Search for photons from the decay of the delta resonance in heavy-ion collisions

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Results are presented from a search for high-energy gamma rays ($E_\gamma > 140$ MeV) resulting from the decay of the delta resonance produced in heavy-ion collisions. The energy spectrum of gamma rays in the energy range $15 < E_\gamma < 180$ MeV was measured at a laboratory angle of 90° for the reaction ^{14}N+Zn. The incident beam energy was $E/A = 75$ MeV. The energy spectrum in the region $50 < E_\gamma < 180$ MeV is exponential with an inverse slope parameter of 26 MeV. There is no indication of an enhancement in the spectrum above 140 MeV due to the decay of the delta resonance.

Since the discovery in 1985 of the process of high-energy photon ($E_\gamma > 20$ MeV) production in heavy-ion collisions by Beard *et al.*[1] and by Grosse *et al.*[2] the process has been the subject of much experimental[3–13] and theoretical work.[14–22] Although a wide variety of calculations have been proposed to explain high-energy photon production in heavy-ion collisions, the mechanism which explains the data best is proton-neutron bremsstrahlung in individual nucleon-nucleon collisions within the heavy-ion collision. This mechanism was originally proposed by Nifenecker and Bondorf.[15]

Recently Prakash *et al.*[22] suggested that the photon emission cross sections in heavy-ion collisions could be calculated from measured photoabsorption cross sections using the principle of detailed balance. There are several difficulties with this approach. For example, photon emission in heavy-ion reactions occurs in highly excited nuclei; however, photoabsorption measurements are made on target nuclei in their ground state. In addition, the calculations must assume that statistical equilibrium is achieved in reactions with roughly 1 GeV of available energy. In the calculation the photoabsorption cross section is broken into three energy regions: (i) $E_\gamma < 40$ MeV, the giant resonance region, (ii) $40 < E_\gamma < 140$ MeV, the quasideuteron region, and (iii) $E_\gamma > 140$ MeV, the delta resonance region. Prakash *et al.* predicted that the gamma ray spectrum should have a "shoulder" starting at $E_\gamma = 140$ MeV due to the decay of the delta resonance. At gamma ray energies of roughly 200 MeV the cross section should be enhanced by a factor of 10 over the quasideuteron contribution.

Although there have been many measurements of high-energy gamma rays for a wide variety of heavy-ion reactions few have extended to sufficiently high energies to observe the delta resonance contribution to the spectrum. Previous measurements which could have seen the delta resonance enhancement, $E/A = 84$ MeV C+C by Grosse *et al.*,[6] and $E/A = 84$ MeV Ar+Al by Kwato Njock *et al.*,[23] show no evidence of such an enhancement. These experiments were performed with detectors with modest resolution (FWHM $\geq 20\%$ at $E_\gamma = 100$ MeV) for which it is not clear that a delta enhancement would be resolved. In this paper we present the first high resolution measurement (FWHM $\leq 10\%$) of the photon spectra up to 180 MeV gamma ray energy from intermediate-energy heavy-ion induced reactions. The reaction studied was ^{14}N+Zn at $E/A = 75$ MeV.

The high-energy gamma ray spectrum was measured at a laboratory angle of 90° using a cylindrical 12.7 cm by 22.9 cm barium fluoride detector. The detector was collimated with a 15.2 cm thick lead collimator with an inside diameter of 10.2 cm. Charged particles and neutrons were suppressed by placing a 20 cm thick nylon plug in front of the collimator. This plug has been measured to attenuate high-energy gamma rays by approximately 20%. The barium fluoride detector was operated at a distance of 75 cm from the target and was surrounded by a 2.5 cm thick plastic scintillator anticoincidence shield, which was used to reject cosmic ray background events. Fast neutrons were separated from high-energy photons on the basis of their time of flight measured relative to the cyclotron rf. Two time-of-flight spectra are shown in Fig. 1, one for an energy cut of $E_\gamma > 50$ and the other for $E_\gamma > 100$ MeV. The time resolution is roughly 1.0 ns for all energies and is limited by the rf pulse width of the K1200. Neutrons and gamma rays are, however, clearly separated at all gamma ray energies.

