predominant photon production mechanism is believed to be that of nucleon-nucleon bremsstrahlung,[32] hard photon production from individual nucleon-nucleon collisions in early stages of the heavy-ion collision. In the long wavelength limit dipole radiation dominates; however, in its center of mass the p-p system has no dipole moment. Therefore radiation from p-p collisions should be highly suppressed compared to that from n-p collisions. Thus the yield of high-energy photons is expected to scale roughly as the product of the average number of neutron-proton collisions,[8,12] $\langle N_{pn}\rangle$, and the total reaction cross section, $\sigma_R = \pi(1.2\text{ fm})^2(A_t^{1/3} + A_p^{1/3})^2$, where A_t and A_p are the target and projectile masses, respectively. The prediction of $\langle N_{pn}\rangle$ in the equal participant model is given in Ref. 12, and for the systems studied in the present work the fractional change in $\langle N_{pn}\rangle$ scales roughly as the fractional change in the number of nucleons in the projectile or target. For photon production via the nucleon-nucleon bremsstrahlung mechanism one would expect the ratio of the cross section for ^{12}C+^{100}Mo to that for ^{12}C+^{92}Mo to be approximately 1.1.

Another production mechanism that has been suggested is that of collective bremsstrahlung created by the mutual deceleration of the nuclei in the mean field. In asymmetric heavy-ion collisions as in the present work, one would expect the yield to scale roughly as the square of the $E1$ effective charge for the reaction, $\mu^2(Z_p/A_p - Z_t/A_t)^2$, where μ is the reduced mass of the system. Thus for ^{12}C+^{100}Mo one would expect a yield approximately 3 times larger than that for ^{12}C+^{92}Mo. Moreover, for ^{13}C induced reactions on the two Mo isotopes one can expect even larger differences in the yields, since the $E1$ effective charge for ^{13}C+^{92}Mo is nearly zero.

In Table I are listed $R_{\rm exp}$, the ratio of the integrated photon yields for $E_\gamma \geq 30$ MeV measured at 11 MeV/nucleon and at a laboratory angle of 90°, and $R_{\rm coll}$ and R_{NN}, the relative yields predicted for high-energy

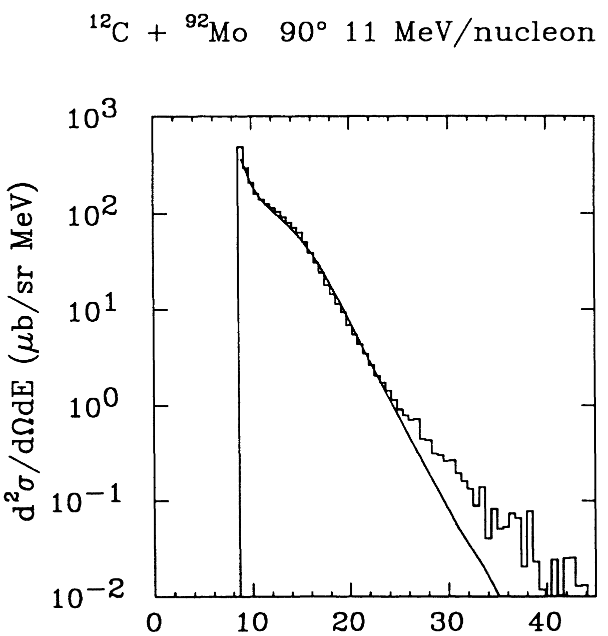

FIG. 1. High energy γ emission from the ^{12}C+^{92}Mo reaction at $E/A = 11$ MeV/nucleon measured at $\theta_{\rm lab} = 90°$ (histogram). The solid curve is a statistical model calculation including the effects of γ decay of the giant dipole and quadrupole resonances built on excited nuclear states.

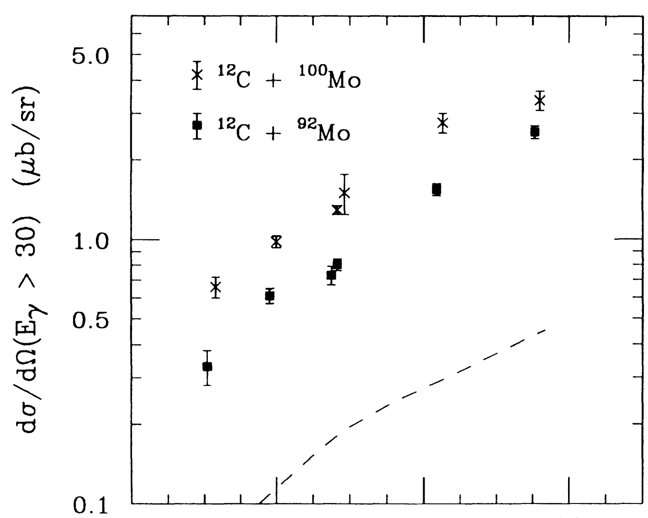

FIG. 2. Energy dependence of the high-energy photon yield for $E_\gamma \geq 30$ MeV for the ^{12}C+^{100}Mo (crosses) and ^{12}C+^{92}Mo (squares) reactions measured at $\theta_{\rm lab} = 90°$. The energy is in terms of the mean laboratory energy corrected for energy loss to the center of the target. The uncertainties in the cross section are statistical only and do not include systematic uncertainties estimated to be $\approx \pm15\%$. The contribution to the ^{12}C+^{100}Mo yield due to statistical decay of the compound system is shown as the dashed curve.

