High energy photon production in low energy $^{12}$C + $^{112,124}$Sn collisions

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Photons with energies of 5–40 MeV have been measured in the $^{12}$C + $^{112,124}$Sn reactions at incident energies of 7.5 and 10.5 MeV/nucleon and at laboratory angles of 60°, 90°, and 120°. Statistical model calculations which describe the photon yields in the 5–20 MeV photon energy range cannot account for the relatively large yields measured at $E_\gamma > 20$ MeV. For these energies, the angular distribution suggests photon emission from a source moving at the nucleon-nucleon center-of-mass velocity. The magnitude of the nonstatistical photon yields is roughly consistent with a scaling relationship based on nucleon-nucleon bremsstrahlung. However, this does not account for the observation that the $^{124}$Sn yield is considerably larger than the $^{112}$Sn yield and suggests differences in the neutron-proton dynamics play a role in these low energy collisions.

High energy photon production in heavy-ion collisions has been studied vigorously at intermediate incident energies ($E_{\text{lab}} > 20$ MeV/nucleon). In general, the cross-section magnitudes and not-very-structured angular distributions are in accord with collisional models where the photons arise primarily from first chance proton-neutron collisions. For example, at a given incident energy per nucleon, the cross-sections scale with the reaction cross-section times the number of such first chance collisions as estimated in an “equal participant” model. At lower incident energies ($E_{\text{lab}} < 20$ MeV/nucleon), it is expected that collective mechanisms for photon production will become relatively more important because of increased Pauli blocking. We report here on photon cross sections in the $^{12}$C + $^{112,124}$Sn reactions at 7.5 and 10.5 MeV/nucleon. In this energy regime, target specific effects related to potential nucleus-nucleus bremsstrahlung or, for example, to differences in the neutron/proton distributions in configuration and/or momentum space might be manifest.

The experiment was performed using the Stony Brook superconducting linac. Beams of 90 and 127 MeV $^{12}$C ions were incident on enriched self-supporting foil targets of 82% $^{112}$Sn (2.8 mg/cm²) and 97% $^{124}$Sn (3.5 mg/cm²). A 25×38 cm NaI(Tl) crystal surrounded by a 10 cm thick plastic anticoincidence shield was used for the detection of $\gamma$ rays. This system, used in several studies of giant dipole resonances, has been described previously. Measurements were made with the front face of the detector at distances of 50 and 70 cm and at angles of 60°, 90°, and 120°. The overall time resolution of 2 ns (full width at half maximum) allowed gamma/neutron discrimination. Detector signals integrated over the first part of pulse and the full pulse were compared in order to alleviate pileup. The absolute normalization was obtained by comparison to the Rutherford cross section collected from two silicon surface-barrier detectors positioned at ±15° with respect to the beam axis. After the measurements, the targets were tested for $^{12}$C and $^{16}$O contamination by low energy deuteron activation. The $^{124}$Sn target was found to have 2% and 3% of $^{12}$C and $^{16}$O to Sn nuclei, respectively. For the $^{112}$Sn target, the percentages were 1% and 2%.

The $\gamma$-ray spectra measured at 90° are shown in Fig. 1 and exhibit features typical of heavy-ion induced reactions—a steeply falling yield of statistical decay $\gamma$ rays including a giant dipole resonance (GDR) bump. As the incident energy is increased from 7.5 to 10.5 MeV/nucleon, the yield of higher energy ($E_\gamma > 20$ MeV) photons increases rapidly for both $^{112,124}$Sn targets. At both energies, the yield of high energy photons from the $^{124}$Sn reaction is larger than the yield from $^{112}$Sn, opposite to what is observed in the GDR region. It is unlikely that $\gamma$ rays
from light contaminants contribute significantly to the yield. For example, the $^{12}$C+$^{12}$C reaction contributes less than 0.4% to the observed yields in this energy range, based upon the known $^{12}$C fraction in the target and a measured $^{12}$C+$^{12}$C $\gamma$-ray spectrum.

