

## EXPERIMENTAL DETERMINATION OF THE ENERGY GENERATED IN NUCLEAR CASCADES BY A HIGH ENERGY BEAM

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### Abstract

An already existing, sub-critical arrangement made of natural Uranium and water moderator has been exposed to a low intensity ( $\approx 10^9$  ppp) proton beam from CERN-PS at several kinetic energies from 600 MeV to 2.75 GeV. The energy delivered by the hadronic cascade induced by the beam in the device has been measured by the temperature rise of small sampling blocks of Uranium located in several different positions inside the device and counting the fissions in thin probe foils of natural Uranium. We find typically  $G \approx 30$  in reasonable agreement with calculations, where  $G$  is the ratio of the energy produced in the device to the energy delivered by the beam. This result opens the way to the realisation of the so-called Energy Amplifier, a practical device to produce energy from Thorium or depleted Uranium targets exposed to an intense high energy proton beam. Results show that the optimal kinetic energy is  $\geq 1$  GeV, below which  $G$  decreases but is still acceptable in the energy range explored.

Nuclear reactors produce today a significant fraction ( $\approx 6\%$ ) of the world's energy supply and they are likely to continue to do so in the foreseeable future. Notwithstanding, new approaches to energy extraction from nuclei are of interest, especially provided they could eliminate or at least greatly reduce (i) the environmental impact of the long-lived highly radioactive waste; (ii) the possibility of diversions toward military applications; (iii) the risks of an accidental divergence related to the critical operation of the chain reaction and (iv) make a more efficient use of a fuel which is less radio-toxic to extract and more abundant on Earth than Uranium.

Thermonuclear fusion may hold the expectation of satisfying all these requirements, but only in a very distant future and with very sophisticated technologies. Recently some of us [1] have elaborated a much simpler scheme of energy extraction from nuclei, called "Energy Amplifier" (EA) allowing in particular the use of natural Thorium as a fuel. This is based on a proton initiated, high energy ( $\approx 1$  GeV) nuclear cascade absorbed in a "calorimeter". A calorimeter is made of a large number of heavy material elements alternated with a sampling medium, usually scintillator or liquid Argon. Such instruments are widely used to measure the energy for instance of parton "jets" through observation of the energy depositions of fully contained nuclear cascades. The fraction of the energy lost by hadrons in the sampling material can be increased by some 30–50% by adding some fissionable material in the plates [2]. This method is used in order to equalise the response of calorimeters to hadronic and electromagnetic cascades, as required for instance in measurements of jets. In the present paper we demonstrate experimentally that it is possible to "amplify" the energy deposition of a high energy cascade to such an extent as to potentially recover the energy of the incident beam and to make in addition a considerable net energy gain. In the experimental conditions of this investigation, the energy produced by the cascade has been typically some thirty times the one delivered by the beam.

In a proton induced cascade one can distinguish two qualitative and successive physical regimes: (1) a spallation driven, high energy phase and (2) a neutron driven, fission dominated regime. When the energy of the cascade products falls below several MeV, ionisation losses bring particles rapidly to rest, with the exception of neutrons which continue to exhibit a rich phenomenology eventually down to thermal energies. Neutrons from the first phase are acting as "source" for the second phase. The first phase has been widely explored in calorimeters: since it is rather complicated and the relevant cross sections are often poorly known, it can be approximately parametrized with the help of phenomenological models and Monte Carlo calculations [3], generally sufficiently detailed to give a first order agreement with the experimental measurements [4].