The measured gamma ray energy spectrum is shown in Fig. 2. The energy scale was calibrated by two methods. First, the gamma decay of the 15.1 MeV state of ^{12}C was observed using the reaction ^{14}N+C at $E/A = 75$ MeV. In addition, the light output from cosmic ray muons passing along the diameter of the crystal was measured using scintillators above and below the crystal as a simple telescope. This was done during the run and later shown in a calibration with tagged photons to correspond to an energy deposition of 83 MeV. The detector response was measured with tagged photons at the Saskatchewan Accelerator Laboratory over the energy range $80 < E_\gamma < 200$ MeV. The response functions were also compared to

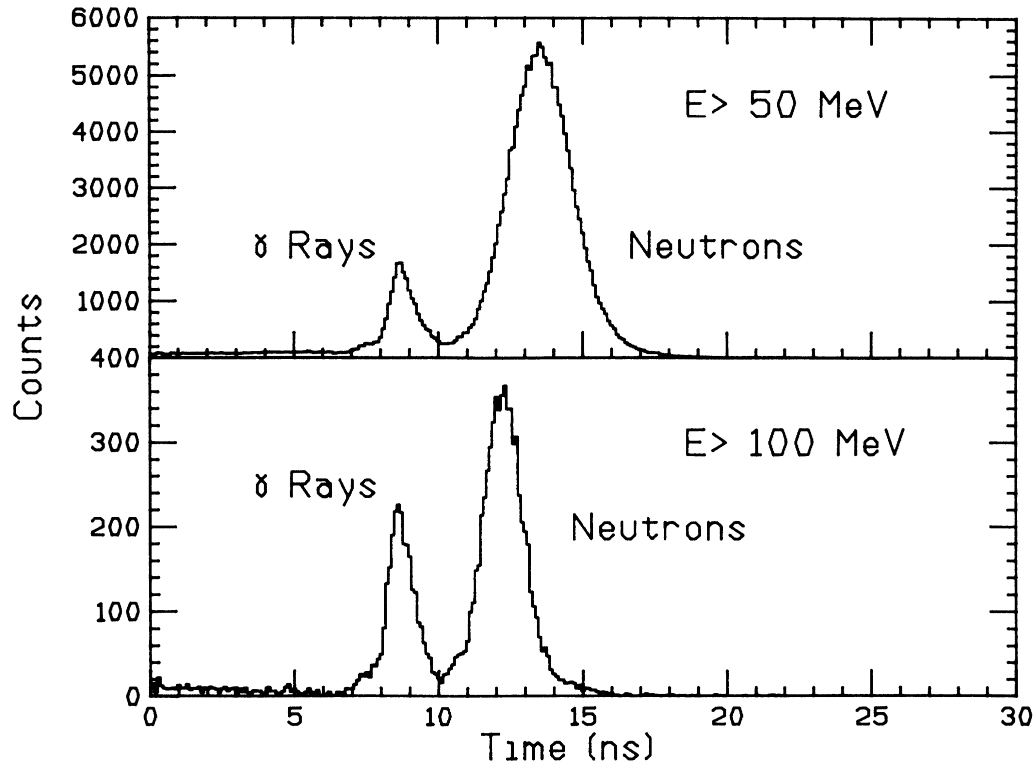

FIG. 1. Time-of-flight spectra for events with equivalent gamma ray energy greater than 50 MeV (upper), and greater than 100 MeV (lower).

simulations of the detector with the electron-gamma shower code EGS4 (Ref. 24) and were found to be in good agreement. The most important feature of the detector response function is an energy dependent downwards shift of the peak of the response function $\Delta E(E_\gamma)$ due to incomplete containment of the electromagnetic shower in

