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Abstract :*High energy photons (E, ≥ 30 MeV) have been* measured in coincidence with *light* particles *observed* in a multidetector array *for the* $^{40}Ar+^{51}V$ *system at a* bombarding energy of $E/A = 65$ *MeV.* Double *differential cross* sections were obtained as a function *of the* midrapidity *charge representation of the* centrality *of the collision. The inverse slope* parameter increases with *centrality more strongly* than *predicted by* a *BUU* model.

Since the first experimental evidence [1,2] that high energy photons are produced in heavy-ion collisions, they have been intensively studied both experimentally and theoretically. The initial explanation for these photons was coherent nucleus-nucleus bremsstrahlung characterized by a quadrupolar angular distribution in the nucleus-nucleus center of mass. However, it is now accepted that the gamma rays are produced mainly by incoherent nucleon-nucleon bremsstrahlung [3]. This model successfully explains the energy and mass dependence of the inclusive cross section and the inverse slope parameter. However there have been very few comparisons to exclusive data, and in the present work we present results from a high gamma ray measurement carried out in coincidence with a large, multiparticle detector array.

The features extracted from the previous data, which have been thoroughly reviewed [3], were the angular distributions and the energy spectra, the latter being characterized by an exponential function with a characteristic slope parameter E_0. This slope parameter as well as the total and differential cross-sections have been measured over a wide range of targets, projectiles and bombarding energies. However, there is a fairly poor knowledge of the variation of E_0 as a function of the impact parameter. Hingmann et al.[4] have studied the gamma rays produced in the reaction $^{40}Ar+^{158}Gd$ at $E/A = 44$ MeV in coincidence with fragments detected in parallel plate avalanche counter (PPAC) detectors. They found that the high energy gamma-ray production as well as E_0 decreases as the impact parameter increases. Their conclusion was that the production mechanism for gamma rays above 25 MeV is incoherent nucleon-nucleon bremsstrahlung. In an other coincidence experiment, Herrmann et al.[5] studied the gamma-ray production in the $^{92}Mo+^{92}Mo$ system at $E/A = 19.5$ MeV. Heavy fragments were also detected by the means of PPAC detectors. Their analysis was based on the total kinetic energy loss (TKEL) in the collision, and they found that E_0 became larger as the TKEL increased. Interestingly, their conclusion was that the gamma rays were produced by statistical emission from the excited fragments rather than by nucleon-nucleon bremsstrahlung, but the experiment was carried out at much lower energy and with heavier beams than the other semi-inclusive work. The most recent exclusive measurement was carried out by Kwato Njock et al. [6]. They studied the $^{40}Ar + ^{27}Al$ system at $E/A = 85$ MeV. Their results also indicated that E_0 increases with charged particle multiplicity, but they interpret this as support for the first collision nucleon-nucleon model. In order to investigate this dependence further, we have measured the gamma-ray production in the reaction $^{40}Ar+^{51}V$ at $E/A = 65$ MeV in coincidence with light charged particles observed in the MSU 4π array.

The argon beam was produced by the K1200 cyclotron at the National Superconducting Cyclotron Laboratory at Michigan State University, and bombarded a 25 mg cm^{-2} vanadium target. The gamma-rays were detected with two identical BaF_2 cylindrical crystals, called $BaF_2(1)$ and $BaF_2(2)$, of 12.7 cm diameter and 22.9 cm length. The two detectors were placed at angles of θ_1=100.6°,ϕ_1=234.0° and θ_2=79.4°, ϕ_2=270.0° with respect with the beam axis, at a distance of 75 cm from the target. A tungsten collimator 7.82 cm in diameter limited the solid angle to 11 msr per detector. The response of the detectors was simulated with the code EGS4 [7] and has been measured with a tagged photon beam at the Saskatchewan Accelerator Laboratory [8,9]. The data shown in the present paper are not corrected for the detector response; this unfolding would have a negligible effect on the results because of the use of the collimator. The counters were surrounded by several plastic scintillators which were used to reject the charged particles coming from the target as well as the cosmic rays muons. In addition, a 20 cm thick polyethylene bar was placed in front of the gamma detectors in order to attenuate the neutron flux. The energy calibration was carried out with the 15.1 MeV photons from reactions in a carbon target.

The detection of charged particles and light fragments in the 4π Array has been described previously [10]. In the present experiment, the gains of the phoswich detectors were set to measure fragments with Z≤16 between 7° and 20° and Z≤4 at larger angles. Isotopic identification was possible for Z=1 particles emitted between 20° and 160°. The whole experimental device was triggered by the gamma ray detectors. Some data were also taken using only the 4π detector as the trigger in order to check the behavior of the charged particle detectors.