In the second phase (for which an almost complete set of cross sections exists) the main physical process is a diffusive process of neutrons which gradually lose energy by collisions and are multiplied by fissions and (n,2n) reactions. This phenomenology is reminiscent of the one of Nuclear Reactors. However, because the EA is not critical, there are important differences : in a Reactor the flux distribution inside the volume is determined essentially by the boundaries [5], in the EA the location and geometry of the initial cascade acting as neutron source is dominant. A simple analytic theory based on diffusion has been developed [6]. The neutron source excites a superposition of ortho-normal modes of the "buckling" equation representing the neutron flux, of which only the fundamental mode is relevant in a Reactor Theory. In this description a Reactor is a limiting case in which the strength of the initiating source tends to zero and the criticality to one. Each of these modes has a different buckling parameter  $B_i$  and a different multiplication coefficient  $k_i$ . As a consequence, in the conditions of our experiment in which the microscopic multiplication coefficient  $k_{\infty}$ , defined as the number of neutrons produced at each absorption in the fuel-moderator mixture is  $k_{\infty} < 1$ , (i) the spatial neutron flux is expected to decay exponentially from the point of the source [7], rather than having the characteristic cosine distribution centred with respect to the volume as in a critical Reactor [5] and (ii) for a proton pulse sharp in time ( $\delta$ -function), the neutron population decreases exponentially with a time constant which grows linearly with the effective multiplication coefficient  $1 / (1 - k)$  [6].

The presence of such a second neutron driven phase is essential in order to achieve a large gain. However, it is not necessary to let neutrons reach full thermalization. Different types of EA are possible, according to the amount of moderation introduced for the neutrons before capture. In one instance one may use liquid Lead as a cooling medium and as high energy target, with consequent little or no moderation. In other schemes neutrons may be either partially or completely moderated. We refer to Ref. [8] for more details. In the present test neutrons were almost completely thermalized.

The experimental set-up is shown in Fig. 1 and its main parameters are summarised in Table 1. It consists of an already existing sub-critical assembly [9] made of natural Uranium rods, immersed in a stainless steel tank filled with ordinary, de-mineralised water, which acts as moderator. The beam from the CERN-PS hits a small target of depleted Uranium, which is located such as to approximately centre the source of spallation neutrons with respect to the device. A low density channel (Styrofoam) removes most of the material along the beam path in its way to the target. The beam position has been continuously monitored with wire chamber hodoscopes. The beam kinetic energy has been varied in the interval 600 MeV to 2.75 GeV. The proton beam intensity has been typically of the order of  $10^9$  ppp on a  $\leq 1.0$  cm radius focal spot, in the form of a sharp ( $\leq 100$  ns) fast extracted bunch. The beam intensity has been accurately measured by a beam transformer, periodically cross calibrated with the activation of Aluminium foils and it is known to better than 3%. The beam intensity is far too small to produce bulk transformations of the fuel and one relies entirely on the natural presence (0.71%) of  $^{235}\text{U}$ .

The neutronic behaviour of the assembly has been calibrated with the help of a 1.4 Ci neutron source (Am-Be) inserted in the centre of the device. The neutron flux measured with a Boron loaded counter is shown in Fig. 2 and confirms the expected exponential behaviour as a function of the distance from the source. We note that the water extends somewhat around the uranium bar assembly, acting as a "reflector". Comparing the source results with measurements with only water, we find an effective multiplication coefficient for a point-like centred source of  $k = 0.915 \pm 0.010$  [10]. This result is in good agreement with calculations (Monte Carlo) which give  $k = 0.92$ . We note that the  $k$  factor for the measurement with the beam is slightly different because (1) the source is not point-like (2) additional materials (styrofoam, target etc.) have been introduced. The calculated reduction is  $\Delta k = -0.02$ , leading to a value for the beam configuration of  $k = 0.895 \pm 0.010$ .

The parameters of the detectors are listed in Table 2. The energy delivered by the beam in the device, typically  $\approx 1$  watt, has been measured by the temperature rise of small sampling blocks of Uranium [11] moved at different positions inside the device. Thermometers have been cross calibrated with a known energy deposition produced by a known current pulse in a resistor within each block [12]. This method has been chosen since it is the closest to their expected use in the EA test. In practice the temperature behaviour in a succession of beam-on beam-off cycles (typically one hour each) has been measured and fitted with a simple phenomenological model in which all relevant effects, like heat leaks etc. have been taken into correct account. A "zero" measurement has been performed with a lead block which is known to be largely transparent to low energy neutrons. The major contribution to the gain is expected from fission. This has been demonstrated counting the fissions in thin ( $\approx 1$  mg/cm<sup>2</sup>) Uranium foils near the thermometers with the help of Lexan foils, in which fission fragments produce a characteristic hole after etching [13]. The mass of the foils has been determined by alpha counting of the alpha activity of natural Uranium.