Since one expects a priori compound nucleus emission to be the principle source of $\gamma$ rays for energies up to and including the GDR region, statistical model predictions from CASCADE (Ref. 14) folded with the detector response are also shown in Fig. 1. These predictions were made using a set of parameters listed in Table I and include $\gamma$ decays via the GDR and the quasideuteron mechanisms. The quasideuteron contribution to the photoabsorption cross section was calculated as in Ref. 11 and has the same (to within 20%) strength as the contribution reported by Herrmann et al., in their recent study of high energy $\gamma$ rays in $^{92}$Mo+$^{92}$Mo reactions. For the present study, the quasideuteron enhances the total predicted statistical yield by only 20% at photon energies of $E_{\gamma}$~30 MeV. That this effect was found to be more significant in the work of Ref. 15 may be because the temperatures of the compound systems were much higher than in the present study. Although not included in the final calculations, contributions to the photon yields resulting from the isovector giant quadrupole resonance (IVGQR) built on excited states were also estimated. Using IVGQR strength functions with $E_{Q}$ = 130$A^{-1/3}$ MeV (Ref. 16), $\Gamma_{Q}$ = 8 MeV and $S$ = 100% classical sum rule would have increased the total predicted yield at $E_{\gamma}$ = 26 MeV, the centroid for the IVGQR, by 15%.

Although excellent statistical model fits to the data are achieved in the 5–20 MeV energy range without arbitrarily normalizing the predicted yield, there is a large excess yield at the higher energies. The lower $\gamma$-ray yield in the GDR region of the $^{124}$Sn target, relative to the $^{112}$Sn target, is associated with the greater neutron multiplicity.

The yields of nonstatistical photons, determined by first unfolding the detector response from the measured spectrum at $E_{\gamma}$ > 20 MeV and then subtracting the statistical model predictions, are shown in Fig. 2 for $^{112}$, $^{124}$Sn at 10.5 MeV/nucleon. The absolute yield of excess high energy $\gamma$ rays is somewhat uncertain because of the sensitivity to statistical model parameters, especially the level density parameter $a$. When the level density parameter is decreased, the predicted statistical yield of photons with $E_{\gamma}$ > 20 MeV increases. The best fits in the GDR region were found with $a$ = $A/9$ MeV$^{-1}$, in agreement with a value used in previous studies of giant resonances in this range of excitation. Calculations performed with $a$ less than $a$ = $A/10$ MeV$^{-1}$ or greater than $a$ = $A/8$ MeV$^{-1}$ resulted in unacceptable fits to the data in the 5–20 MeV energy range. The ratio of nonstatistical photon yields from the two targets in the energy range 20–40 MeV is $d\sigma_{^{124}Sn}/d\sigma_{^{112}Sn}$ = 1.8 for the set of statistical model parameters given in Table I. (If the level density parameter is decreased to $a$ = $A/10$ MeV$^{-1}$, this ratio increases to 2.5. If $a$ is increased to $a$ = $A/8$ MeV$^{-1}$, then the ratio decreases to 1.4.) Both data sets are characterized by a slope parameter of 4.1 ± 0.2 MeV.

As mentioned in the introduction, the relative importance of collective mechanisms of high energy photon pro-

![Graph](image-url)

**FIG. 1.** The $\gamma$-ray spectra from the $^{12}$C+$^{112,124}$Sn reactions at $E_{\text{lab}}$ = 7.5 and 10.5 MeV/nucleon and at a scattering angle of $\theta_{\text{lab}}$ = 90$^\circ$. The photon yields for the two targets represent the differential cross section $d^2\sigma/dE_d\Omega$ folded with the detector response. The smooth curves are the results of statistical model calculations discussed in the text.