In the analysis most of the neutrons were rejected by pulse shape discrimination (PSD) using the two components of light produced in the barium fluoride. Time of flight between the gamma ray detectors and the radio frequency of the cyclotron was also used to separate gamma rays from the remaining (primarily slow) neutrons. The time resolution of the BaF_2 detectors is of the order of 0.7 ns, but, due to the intrinsic time width of the beam, the observed time resolution was 2.5 ns. Figure 1 shows a typical time of flight spectrum obtained after PSD. The neutron contribution to the high energy gamma spectrum is not significant.

The inclusive data are in good agreement both in the magnitude of the cross section and the slope with the systematics of the previous data, as reviewed by Nifenecker and Pinston [3], and the incoherent nucleon-nucleon bremsstrahlung model, as described by Nifenecker and Bondorf [11]. To extract the slope parameters E_0, we have performed an exponential fit of the double differential cross section $\frac{d^2\sigma}{d\Omega dE_\gamma}$ from E_γ = 30 MeV up to the maximum observed energy in the laboratory frame. A lower limit of 30 MeV avoids the contribution from statistical emission. The small number of cosmic ray muons still present in the data have been removed by the subtraction of scaled data taken with no beam. Figure 2 displays the inclusive energy spectrum of the gamma rays in the laboratory frame. The E_0 values extracted for the two detectors after transformation into the nucleon-nucleon center of mass are $E_0(1) = 20.7 \pm 0.4[1.5]$ MeV and $E_0(2) = 17.5 \pm 0.3[1.2]$ MeV. The first error is of statistical origin while the error in brackets indicates a 7% systematic uncertainty due to gain shifts in the detectors over the very long data collection time of the experiment.

The method used to determine the impact parameter was based on the midrapidity charge (Z_{mr}) filter. Z_{mr} is the total charge of the fragments with a rapidity y such that

$$0.75 y_t \leq y \leq 0.75\ y_p$$

in the center of mass frame, where y_t and y_p are the target and projectile rapidities, respectively. A full description of this method may be found in ref. 12. This method is particularly well adapted to nearly symmetric systems like the one studied here. We have divided the full range of Z_{mr} into four bins corresponding to peripheral, midperipheral, midcentral and central collisions.

Figure 3 shows the energy spectra as a function of impact parameter for $BaF_2(2)$, the detector located at $\theta = 79.4^o$ in the laboratory. (The results for $BaF_2(1)$ are very similar but contain a larger muon background in the peripheral bin, due to the nearly vertical geometry of the detection.) The spectra were fitted with a function that included an exponential and a constant background. The constant was included to account for cosmic ray muons that were not rejected by the scintillators. This background contribution was negligible except for the data from the peripheral bin. The slope parameter increases as the midrapidity charge increases. This increase is a signature that the energy available to produce the photons is larger in central collisions than that in peripheral ones. Previous calculations based on BUU microscopic models predicted such an increase,[13] which arises from the higher relative momenta of the colliding nucleons in central collisions.

A detailed calculation has been carried out with the BUU equation. The BUU results were separated into bins using the previously established correlation (and its dispersion) between midrapidity charge and multiplicity response of the 4π Array.[12] The absolute value of the differential cross section is found to be smaller than that observed, as seen in Fig. 3. However, the evolution of E_0 with impact parameter is only qualitatively reproduced. The model predicts a slope parameter increase of 8 % whereas the data give an increase of 33[8] %. The measured increase can be compared to the results of Kwato Njock et al. [6], who observed an increase of 35 to 40 %. The increasing discrepancy between the model and the data as the events become more central might be explained by a difference between the real Fermi momentum distribution and that used in the model.[14] This increase in slope parameter with centrality means that the higher the energy of the gamma ray detected, the more likely it is that the collision was a central or violent one. About 50 % of the events fall in the midcentral and central bin at a gamma energy of 30 MeV, but this would rise to 70 % at 150 MeV.

To summarize, we have studied the impact parameter dependance of E_0, the slope parameter, of high energy photons produced in the reaction $^{40}Ar+^{51}V$ at $E/A = 65$ MeV. Our results for the inclusive total cross section and slope parameters are in good agreement with previous measurements. We observed that E_0 increases with the centrality of the events. This result is consistent with that of Hingmann et al.[4] and is in very good agreement with that of Kwato Njock et al.[6]. A comparison with the conclusions of Herrmann et al.[5] is made difficult by the fact that they studied a much heavier system at a much lower energy. A calculation based on the BUU equation reproduces the trend of the present data only qualitatively and indicates that there are still some problems in the BUU representation of the reaction mechanism. A more detailed analysis of the present data and new data with a heavier target will be presented in a future paper.