To build up a fine grid of measurements, inside the device, a large number of counters sensitive to fissions mounted at regular distances on supporting rods have been inserted between the Uranium bars and moved in different, successive positions during the data taking. These detectors (see Table 2) detect fission fragments from a thin ( $\approx 1 \text{ mg/cm}^2$ ) Uranium foil with the help of solar cells operated as semiconductor detectors [14] and Argon proportional counter gaps at 3 ata [15]. Pulse-height and time information of each count are individually recorded over a window of  $800 \mu\text{s}$  after the beam pulse. The Uranium foils can be displaced away periodically in situ during the data taking in order to determine the (negligible) background level due to interactions other than fissions in the foils. Typically one records some 20–100 fission/pulse, of course with rates widely dependent on the position of the counters. The proton beam intensity has been varied in order to ensure a data rate free of pile-ups.

Electronic counters are insensitive to the prompt neutrons and charged particles ( $\approx 5\%$ ) because of saturation around  $t = 0$  and to delayed neutrons ( $\approx 7\%$ ), but they allow to observe exponential decay of the activity. A typical distribution is shown in Fig. 3 and shows good agreement with the (asymptotic) exponential behaviour predicted by the theory. The value of the multiplication constant determined with this method is  $k = 0.89 \pm 0.03$ , in agreement with expectations. A value of  $k$  has also been determined using the delayed neutron signal. The result,  $k = 0.915 \pm 0.010$  is in good agreement with the other methods.

In order to calculate the energetic gain  $G$  of the device, defined as the ratio between the energy produced in the device divided by the energy delivered by the beam, we must integrate the energy depositions sampled by the thermometers over the full volume. A correction (typically  $\leq 20\%$ ) must also be applied for the different opacities of the Uranium in the bars and in the thermometers and for the fact that the insertion of detectors depletes some of the moderating medium nearby. We have parametrized the spatial distribution of the energy deposition with a formula of the type  $\phi(x, y, z) = \text{const} \times \exp(-d/\lambda)$ , where  $d = \sqrt{(\alpha x + \delta)^2 + y^2 + z^2}$  (x-axis along the beam line, z-axis vertical) with the (fudge) parameters  $\delta$  and  $\alpha$  taking into account respectively the average effective longitudinal displacement and the first moment of the longitudinal extent of the hadronic high energy cascade (neutron source) and  $\lambda$  the common exponential decay length. Such a parametrization is in

agreement with the information of the electronic counters and the Monte Carlo simulation of the device. The fitted values for the parameters based on some  $10^3$  counter position measurements and the thermometer measurements show excellent agreement with the parametrization and give (1)  $\alpha \approx 0.85$  slightly increasing with energy, (2) an universal exponential slope, as expected by the behaviour of the subcritical device and (3) a progressive movement of the centroid of the beam source  $\delta$  as shown in Fig. 4a. The experimental dependence of the fission rate as a function of the distance  $d$  is shown in Fig. 4b for the different measurement methods (in excellent agreement). The same quantity, normalised to the expectation of the parametrization is given as function of the cosine of the angle with respect to the beam direction in Fig. 4c. Agreement is good, especially if one take into account that only an integral over the distribution is needed in order to determine  $G$ .

The integrated values of  $G$  from (1) the thermometers (2) from the fissions measured with the Lexan foils and (3) the electronic counters after the indicated corrections as a function of the proton kinetic energy are in excellent agreement. Combined results are shown in Fig. 5. The gain  $G$  is essentially constant above a proton kinetic energy of 1 GeV and drops somewhat for lower values. A practical EA can therefore be operated conveniently with proton beam energies of the order of 800 MeV to 1.2 GeV. A sector focused cyclotron scaled up from the PSI machine appears to be the most adequate device to produce currents of the order of 10 mA in this energy range [16].