TABLE I. Relative photon yields for $E_\gamma \geq 30$ MeV for ^{12,13}C+^{92,100}Mo reactions measured at E/A = 11 MeV/nucleon and θ_{lab}=90° and predicted by collective $E1$ and nucleon-nucleon bremsstrahlung mechanisms.

	R_{exp}	R_{coll}	R_{NN}
^{12}C+^{100}Mo/^{12}C+^{92}Mo	1.49 ± 0.20	3.4	1.1
^{13}C+^{100}Mo/^{13}C+^{92}Mo	1.01 ± 0.21	69	1.1
^{13}C+^{100}Mo/^{12}C+^{100}Mo	0.96 ± 0.08	0.31	1.1
^{13}C+^{92}Mo/^{12}C+^{92}Mo	1.47 ± 0.12	0.01	1.1

photon production via collective and nucleon-nucleon bremsstrahlung mechanisms, respectively. The uncertainties for the measured ratios with common targets are much smaller than those with common projectiles due to cancellation of the uncertainties due to target thickness. One observes that the measured ratios of the yields are in reasonable agreement with the expectations for nucleon-nucleon bremsstrahlung with yield ratios near 1, and are clearly inconsistent with predictions for classical collective bremsstrahlung for which very large differences in the yields would be expected. The values listed for R_{coll} in Table I have been calculated assuming the cross section scales as the square of the $E1$ effective charge. Contributions due to quadrupole radiation may be significant, particularly for the ^{13}C+^{92}Mo reaction where the dipole effective charge is very small. However, no simple combination of collective dipole and quadrupole radiation, scaling as the squares of the $E1$ and $E2$ effective charges,

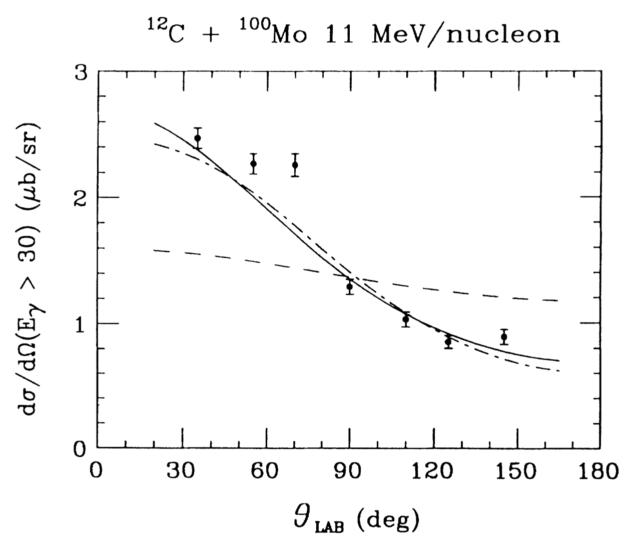

FIG. 3. Angular distribution of high-energy photons for $E_\gamma \geq 30$ MeV for ^{12}C+^{100}Mo at E/A = 11 MeV/nucleon. The error bars shown are the statistical uncertainties and do not include an overall normalization uncertainty of ±15%. The curves are the laboratory angular distributions calculated from fits to the measured γ-ray spectra as described in the text. Dashed curve: isotropic emission in frame moving with compound-nucleus velocity. Solid curve: isotropic emission in frame moving with best-fit velocity. Dot-dashed curve: emission with best-fit anisotropy and moving frame velocity.

reproduces the measured ratios in Table I. In addition, there is no direct correlation between the values for R_{exp} and R_{coll}.

We have also measured the angular distribution of the high-energy photons. The measured angular distribution for $E_\gamma \geq 30$ MeV from ^{12}C+^{100}Mo at E/A =11 MeV/nucleon is shown in Fig. 3. The relative shape of the angular distribution for ^{12}C+^{92}Mo is the same within statistical error. The similarity of the photon angular distributions for ^{12}C+^{100}Mo and ^{12}C+^{92}Mo provides additional evidence against the dominance of collective bremsstrahlung in these reactions for which the quadrupole contributions would be comparable but for which the dipole contributions would be quite different. We have fit the measured γ-ray spectra at each angle assuming an exponential spectrum shape with variable slope parameter E_0, assuming isotropic emission in the center-of-mass frame of an emitting system moving with velocity, β, and accounting for the Lorentz transformation from the emission frame to the laboratory frame. The angular distribution calculated from our best fit to the measured spectra for ^{12}C+^{100}Mo, from which we extract E_0=4.06±0.06 and β=0.073±0.002, is shown as a solid curve in Fig. 3. This value of β is in agreement with the value expected for photon production via nucleon-nucleon bremsstrahlung, that is, one-half of the beam velocity. In our case $\frac{1}{2}\beta_{beam}$=0.077. A fit to the ^{12}C+^{100}Mo spectra with β fixed at the compound nucleus velocity, β=0.016, is shown as a dashed curve in Fig. 3 and clearly does not reproduce the observed strong forward peaking. We have also fit the spectra assuming an angular distribution in the emitting frame of the form $(1 + \alpha \sin^2 \theta)$ and extract a value for α of 0.16±0.06 and values for E_0 and β in agreement with the best fit values above. The χ^2 for this fit is only slightly smaller than for the fit assuming isotropic emission, and the calculated angular distribution shown as the dot-dashed curve in Fig. 3 is visually not much superior.