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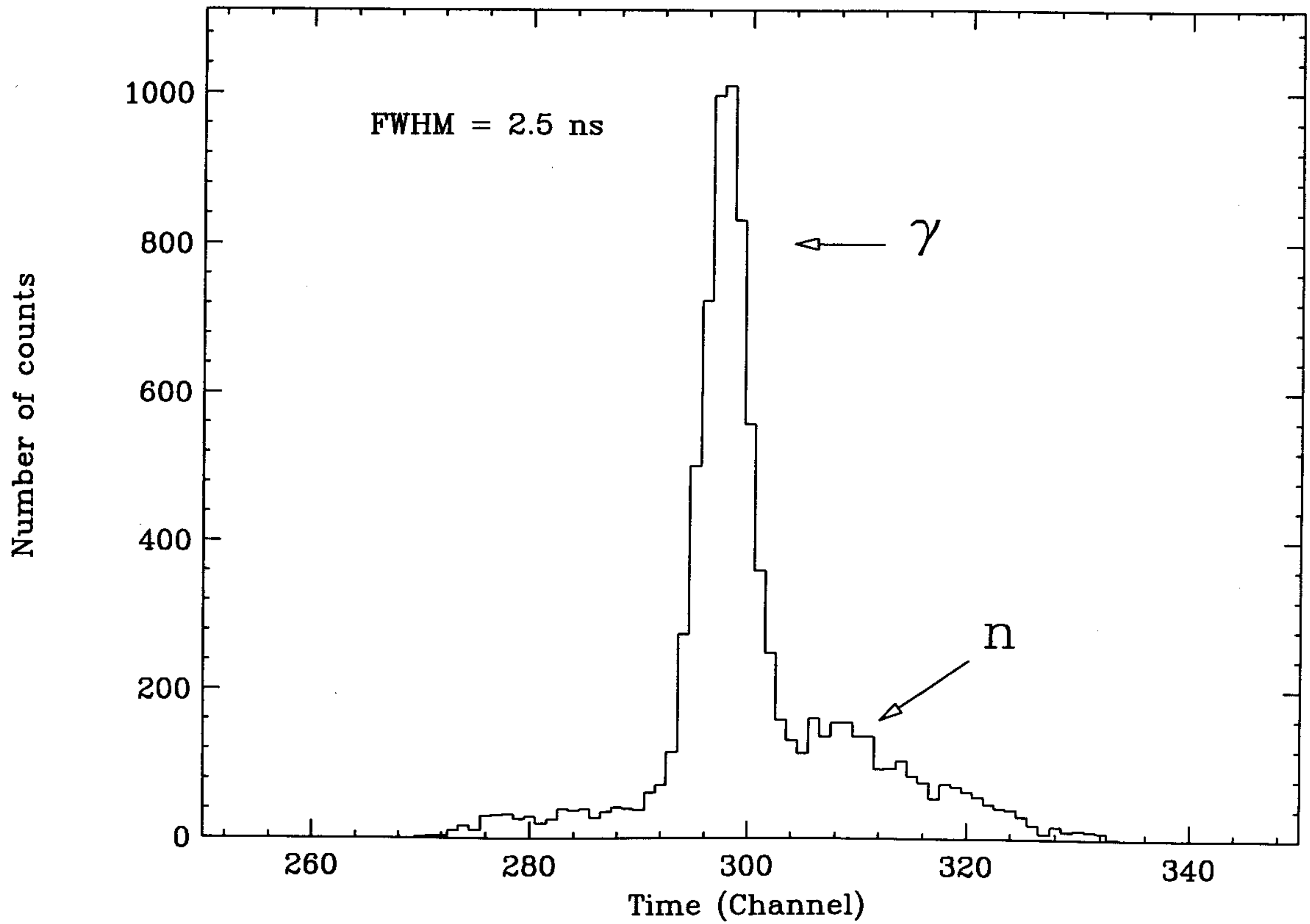
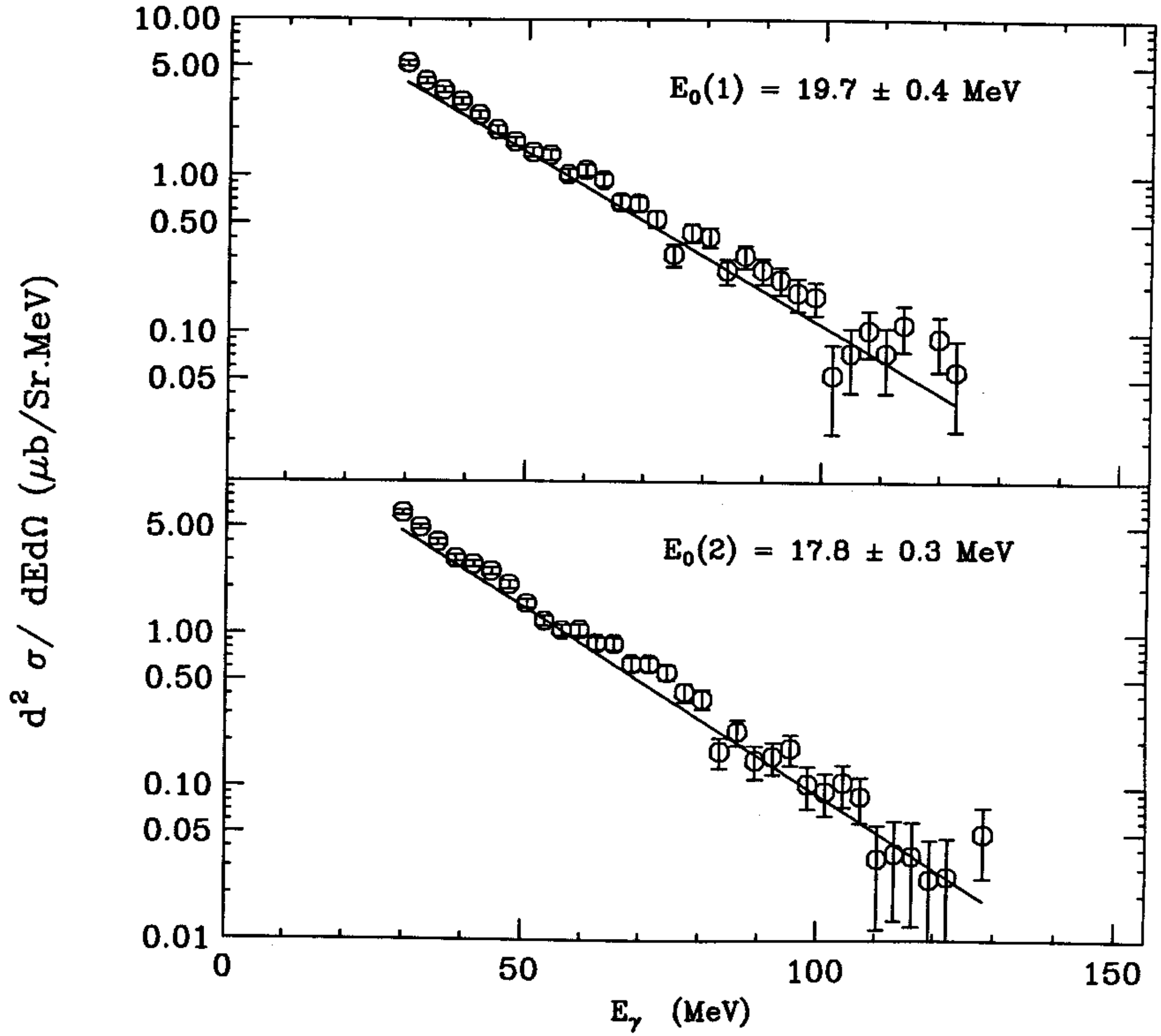
FIGURE CAPTIONS