Results (Fig. 5) are in satisfactory agreement with Monte Carlo calculations based on FLUKA [3] for the energy cascade complemented by a home made Monte Carlo based on the ENDF-6 cross sections [17] for the neutronic behaviour. Typically we find agreements of the order of 10% for the gain, the spatial distribution of the fissions and the time decay of the time dependence of the neutron activity. This confirms the validity of our previous predictions on the EA [1],[8], then based only on the Monte Carlo.

A simple expression can be used to calculate the energy gain of a general EA,  $G = G_0 / (1 - k)$ , where  $G_0$  relates to the efficiency of the spallation regime and the well known  $(1 - k)$  factor with  $k$  as the effective multiplication coefficient, relates to the neutron driven part of the cascade. Using  $k = 0.895$  from the source measurement and the values for 1 GeV proton energy, we find  $G_0 = 3.1 \pm 0.4$ . A gain  $G = 62 \pm 8$  is then expected with a somewhat larger device and  $k \approx 0.95$ , which is safely away from criticality. The energy produced by the EA ( $E_{ea}$ ) has to be spent in part to run the accelerator. We define the "commercial" gain  $G_c$  as  $E_{ea} / E_{acc}$  where  $E_{acc}$  is the energy output of the accelerator. Assuming a realistic accelerator efficiency of 0.4 [16] and an efficiency of transformation from heat into electricity of 1/3:  $E_{ea} = E_{acc} \times G - E_{acc} / (0.4 \times 1/3) = E_{acc} \times (G - 7.5)$ ;  $G_c = G - 7.5$ . For  $k = 0.95$  we obtain a comfortable "commercial" gain  $G_c = 54.5 \pm 8$ . With a 10 mA, 1 GeV accelerator [16], a suitable EA should deliver a net power of  $545 \pm 80$  MW thermal or about  $181 \pm 30$  MW electrical.

Although the possibility of a high gain has been demonstrated, the set-up of Fig. 1 cannot be used immediately for an extended power production. Some substantial modifications are required [1][8]. In a practical, full scale EA the rate of interactions will be much larger than in the present test. As a consequence, nuclear transmutations of elements are sizeable and modify the evolution of the subsequent cascades. This different regime is quite useful since it permits to "breed" fissionable nuclei from the bulk material of the target and thus (1) achieve useful gains from targets which otherwise would not be suitable, like for instance natural Thorium ( $\text{Th}^{232}$ ) or depleted Uranium ( $\text{U}^{238}$ ); (2) the fissionable fuel being continuously regenerated from the bulk material rather than only supplied initially with the fuel, a much longer burn-up is possible. Previous experience with reactors indicate that most of these procedures are basically feasible.



According to the EA proposal [8], after an extended exposure of the target to the beam (corresponding to the burning of some 3 – 15 % of the mass of the target, depending on the specific conditions) the used fuel is extracted and after an adequate cool-down period is (1) topped with fresh  $\text{Th}^{232}$  or  $\text{U}^{238}$ ; (2) many reaction products which are either stable or environmentally acceptable ( $T_{1/2} \leq 32$  years) elements are extracted and stored in a "secular" repository and (3) new regenerated fuel is constituted with the rest. Over the lifetime of the plant, the composition of the fuel will change and reach an equilibrium condition, as a balance between production and "neutron incineration". Similar schemes of transmutation and/or energy generation by nuclear cascades have been proposed, in particular the (ADWT) one from Los Alamos based on molten salt, thermal neutrons, high flux capability and continuous recirculation of the fuel [18] and others [19]. The experimental results reported here have of course equally positive relevance for these proposals.

The conclusions of the analysis of a full scale device [1][8] are also that (1) Thorium is a far cleaner fuel than  $\text{U}^{238}$  and it is used very efficiently (750 kg of natural  $\text{Th}^{232}$  deliver the same useful energy ( $800 \text{ MWatt} \times \text{year}$ ) as 167 tons of natural Uranium with the ordinary Pressurised Water Reactors (PWR) operating with isotopically enriched Uranium) (2) the fuel properties are such to permit indefinite recycling (3) the long term total radio-toxicity spilled in the environment due to mineral mining and chemical handling of the fuel is at least four to five order of magnitudes smaller than the one for PWR's for an equivalent power production [20] and (4) diversion of the spent fuel to military applications can be made practically impossible or extraordinarily difficult [8][21].

