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A comparison has been made between the production of high energy (E, $\geq$ 30 MeV) γ rays from the bombardment of ^{124}Sn and ^{112}Sn targets with E/A = 10 MeV ^{12}C ions. The results are well explained by the n-p bremsstrahlung model and do not indicate the need for any new processes.

In the past few years there have been many studies, both experimental and theoretical, on high energy photon production in heavy ion collisions. These studies are thoroughly reviewed in a recent article by Nifenecker and Pinston[1]. At beam energies above E/A = 20 MeV, the high energy photons have been shown to be produced primarily by incoherent nucleon-nucleon bremsstrahlung. Recent work[2–4] has concentrated on lower incident energies (5 MeV/nucleon $\leq E_{inc} \leq$ 20 MeV/nucleon). Experiments by Vojtech *et al.*[3] and Gossett *et al.*[4], studied the isotopic effect on the production mechanism of high energy photons, using the same beam on different isotopes of the same element, and, in the case of Gossett *et al.*[4], beams of different isotopes as well. A ratio of the production of high energy γ rays from the higher A target to that from the lower A target which was higher than that expected in the n-p bremsstrahlung model was observed in the work of Vojtech *et al.*[3]. The present experiment is an attempt to corroborate this interesting and surprising result.

The experiment was performed at the National Superconducting Cyclotron Laboratory with a ^{12}C beam from the K500 Cyclotron at an energy of E/A = 10 MeV. The beam was incident upon self-supporting foil targets of ^{112}Sn (3.29 mg/cm^2) and ^{124}Sn (3.44 mg/cm^2). Both targets had isotopic purity greater than 98.9 %. The γ-ray detection system consisted of two 12.5 cm diameter by 22.9 cm long cylindrical barium fluoride (BaF_2) crystals surrounded by 2.54 cm thick plastic anticoincidence shielding. Polyethylene bars 35 cm or 40 cm in length with a diameter of 12.5 cm were placed in front of the BaF_2 detectors in order to reduce the reduce the background due to fast neutrons. The γ-ray yield was corrected for the attenuation in these bars. The BaF_2 detector energy vs. time of flight (for a 1 m flight path) relative to the cyclotron radio frequency was recorded with a time resolution of 2 ns FWHM for γ-ray energies above 15 MeV. This combined with pulse shape discrimination led to excellent neutron/gamma separation. To minimize the effect of drifts on the ratio of the yield from the two isotopes, the targets were interchanged periodically during the experiment.

Four silicon surface barrier detectors in a cloverleaf pattern were located 17.1 cm downstream in order to monitor target thickness and beam current. Each of the four detectors was collimated by a 0.32 cm diameter circular hole centered about 20 degrees, just inside the grazing angle for 120 MeV ^{12}C on the tin isotopes. These detectors aided in monitoring both the ^{12}C beam intensity and the target thickness. The number of particles detected in the silicon detectors was compared to the Faraday cup readings in order to monitor fluctuations in the target thickness. Comparisons between the four detectors were made to insure that the beam was striking the targets in approximately the same position during each run. The ratio of the total number of ions detected in the silicon detectors to the Faraday cup readings remained constant within statistics. The ratio of the elastic scattering from the ^{112}Sn target to that of the ^{124}Sn target gave a value of 1.06 for the relative target thickness in nuclei per unit area. This is based on the assumption that the elastic scattering cross section from the two targets is the same at this angle and energy as is predicted by the optical model code ECIS79 [5]. The determination of the target thicknesses by weighing gave good agreement with this elastic scattering value (to within 2 %).

In Fig. 1 the γ-ray spectra from ^{12}C + ^{112,124}Sn at 10 Mev/nucleon are shown for a laboratory angle of 90 degrees. The spectra, which were normalized relative to the elastic scattering measured in the silicon array, exhibit a number of typical features. In the giant dipole resonance (GDR) region the ^{112}Sn has a higher photon yield due to statistical decay, and at higher photon energies ($E \geq 20$ MeV) the ^{124}Sn has a greater yield, in agreement with Vojtech *et al.*. The statistical γ-ray contribution to the ^{112}Sn spectrum, also shown in Fig. 1, was calculated with the code CASCADE[6] with the same parameters used by Vojtech *et al.* folded with our detector response. Independent of the choice of parameters the statistical photon yield becomes insignificant above 30 MeV as compared to the total yield. The ratio of $d\sigma_\gamma(^{124}Sn)/d\sigma_\gamma(^{112}Sn)$ summed over the energy range 30-50 MeV is then found to be 1.19 ± 0.20.