Although as yet there have been no detailed theoretical predictions for the magnitude of the hard photon cross section for nucleon-nucleon bremsstrahlung in heavy-ion collisions at E/A <20 MeV/nucleon, comparision of the cross sections measured at low bombarding energies with those measured at higher energies may provide information about the photon production mechanism. When scaled as the number of first proton-neutron collisions[12,32] and as a function of $(E - V_c)/A$, where V_c is the Coulomb barrier for the reaction, our measured cross sections are in good agreement with the recent measurements[28] of C+Sn at 10.5 MeV/nucleon. Our results appear to be consistently slightly higher than the photon yields[27] for Kr+Zr, Ar+Ca, and Ar+Zr measured at 15 MeV/nucleon. However, due to the large uncertainties in that experiment, roughly ±50%, the difference is at the level of about one standard deviation and does not indicate clear disagreement. Our results appear to be significantly, roughly a factor of 6, higher than the extrapolation of higher-energy cross sections suggested in References 32 and 35 and also higher than measurements[29] of

TABLE II. Reaction Q values.

	Q value (MeV)[a]
$^{12}C+^{92}Mo$	−2.83
$^{13}C+^{92}Mo$	0.66
$^{12}C+^{100}Mo$	4.40
$^{13}C+^{100}Mo$	5.99

[a]See Ref. 36.

O+W at 15 MeV/nucleon. One explanation for the differences may be that the suggested scaling with projectile and target masses and with bombarding energy above the Coulomb barrier is not appropriate for describing hard photon yields at low bombarding energies. For example, at low bombarding energies hard photon production may become more sensitive to the effects of nuclear structure than at higher energies. It remains a challenge for nucleon-nucleon bremsstrahlung calculations to produce quantitative agreement with the extensive data set provided by the present work including absolute yields and yield ratios, angular distributions, and bombarding energy dependences of high-energy photon cross sections at low bombarding energies, $E/A < 20$ MeV/nucleon.

At E/A=10.5 MeV/nucleon Vojtech *et al.*[28] observed a difference in the high-energy photon yields for $^{12}C+^{112}Sn$ and $^{12}C+^{124}Sn$ reactions, which was larger but similar to the difference in yields for the $^{12}C+^{100}Mo$ and $^{12}C+^{92}Mo$ reactions studied in the present work. Vojtech *et al.* presented several speculations to account for their results including: (1) sensitivity to differences in neutron and proton Fermi momentum distributions, (2) existence of a neutron "skin" resulting in a higher yield for the ^{124}Sn target, and (3) sensitivity to differences in Q values. When one compares both ^{12}C and ^{13}C induced reactions on ^{92}Mo and ^{100}Mo, our results do not support simple arguments that targets with larger neutron excess have higher photon yields. In the present work there does not appear to be a straightforward correlation of photon yield with reaction Q value when the relative yields in Table I are compared with the reaction Q values in Table II. However, the differences in yields between $^{12}C+^{92}Mo$ and $^{12}C+^{100}Mo$ observed in Fig. 2 would be reduced, but not eliminated, if the yields were compared at the same $(E_{\text{c.m.}} + Q)/A$. Therefore based on our measurements we cannot draw a clear conclusion about the dependence of the high-energy photon yield on the reaction Q value. Future work measuring, in a fixed experimental configuration, the bombarding energy dependence of the high-energy photon cross sections from several reactions with largely different Q values might provide clarification of this issue.

In conclusion, the ratios of the measured yields and the angular distributions strongly suggest that the high-energy photon production mechanism in C+Mo reactions at $E/A = 9 - 14$ MeV/nucleon is that of nucleon-nucleon bremsstrahlung. The data are clearly inconsistent with an interpretation via a collective mechanism. The measured yields are far from scaling with the square of the dipole effective charge of the colliding system. In particular, the comparison of $^{13}C+^{100}Mo$ with $^{13}C+^{92}Mo$ shows nearly equal yields, while in the collective bremsstrahlung model the yield from $^{13}C+^{92}Mo$ would be suppressed by a very large factor. Instead, the measured data are in qualitative agreement with the simple nucleon-nucleon bremsstrahlung picture, with yield ratios near 1 as predicted, and with angular distributions consistent with nearly isotropic emission in a frame moving at the nucleon-nucleon center of mass velocity.

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