We believe that in most respects the EA (or equivalent scenarios) is comparable in performance to Thermonuclear Fusion. Both approaches offer practically unlimited fuel resources: the energetic content of Lithium on the Earth's crust needed by Fusion is estimated to be seven times the one of Thorium and they are both adequate for millions of years of very intensive utilisation. However the EA can be built economically [22], in a variety of sizes and it offers a much greater flexibility of utilisation. Moreover it presents no major technological barriers and it is far more suited because of its simplicity as an alternative to fossil fuels and to respond to the growing energy demands of the developing countries.

We are grateful to UPM and ENRESA for their support in making available the assembly, to the Spanish and Swiss Office of Energy for their special care in providing the necessary authorizations, to the CERN ECP/DS and ECP/ESS/OS Groups for having provided and supported the CASCADE data acquisition system, and to the Commissariat à l'Energie Atomique-Marcoule for providing the neutron source used for calibration. In particular, we would like to mention the outstanding dedication of R. Cappi, L. Durieu and J.P. Riunaud of the CERN PS Division who succeeded in stretching the performance of the accelerator to accommodate the needs of the experiment. This experiment would not have been possible without the enthusiastic contribution of many members of all the collaborating institutions.

## REFERENCES

1. F. Carminati, C. Gelès, R. Klapisch, J.P. Revol, Ch. Roche, J.A Rubio and C. Rubbia, "An Energy Amplifier for Cleaner and Inexhaustible Nuclear Energy Production Driven by a Particle Beam Accelerator", CERN/AT/93-47 (ET) (1993).
2. C.W. Fabjan et al., Nucl. Instr. and Methods 141 (1977) 61-80 and "Preliminary Design of a Warm Liquid Version for the UA1 Calorimeter, SPSC/85-57/M 415.
3. OECD has organised an "Intercomparison of Data and Codes for Intermediate Energy". The result of this exercise for thin targets shows that proton and neutron double differential cross-sections can be considered reliable to better than a factor of 2 and single differential cross sections are coherent to within 30%. The thick target results - which incorporate inter alia transport properties - are more relevant to Accelerator Driven Systems. They are still being analysed by the OECD task force. We have therefore chosen the FLUKA code which has been very successful at CERN in calculating shielding and the properties of calorimeters, (see ref. 4). FLUKA is largely adequate for the low energy neutron part of these and other High Energy Physics applications, but has not been designed for reactor type calculations. We have stopped, somewhat arbitrarily, the FLUKA calculation when the energy of the neutron falls below 1 MeV and a special transport code developed by one of us (C. Rubbia) and based on pointwise cross sections has been used. Concerning the FLUKA code, we refer in particular to A. Fassó et al, in "Intermediate Energy Nuclear Data: Models and Codes", Proceedings of a Specialists' Meeting, Issy les Moulineaux (France) 30 May-1-June 1994, p. 271, published by OECD, 1994, and references therein.
4. A. Fassó, A. Ferrari, J. Ranft, P.R. Sala, G.R. Stevenson and J.M. Zazula, Nuclear Instruments and Methods A, 332, 459 (1993), also, CERN Divisional Report CERN/TIS-RP/93-2/PP (1993).
5. See for example S. Glasstone, "Principles of Nuclear Reactor Engineering", D. Van Nostrand Inc. (1955).
6. C. Rubbia, "An Analytic Approach to the Energy Amplifier", Internal Note, CERN/AT/ET/ 94-036. Also C. López, Private Communication.
7. C. Rubbia, "Why So Many Exponentials?", Internal Note, CERN/AT/ET/ 94-032.