**TABLE I.** Statistical model parameters used in calculations. $E^*$ is the excitation energy of the compound nucleus. $E_{\text{GDR}}$ and $\Gamma_{\text{GDR}}$ were determined in the fitting process.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$E_{\text{lab}}$ (MeV)</th>
<th>$E^*$ (MeV)</th>
<th>$\sigma_{\text{tot}}$ (mb)</th>
<th>$E_{\text{GDR}}$ (MeV)</th>
<th>$\Gamma_{\text{GDR}}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}$C+$^{112}$Sn</td>
<td>90</td>
<td>71</td>
<td>1450</td>
<td>15.0 ± 0.3</td>
<td>8.0 ± 0.4</td>
</tr>
<tr>
<td></td>
<td>127</td>
<td>105</td>
<td>1700</td>
<td>15.5 ± 0.3</td>
<td>8.5 ± 0.4</td>
</tr>
<tr>
<td>$^{12}$C+$^{124}$Sn</td>
<td>90</td>
<td>83</td>
<td>1550</td>
<td>14.9 ± 0.3</td>
<td>7.8 ± 0.4</td>
</tr>
<tr>
<td></td>
<td>127</td>
<td>116</td>
<td>1850</td>
<td>15.2 ± 0.3</td>
<td>8.3 ± 0.4</td>
</tr>
</tbody>
</table>
d^2 \sigma / dE d\Omega (\text{ab}/\text{MeV}^2\text{sr})

\begin{align*}
E_\gamma (\text{MeV}) & \quad 1000 \\
25 & \quad 100 \\
30 & \quad 10 \\
35 & \quad 1 \\
40 & \quad 1
\end{align*}

\text{FIG. 2.} The nonstatistical photon yield at 10.5 MeV/nucleon. The solid line passing through the \(^{112}\text{Sn}\) data points comes from the scaling relationship of Bertholet using a slope parameter of 4.1 MeV. The dotted line is the result of the potential field calculation of Nakayama and Bertsch for \(^{112}\text{Sn}\), the dashed line is the result for \(^{124}\text{Sn}\).

\text{FIG. 3.} The \(E_\gamma = 15\) and 32.5 MeV angular distributions from \(^{12}\text{C} + ^{112}\text{Sn}\) at \(E_{\text{lab}} = 10.5\) MeV/nucleon. The solid curves represent the isotropic emission of photons from the nucleon-nucleon center-of-mass system; the dashed curves represent isotropic emission from the nucleon-nucleon center-of-mass system. Both sets of curves are normalized to the data yield at 90°.

\begin{align*}
\sigma_\gamma & = \sigma_r N_{np} P_x, \\
\frac{d^2 \sigma}{dE_x d\Omega} & = \left( \frac{k}{E_0} \right) e^{-E_\gamma/E_0},
\end{align*}

where \(\sigma_r\) is the reaction cross section, \(N_{np}\) is the number of first chance neutron-proton collisions in an equal participant model, and \(P_x\) is the probability of photon emission per \(n-p\) collision. In this context, a wide body of measurements at incident energies greater or equal to 20 MeV/nucleon suggest a "universal" \(P_x\) factor given by

\text{production is expected}^{10} \text{ to increase as the incident energy per nucleon decreases. We show in Fig. 2 the predicted yields of photons generated by nucleus-nucleus bremsstrahlung in a potential field according to the model}^{10} \text{ of Nakayama and Bertsch. A pronounced target dependence is intrinsic to this approach, since the cross section is approximately proportional to the square of the effective dipole charge (}Z_p/A_p - Z_i/A_i\text{). The predicted cross section is much too small and the spectral shape is very different from that observed. The model predictions are only weakly sensitive to adjustments in its parameters (i.e., to variations in the optical potential)\(^{10}\); hence we conclude that such a description does not work for these data.}