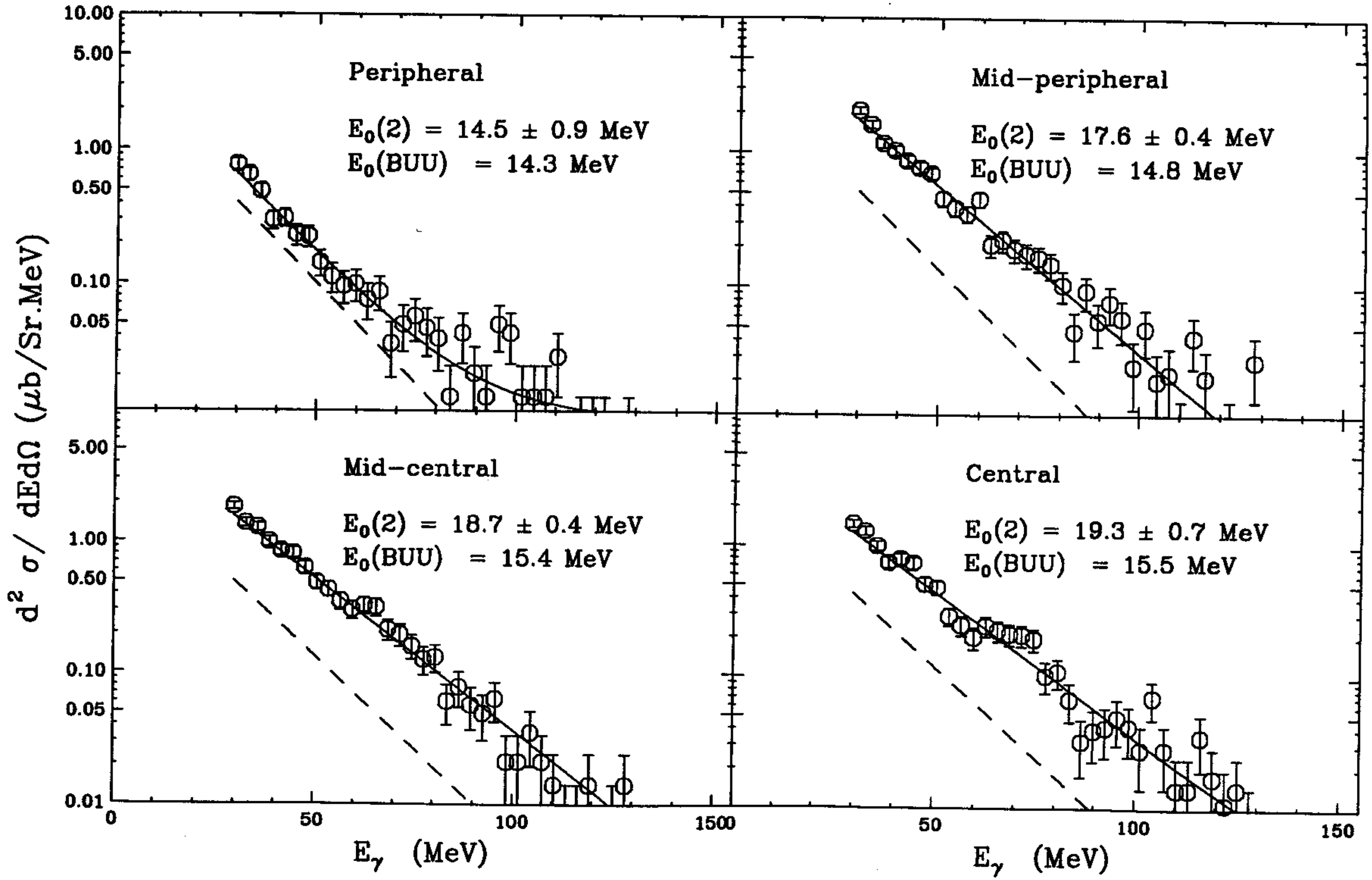
Figure 1 : Time of Flight spectrum after PSD analysis; the threshold for gamma-rays was 30 MeV.