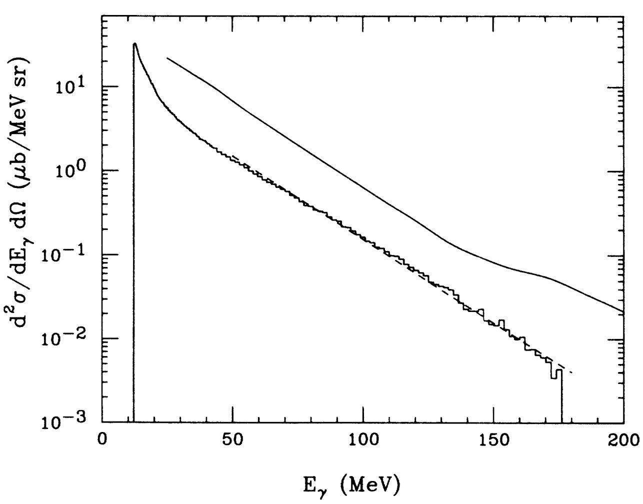

FIG. 2. The histogram is the gamma ray spectrum measured in this experiment for the reaction ^{14}N+Zn at $E/A=75$ MeV. The solid curve is the calculation of Prakash *et al.* (Ref. 22) for the reaction $E/A=95$ MeV ^{16}O+^{58}Ni. The shoulder in the calculated spectrum for gamma rays $E_\gamma \geq 140$ MeV is due to photon decay of the delta resonance. The dashed curve is an exponential drawn through the data.

the crystal. The shift is negligible for gamma ray energies below 50 MeV but is $\Delta E=6$ MeV at $E_\gamma=100$ MeV, and $\Delta E=23$ MeV at $E_\gamma=200$ MeV. The spectrum in Fig. 2 has been corrected for this energy dependent shift in the detector response. The correction procedure was checked by convoluting the corrected spectrum with the detector response function and checking that it reproduced the raw energy deposition spectrum.

Figure 2 compares the measured gamma ray spectrum to a calculation by Prakash *et al.* for a similar reaction, ^{16}O+Ni at $E/A=95$ MeV. The enhancement of the cross section for gamma rays above 140 MeV due to the delta resonance is clearly seen in the calculation but is not present in the data. Although the calculation of Prakash *et al.* also overpredicts the cross section for gamma rays below 140 MeV by roughly a factor of 3, most of this can be accounted for by the higher beam energy ($E/A=95$ MeV) used in the calculation compared to the experiment ($E/A=75$ MeV). Prakash *et al.* show that the enhancement above 140 MeV is not very beam energy dependent so the lower energy of the present data does not explain the missing strength.

Bauer and Bertsch[25] have recently included excitation of the delta resonance within their Boltzmann-Uehling-Uhlenbeck (BUU) transport calculations. This allowed them to predict the cross sections for pion production, and high-energy gamma ray production from both proton-neutron bremsstrahlung and decay of the delta resonance. Bauer[26] first used the modified BUU calculation to calculate neutral pion production cross sections in the reaction ^{12}C+^{12}C at beam energies ranging from