Theoretically the γ-ray yield from the n-p bremsstrahlung model may be expressed following the work of Ref. 7 by

$$\sigma_\gamma = \sigma_R \cdot \langle N \rangle_{np} \cdot P_x \tag{1}$$

where σ_R is the reaction cross section which can be given by $\pi \cdot (1.2 fm)^2 \cdot (A_t^{1/3} + A_p^{1/3})^2$, where A_t and A_p are the target and projectile masses respectively, and $\langle N \rangle_{np}$ is the number of first chance neutron-proton collisions in an equal participant model. P_x is the probability of photon emission per n-p collision with P_x given by

$$\frac{d^2 P_x}{dE_\gamma d\Omega} = \frac{k}{E_o} \cdot e^{-\frac{E_\gamma}{E_o}} \tag{2}$$

where E_o is the experimental slope parameter, E_γ is the γ-ray energy and k is the probability of producing a bremsstrahlung photon per n-p collision as discussed in Ref. 7. Since the slope parameter E_o is approximately the same in the two reactions, the P_x term cancels when the ratio of the high energy photon yield $d\sigma_\gamma(^{124}Sn)/d\sigma_\gamma(^{112}Sn)$ is taken. From Eq. (1), the ^{124}Sn cross section is predicted to be approximately 15% greater than that of ^{112}Sn , which compares favorably with the present data but disagrees with Vojtech *et al.* The slope parameter determined from the current data yields a value of $E_o = 3.8 \pm 0.2$ MeV which agrees with the slope determined by Vojtech *et al.*

Collective (i.e. nucleus-nucleus) bremsstrahlung has also been discussed[3, 4] as a possible production mechanism in the intermediate energy region. In this model the yield of high energy photons would be approximately given by $\mu^2(Z_p/A_p - Z_t/A_t)^2$, where μ is the reduced mass of the system and $Z_p/A_p - Z_t/A_t$ is the effective dipole charge of the system. This theory predicts a ratio $d\sigma_\gamma(^{124}Sn)/d\sigma_\gamma(^{112}Sn) = 3.4$ which does not compare favorably with the data. As has also been shown in Ref. 3 for this particular reaction, the theoretical slope parameter for a nucleus-nucleus model does not correspond well to the experimental slope parameter of 3.8 MeV. It would appear that collective bremsstrahlung does not contribute significantly to the total yield in the measured energy domain.

Vojtech *et al.* studied the emission of high energy γ rays in the same system as in the present experiment ^{12}C + ^{112,124}Sn at almost the same energy (E/A = 10.5 MeV). However, in the γ-ray energy range considered, 20-40 MeV, the statistical contribution is significant and must be subtracted from the total γ-ray yield. In order to account for the statistical γ rays, Vojtech *et al.* fitted the low energy γ-ray (5 MeV $\leq E_\gamma \leq$ 20 MeV) spectrum with the prediction of the code CASCADE[6] and then subtracted the calculated statistical γ rays from the spectrum in the 20-40 MeV range. The result was a $d\sigma_\gamma(^{124}Sn)/d\sigma_\gamma(^{112}Sn)$ ratio of 1.8 which was high enough to indicate that the n-p bremsstrahlung model could not fully explain the high energy γ ray production in the system. Gossett *et al.* on the other hand studied the ^{12,13}C + ^{92,100}Mo system at 9-14 MeV/nucleon. They investigated the photons produced in the same energy range as the present analysis (30-50 MeV) so that they also did not have to subtract any statistical contributions from the total yield. Although most of the ratios from the various beam and target combinations are well represented by the n-p bremsstrahlung model, there was still ambiguity in the fact that the ratio of $^{12}C +^{92} Mo$ cross section to that of any other system was larger than expected ($\sim$1.5) at all measured incident beam energies.