Figure 2 : Inclusive laboratory energy spectrum for the two detectors. The curve is the result of an exponential fit. The laboratory frame E_0 values are given, and the error is of statistical origin.

Figure 3 : Laboratory energy spectra for different impact parameters from the detector $BaF_2(2)$ at $\theta_2 = 79.4^o$. The full curves are the result of fitting an exponential plus constant background to the data. The dashed curves are the results of the BUU calculation; see the text.


FWHM = 2.5 ns
γ
n
Number of counts
0
200
400
600
800
1000
260
280
300
320
340
Time (Channel)


E0(1) = 19.7 ± 0.4 MeV
E0(2) = 17.8 ± 0.3 MeV
d2 σ/ dEdΩ (μb/Sr.MeV)
Eγ (MeV)
10.00
5.00
1.00
0.50
0.10
0.05
0.01
0
50
100
150


Peripheral
$E_0(2)$ = 14.5 ± 0.9 MeV
E_0(BUU) = 14.3 MeV
Mid−peripheral
$E_0(2)$ = 17.6 ± 0.4 MeV
E_0(BUU) = 14.8 MeV
Mid−central
$E_0(2)$ = 18.7 ± 0.4 MeV
E_0(BUU) = 15.4 MeV
Central
$E_0(2)$ = 19.3 ± 0.7 MeV
E_0(BUU) = 15.5 MeV
$d^2\sigma/dEd\Omega$ (μb/Sr.MeV)
E_γ (MeV)
E_γ (MeV)
10.00
5.00
1.00
0.50
0.10
0.05
5.00
1.00
0.50
0.10
0.05
0.01
0
50
100
1500
50
100
150