$E/A=60$ to $E/A=84$ MeV/nucleon. He compared them with the measurements of Noll *et al.*,[27] and found that the calculation reproduced both the shape of the measured pion spectra, and the magnitude of the cross sections. Bauer and Bertsch have calculated the production cross sections for high-energy gamma rays for the reaction, $E/A=75$ MeV $^{12}C+C$, with three different mechanisms: proton-neutron bremsstrahlung, gammas from neutral pion decay $\Delta \rightarrow \pi^0 + N \rightarrow \gamma + \gamma$, and gammas from the direct decay of the delta $\Delta \rightarrow \gamma + N$. The branching ratio for the direct decay of the delta was taken as the free value of 0.6%. Figure 3 shows the relative contributions from the three processes for the reaction $^{12}C+^{12}C$ at $E/A=75$ MeV for gamma rays at 90° in the laboratory. The results of the BUU calculation show that for gamma rays with energies below 70 MeV the dominant process is bremsstrahlung. At higher gamma ray energies, the neutral pion contribution to the spectrum becomes roughly 20% of the bremsstrahlung contribution. At a gamma ray energy of 160 MeV the direct gamma decay of the delta becomes comparable to bremsstrahlung. Thus, the BUU calculation of Bauer and Bertsch indicates that at a beam energy of $E/A=75$ MeV the delta contribution to the photon spectrum is too small to make a pronounced change in the shape of the gamma ray spectrum. Bauer and Bertsch performed additional calculations at a beam energy of $E/A=200$ MeV and found that while the direct delta decay contribution exceeded the bremsstrahlung contribution, the dominant source of gamma rays becomes neutral pions. This indicates that observation of the direct photon decay of the delta may be possible, but it will require the rejection of neutral pion events.

Figure 4 compares the BUU calculation of the bremsstrahlung contribution to the photon spectrum calculated

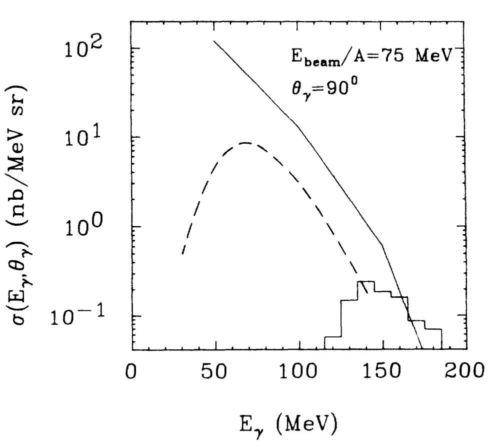

FIG. 3. Results from BUU calculations of Bauer and Bertsch (Ref. 25) of the high-energy photon spectrum for the reaction $E/A=75$ MeV $^{12}C+^{12}C$ at a laboratory angle of 90°. The solid curve is the bremsstrahlung contribution, and the dashed curve is from neutral pions. The histogram is the contribution from direct photon decay of the delta resonance. The direct delta decay contribution is too small to significantly change the shape of the total spectrum.

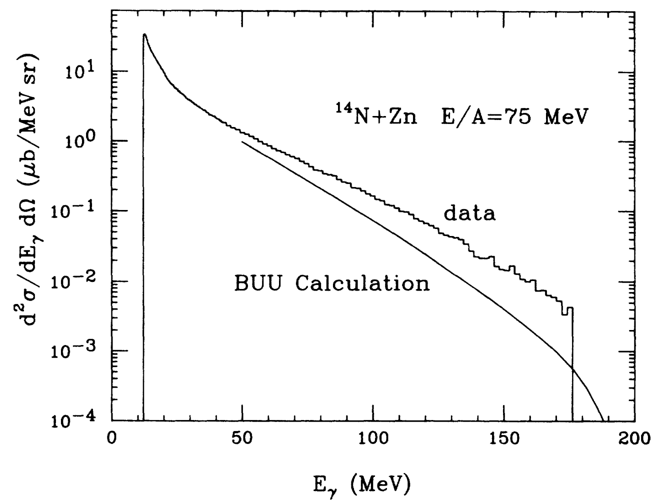

FIG. 4. A comparison of BUU calculations of the bremstrahlung contribution to the gamma ray spectrum for $E/A=75$ MeV $^{14}N+Zn$ to the measured spectrum. The solid curve is the BUU calculation, and the histogram is the data.

for the reaction $E/A=75$ MeV $^{14}N+Zn$ to our data. The calculation somewhat underpredicts the magnitude of the cross section and has too steep a slope. The BUU calculation also predicts a very sharp falloff in cross section for photons above 150 MeV. This is presumably because the Fermi momentum distributions used in the calculation have a sharp momentum cutoff of 265 MeV/c. This corresponds to a maximum photon energy of 223 MeV for first nucleon-nucleon collisions. A more realistic treatment of the Fermi momentum appears to be required for a quantitative understanding of such high-energy photons.