The cross section ratios found by Vojtech *et al.*[3], Gossett *et al.* [4], and the present data are summarized in Table 1. There is an overall agreement with the data of Gossett *et al.* except for the deviations of the ratios which include the $^{12}C +^{92} Mo$

reaction. More important is the discrepancy between the present data and the ratio of Vojtech *et al.* for the same reaction. The only difference is the γ-ray energy range considered for extracting the ratio. Since the spectrum is a rapidly decreasing function, the first channels of summation are the largest contributors to this ratio. Thus the extracted ratio of 1.8 found by Vojtech *et al.* is dominated by the energy range below 25 MeV where the statistical contributions are not negligible. In the present paper we tried to avoid the uncertainties due to the statistical contributions by extracting the ratio at energies above 30 MeV. In order to demonstrate that the present ratio is not dominated only by the first channels Fig. 2 shows the ratio when starting at various energies beginning at 28 MeV and running through 40 MeV. The ratio of 1.19 is consistent with the theoretical predictions of n-p bremsstrahlung over the whole energy range and does not depend on the starting channel. The present data thus indicate no need for additional mechanisms for γ-ray energies above 30 MeV. The discrepancy with Ref. 3 could arise because of other bremsstrahlung mechanisms which produce γ-rays in that 20-30 MeV energy range. However, since the emission of γ rays from statistical processes and bremsstrahlung are not distinguishable, the discrepancy could also be produced by a possible poor understanding of emission of statistical γ rays above 20 MeV. Further investigations are necessary to explain the γ-ray spectrum in this energy range.

In conclusion, the high energy γ-ray cross section ratio $d\sigma_\gamma(^{124}Sn)/d\sigma_\gamma(^{112}Sn)$ which was found to be 1.19±0.20 agrees with n-p bremsstrahlung predictions even though the bombarding energy is in a range which is very low compared to that of previous measurements. It is suggested that the discrepancy with the conclusions of Vojtech *et al.* might be due to the different γ-ray energy ranges considered and possible unexplained effects of statistical and/or bremsstrahlung mechanisms in the energy range between 20 and 30 MeV.