8. C. Rubbia, "A High Gain Energy Amplifier Operated with Fast Neutrons", Contribution to the Las Vegas Conference on Accelerator Driven Transmutation Technologies and Applications 25-29 July 1994, and C. Rubbia et al, to be published.
9. F. Carminati, P. Cennini, J. Galvez, C. Geles, R. Klapisch, P. Mandrillon, J. Oropesa, J.P. Revol, Ch. Roche, C. Rubbia, J.A. Rubio and F. Saldana "A Test of the Basic Concepts of the Energy Amplifier", Internal Note, CERN /AT/ET/ 94-007 and references therein.
10. Calero et al., "Measurements of Relative Neutron Flux in the Subcritical Assembly used for the First Energy Amplifier Test", Internal Note, CERN/AT/ET/94-041.
11. Calero et al., " Experimental Temperature Measurements for the Energy Amplifier Test", Internal Note, CERN /AT/ET/ 94-038.
12. C. López, S. Vieira et al., "Report on the Energy Output Measurement System for the Energy Amplifier Experiment", Internal Report Universidad Autónoma de Madrid-Instituto de Ciencia de Materiales 'Nicolas Cabrera', September 1994.
13. Angelopoulos et al., "Experimental Determination of the Gain in the Energy Amplifier", Internal Note, CERN/AT/ET/ 94-043 and paper subm. to NIM.
14. J. M. Loiseaux and H. Nifenecker, "Proposal for the Determination of the Physical Parameters of an Energy Amplifier", Internal Note, CERN/AT/ET 94-018, F. Attale et al., "Calibration of the Grenoble Detectors", Internal Note, CERN/AT/ET 94-035 and S. Andriamonje "Caractéristiques des Détecteurs Photovoltaïques pour la détection des fragments de fission à l'intérieur des barreaux d'Uranium" Internal Note, CERN/AT/ET 94-044.
15. F. Casagrande and P. Cennini, "Fission Fragment Argon Gas Detector for the Energy Amplifier Test", Internal Note, CERN/AT/ET 94-042.
16. C. Rubbia, P. Mandrillon and F. Fietier, "A High Intensity Accelerator for Driving the Energy Amplifier for Nuclear Energy Production" in Proceedings of EPAC94, London, June 1994, to be published; Th. Staimbach et al., "Potential of Cyclotron Based Accelerators for Energy Production and Transmutation", Contribution to the Las Vegas Conference on Accelerator Driven Transmutation Technologies and Applications, 25-29 July 1994.
17. The ENDF formats and libraries are coordinated by the National Nuclear Data Center (NNDC) and decided by the Cross Section Evaluation Working Group, (CSEWG), a cooperative effort of national laboratories, industry and universities in the US, and AECL/ Chalk River, Canada.

18. C. Bowman et al., Nucl. Instr. Methods, A320, 336 (1992). More recent developments are to be found in the Proceedings of the International Conference on Accelerator-Driven Transmutation Technologies and Applications, Las Vegas, 25-29 July 1994.
19. The first proposal for large scale use of spallation to cause transmutation (in that case to breed nuclear fuel from a fertile element) came from Chalk River (W. Lewis, AECL report 969, 1953). It is only recently that this has surfaced again as a practical proposition. In addition to the work by the Los Alamos group quoted in reference [16], several different proposals have been made. We quote in particular the PHOENIX concept at Brookhaven (G. Van Tuyle et al. BNL report 52279 (1991) and H. Takahashi, Fusion Technology, 20 657, 1991; the OMEGA project at JAERI (T. Takizuka et al, Specialist Mtg. on Accelerator-driven Transmutation for Radwaste and other Applications, Stockholm 24-28 June 1991) and the project at ITEP, Moscow (V.D. Kazaritsky et al. in "Accelerators Applied to Nuclear Waste", 8th Journées Saturne, Report LNS/Ph/94-12).
20. C. Rubbia et al. (to be published).
21. J. Magill, C. O'Carroll, P. Gerontopoulos, K. Richter, J. Van Geel, "Advantages and Limitations of Thorium Fuelled Energy Amplifiers", Contribution to the Nuclear Society 5th Annual Conference on Nuclear Power and Industry, Obninsk, 7-11 November 1994.
22. C. Geles, G. Lindecker, P. Mandrillon, C. Roche, C. Rubbia, J.A. Rubio, "Energy Amplifier: Notes on Cost Analysis", Internal Notes, CERN/AT/ET 94-002,94-011, and 94-011 addendum; D. Finon and P. Menanteau, "Premiers Eléments d'Analyse de l'Evaluation Economique de l'Amplificateur d'Energie", Institut d'Economie et Politique de l'Energie du CNRS, Grenoble 1994, Internal Report and to be published.