\text{The laboratory photon cross sections for} \(^{112}\text{Sn}\) \text{measured at} 60°, 90°, \text{and} 120° \text{are shown in Fig. 3 for two} 5 \text{MeV bins centered at} 15 \text{(the GDR region)} \text{and} 32.5 \text{MeV. (The angular distribution data for the} ^{124}\text{Sn target is the same within statistics.) For comparison we show the laboratory angular distribution expected}^{4} \text{ for isotropic center-of-mass} \gamma \text{-ray emission of exponential shape from a source moving at the compound nucleus center-of-mass velocity} (\beta = 1.3%), \text{and at the nucleon-nucleon center-of-mass velocity} (\beta = 7.5%). \text{While this angular distribution information is sparse, the clear implication of the forward peaked distribution is that the mechanism responsible for high energy photons is not related to the overall center-of-mass system, but rather to the nucleon-nucleon system.}

\text{Because the potential field mechanism and the statistical models do not give the observed cross section, and because of the angular dependence, we consider the possibility that the photons arise from neutron-proton collisional bremsstrahlung, an important process at higher incident energies. First, we recall a scaling relationship of Bertholet et al.,}^{4} \text{ which is}

\text{where} \(\sigma_r\) \text{is the reaction cross section,} \(N_{np}\) \text{is the number of first chance neutron-proton collisions in an equal participant model, and} \(P_x\) \text{is the probability of photon emission per} n-p \text{collision. In this context, a wide body of measurements at incident energies greater or equal to 20 MeV/nucleon suggest a "universal"} \(P_x\) \text{ factor given by}

\text{Such pronounced target effects have not been discussed in the context of collisional models. One speculation is that the effects seen here signal an extreme sensitivity to differences in neutron and proton Fermi momentum dis-}
distributions at low incident energies. In order to illustrate simply this idea, displaced Fermi spheres relevant to the $^{12}$C+$^{124}$Sn collisions with relative velocity $v_{rel} = \sqrt{2(E - \gamma \nu_{col})/A}$ are drawn in Fig. 4. The nuclear Fermi momenta $k_F$ are taken from electron scattering measurements, with $k_F = 221$ and $260$ MeV/c for $^{12}$C and $^{118}$Sn, respectively. Separate neutron and proton radii are computed from the Fermi gas prescription, which assumes the neutrons and protons occupy the same volume in configuration space. In Fig. 4(a), a representative collision involving a target neutron with a projectile proton scattering to a Pauli-unblocked state after emitting a 30 MeV photon is shown for the $^{12}$C+$^{124}$Sn reaction. In this simplistic picture, high energy photon production is severely inhibited by Pauli blocking. In fact, as shown in Fig. 4(b), collisions between target protons and projectile neutrons cannot produce 30 MeV photons as long as the momentum distributions are sharp spheres. Because $^{118}$Sn has more nearly equal numbers of neutrons and protons, a similar picture would suggest a smaller region of phase space is available for photon production.

A speculation in a somewhat opposing direction is that the larger yield of photons in $^{124}$Sn is due to the existence of a neutron “skin.” Depending on the dynamics of the initial phases of the collisions, a larger effective dipole charge than that of the entire nucleus-nucleus system might exist which could enhance photon production. Clearly, detailed calculations, such as those done by Bauer et al. or Cassing et al., but where neutron-proton distribution differences are taken into account, are needed to establish whether the collisional mechanism approach can describe quantitatively these low energy phenomena.

Differences in $Q$ values for the two reactions may be important. As an example, in the context of the statistical model, the excitation energy ($E^*$) of the compound nucleus $^{136}$Ba is about 10% higher than $^{124}$Ba (Table I). The code CASCADE (Ref. 14) predicts the yields of higher energy photons ($E_\gamma \geq 10$ MeV) to increase with $E^*$. It is the lower neutron separation energies associated with the $^{124}$Sn reaction that make the calculated photon yield smaller than that of the $^{118}$Sn reaction, as indicated in Fig. 1. In realistic collisional models, $Q$-value differences would affect the simple phase space argument illustrated in Fig. 4.

The results reported here expand upon the studies of high energy photon production by Snover in this incident energy regime. Further experiments which study these target effects as functions of bombarding energy and projectile-target combination are needed to elucidate the mechanisms for generating high energy photons in low-energy collisions. It would also be interesting to search for isotope effects at higher bombarding energies.

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