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FIGURES

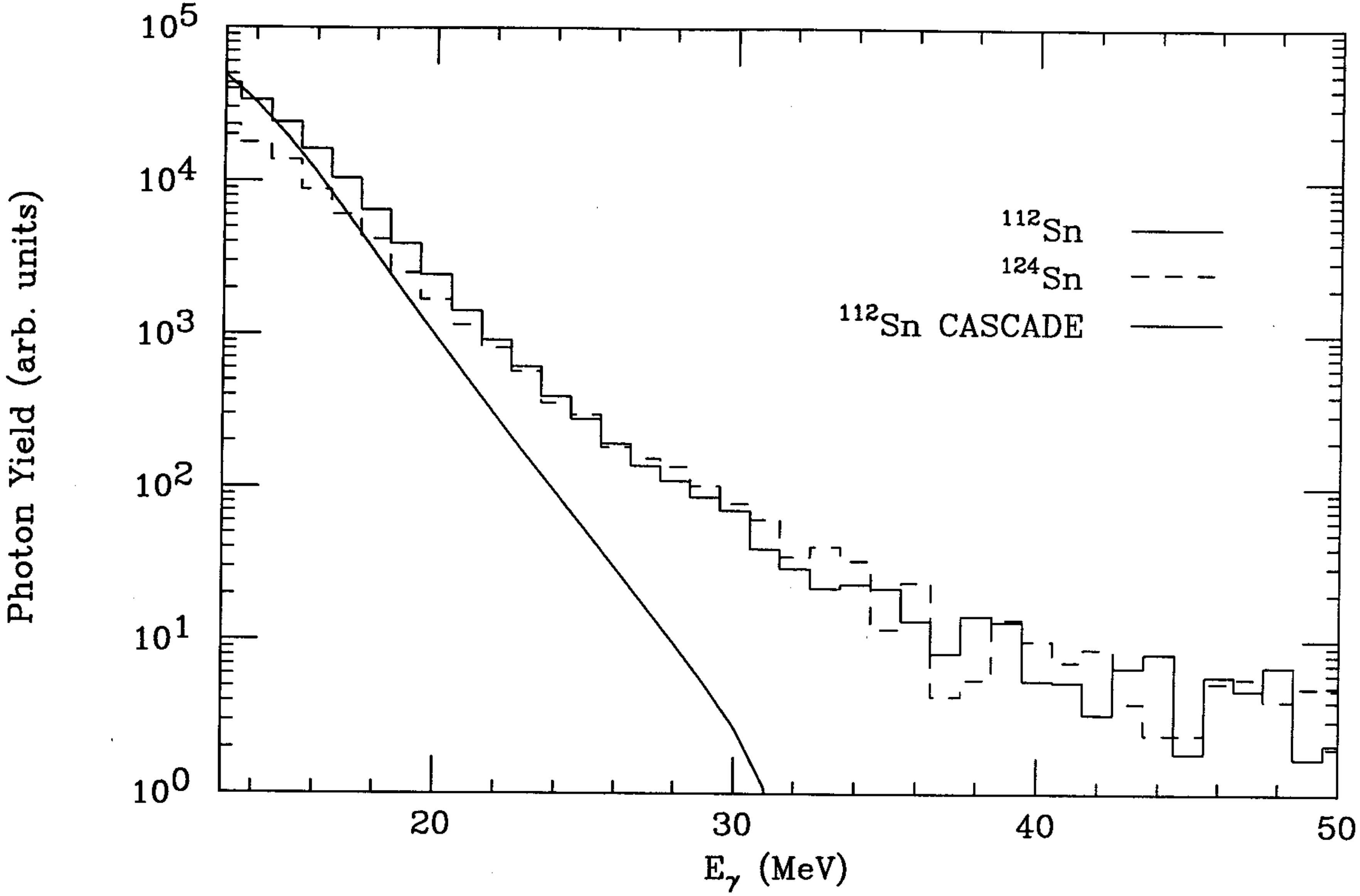
FIG. 1. Measured γ-ray spectra taken at $\theta_{lab} = 90$ deg from the ^{12}C + ^{112,124}Sn at 10 MeV/nucleon. The curve shown is the statistical yield due to the code CASCADE[6] for ^{112}Sn.