## FIGURE CAPTIONS

- Fig. 1 Top view of the subcritical assembly. Distances are in mm.
- Fig. 2 Neutron counting as a function of the distance to the source. The triangles correspond to the Monte Carlo simulation data.
- Fig. 3 Time dependence of fission rate. The line corresponds to the Monte Carlo simulation.
- Fig. 4a x-Displacement of the cascade centre as a function of the beam kinetic energy. The line is the result of an empirical exponential fit to the data.
- Fig. 4b Number of fissions/mg/pulse ( $10^9$  protons) as a function of the distance to the centre of the cascade. The circles, triangles and points correspond to the Thermometer, Lexan and Semiconductor counters measurements respectively. The line is the result of an exponential fit to the semiconductor counters data. Small deviations of the fit at small distances are due to the finite dimensions of the source.
- Fig. 4c Residuals (ratio between experimental data and fit) as a function of  $\cos(\theta)$ ,  $\theta$  being the polar angle of the detector position respect to the beam direction. It shows no forward/backward asymmetries in the fission rate.
- Fig. 5 Average energy gain from the different detectors as a function of the beam kinetic energy. The continuous line is the result of an empirical fit to the data. The dashed line corresponds to the modified FLUKA [3] simulation.

Table 1: Parameters of the sub-critical assembly.

<b>Materials:</b>		
Fuel	<i>Natural Uranium</i>	
Moderator	<i>Light Water</i>	
Reflector	<i>Light Water</i>	
Tubes holding the fuel (cladding)	<i>Aluminium</i>	
Tank	<i>Stainless Steel</i>	
<b>Total mass:</b>		
Fuel	3.62	T
Moderator	0.34	T
Tubes, tank, Reflector	0.35	T
<b>General dimensions: Fuel</b>		
General shape	<i>Hexagonal prism</i>	
Lattice cell	<i>Hexagonal</i>	
Bar infra-centre distances	5.08	cm
Fuel height	107.00	cm
Fuel diameter	89.00	cm
Volume moderator/Volume fuel	1.77	
<b>General dimensions: Reflector</b>		
Lower, upper thickness	16.0	cm
Lateral thickness, max.	15.5	cm
Lateral thickness, min.	12.5	cm
<b>General dimensions: Tank</b>		
Height	152.4	cm
Diameter	122.0	cm

Table 2.- Summary of detector parameters.

Detector	Active Element	Uranium converter	Clustering	Location	Number of units
<i>Gas Ionisation Chamber 4 nla Argon</i>	Circular window, $\Phi=15$ mm vertical plane	1 mg/cm <sup>2</sup> deposit	1 array of 6, spaced 10 cm vertically. 2 arrays of 8, spaced 12.3 cm vertically	in water, between U bars	22
<i>Amorphous Si Diode thickness 300<math>\mu</math>m</i>	Rectangular. window 9.6 x 11.6 mm <sup>2</sup> vertical plane	1 mg/cm <sup>2</sup> deposit	10 arrays of 16 counters, spaced 6.4 cm vertically	in water, between U bars	160
<i>Amorphous Si Diode thickness 300<math>\mu</math>m</i>	90° sector r= 14 mm horizontal plane	1 mg/cm <sup>2</sup> deposit	4 clusters of 6 counters spaced 21.3 cm vertically	in fuel bar, between U cartridges	24
<i>Thermistances in metallic probes</i>	U Cylinders $\Phi=8$ mm Pb Cylinder $\Phi=10$ mm	~ 55 g U	3 thermometers with two U probes	in water, between U bars	6
<i>Lexan foils track detectors</i>	Equilateral triangles r=37mm Circles $\Phi=32$ mm Rectangle 10x25 mm <sup>2</sup> Vertical plane	~ 1 mg/cm <sup>2</sup>	5 vertical sets of 2 detectors	in water, between U bars	10