The systematics of high-energy photon production have been explained in terms of a first collision neutron-proton bremsstrahlung model as first proposed by Ni-

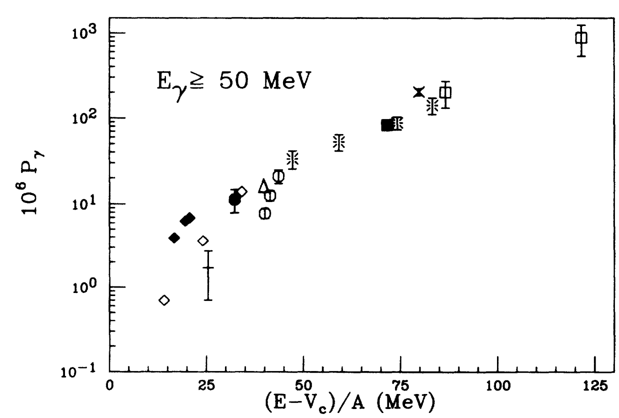

FIG. 5. A comparison of P_γ for a variety of the heavy-ion reactions. The solid square is the current data. The remaining data are as follows: diamonds, $^{14}N+Pb$ data of Ref. 3; stars, $^{12}C+^{12}C$ data of Ref. 6; circles, Kr+C, Ag, and Au from Ref. 28; vertical cross, Ar+Au from Ref. 4; triangle, Ar+Gd from Ref. 7; solid circle, $^{14}N+Ni$ from Ref. 5; square, Xe+Sn from Ref. 12; and solid diamond, S+Al, Ni, and Au from Ref. 22.

fenecker and Bondorf.[15] In this model, the production cross section σ_γ integrated over all angles, and integrated above a threshold gamma ray energy E_γ, can be represented as the product of three quantities, the nuclear reaction cross section σ_R, the impact parameter averaged number of first p-n collisions $\langle N_{pn} \rangle$, and the high-energy gamma ray production probability per p-n collision P_γ. The gamma ray cross section is then given by $\sigma_\gamma = \sigma_R \langle N_{pn} \rangle P_\gamma$. In this model the reaction cross section σ_R, and the average number of first p-n collisions, $\langle N_{pn} \rangle$, are taken from simple geometrical overlap models and are assumed to be independent of beam energy. The reaction cross section is taken to be $\sigma_R = \pi(R_{\rm proj} + R_{\rm targ})^2$, where $R = 1.2 A^{1/3}$ fm. The total cross section σ_γ for gamma rays above $E_\gamma = 50$ MeV for the reaction $E/A = 75$ MeV $^{14}N + Zn$ is $\sigma_\gamma = 390 \pm 80$ μb. The corresponding gamma ray production probability is $P_\gamma = 8.3 \pm 1.7 \times 10^{-5}$. Figure 5 compares the production probability for a variety of reactions, including the current measurement. The production probability is beam-energy dependent but does not depend much on the reaction chosen. The value of P_γ from the current experiment is in good agreement with the data for the reaction $^{12}C + ^{12}C$ of Grosse *et al.*[6]

In summary, we have searched for a contribution to the high-energy photon spectrum for gamma rays above $E_\gamma \geq 140$ MeV due to the decay of the delta resonance. The delta contribution appears to be much smaller than that predicted by Prakash *et al.*[22] The spectrum (up to the limit of our measurement of $E_\gamma = 180$ MeV) appears to be dominated by proton-neutron bremsstrahlung. The steep falloff in the photon cross section for gamma rays above $E_\gamma = 140$ MeV predicted by a BUU model is also not observed. This suggests that accurate predictions of the photon yield for such high-energy gamma rays depend critically on a realistic treatment of the Fermi momentum distribution.

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