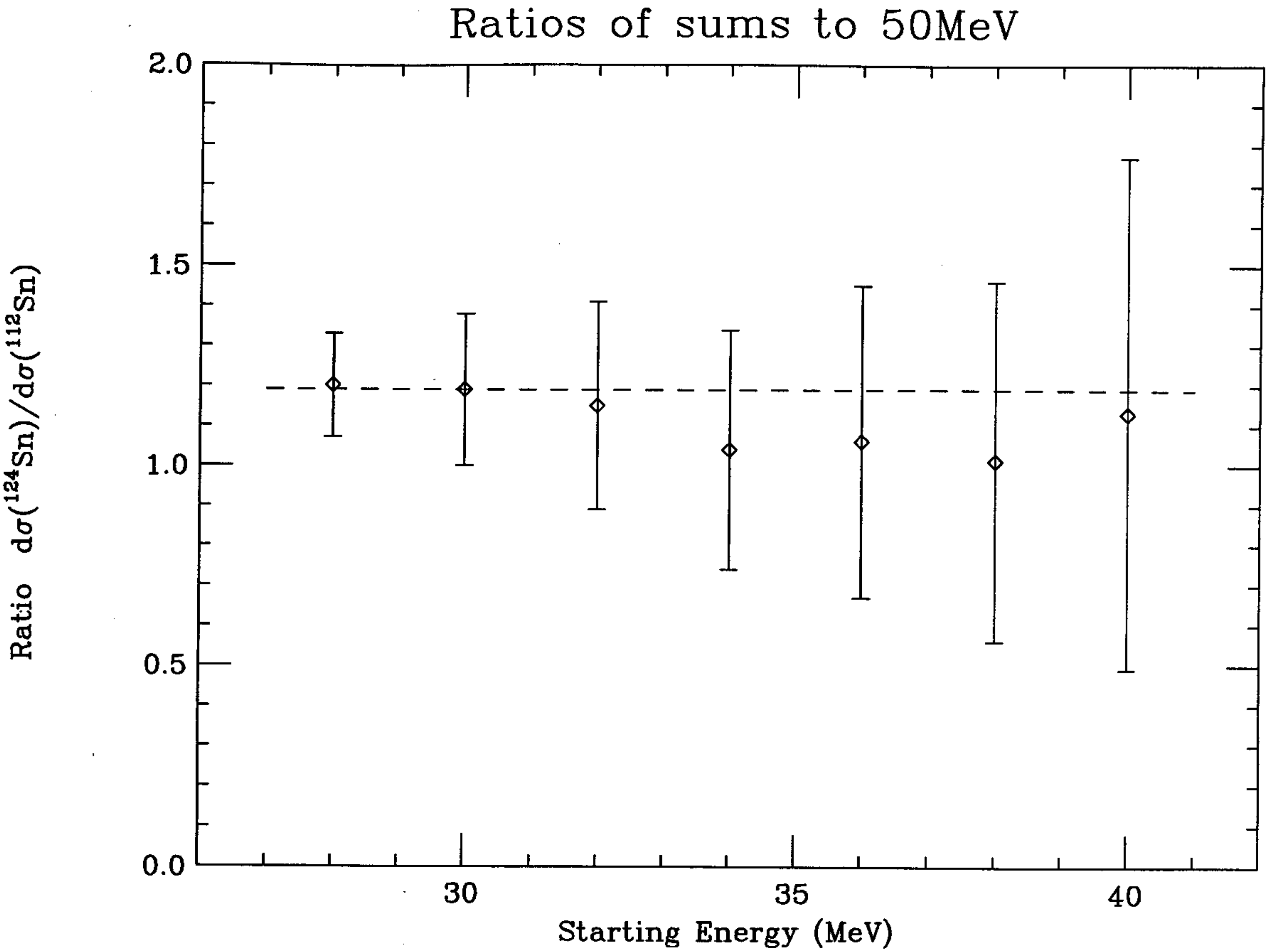
FIG. 2. The $d\sigma_\gamma(^{124}Sn)/d\sigma_\gamma(^{112}Sn)$ ratio as determined from different starting energies and summed to 50 MeV. The dashed line represents the isotopic ratio obtained by the sum from 30-50 MeV. The error bars are statistical in nature and do not include systematic error.

TABLES

TABLE I. The table displays the isotopic ratios found in recent data. R_{np} is the ratio expected from n-p bremsstrahlung and R_{coll} is the ratio expected from collective bremsstrahlung. R_{exp} is the experimental value given.

Authors	Reaction	R_{exp}	R_{np}	R_{coll}
Vojtech *et al.*	$^{12}C+^{124}Sn$ /$^{12}C+^{112}Sn$	1.8 ± 0.4	1.15	3.4
Gossett *et al.*	$^{12}C+^{100}Mo$ /$^{12}C+^{92}Mo$	1.49 ± 0.20	1.1	3.4
	$^{13}C+^{100}Mo$ /$^{13}C+^{92}Mo$	1.01 ± 0.21	1.1	69.0
	$^{13}C+^{100}Mo$ /$^{12}C+^{100}Mo$	0.96 ± 0.08	1.1	0.31
	$^{13}C+^{92}Mo$ /$^{12}C+^{92}Mo$	1.47 ± 0.12	1.1	0.01
Present data	$^{12}C+^{124}Sn$ /$^{12}C+^{112}Sn$	1.19 ± 0.20	1.15	3.4


Photon Yield (arb. units)
10^5
10^4
10^3
10^2
10^1
10^0
20
30
40
50
E_γ (MeV)
^{112}Sn
^{124}Sn
^{112}Sn CASCADE


Ratios of sums to 50MeV
Ratio $d\sigma(^{124}Sn)/d\sigma(^{112}Sn)$
2.0
1.5
1.0
0.5
0.0
30
35
40
Starting Energy (MeV)