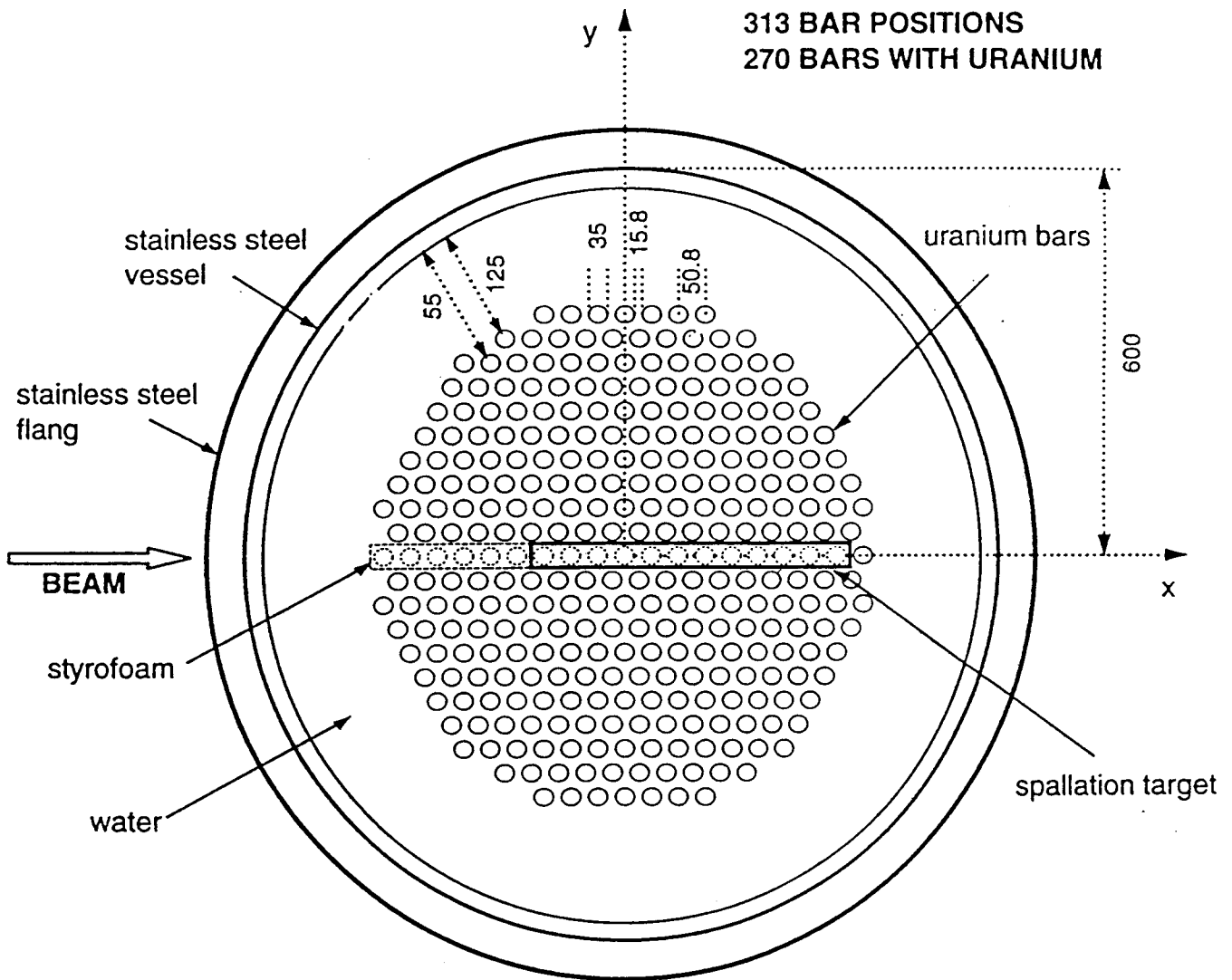


Figure 1

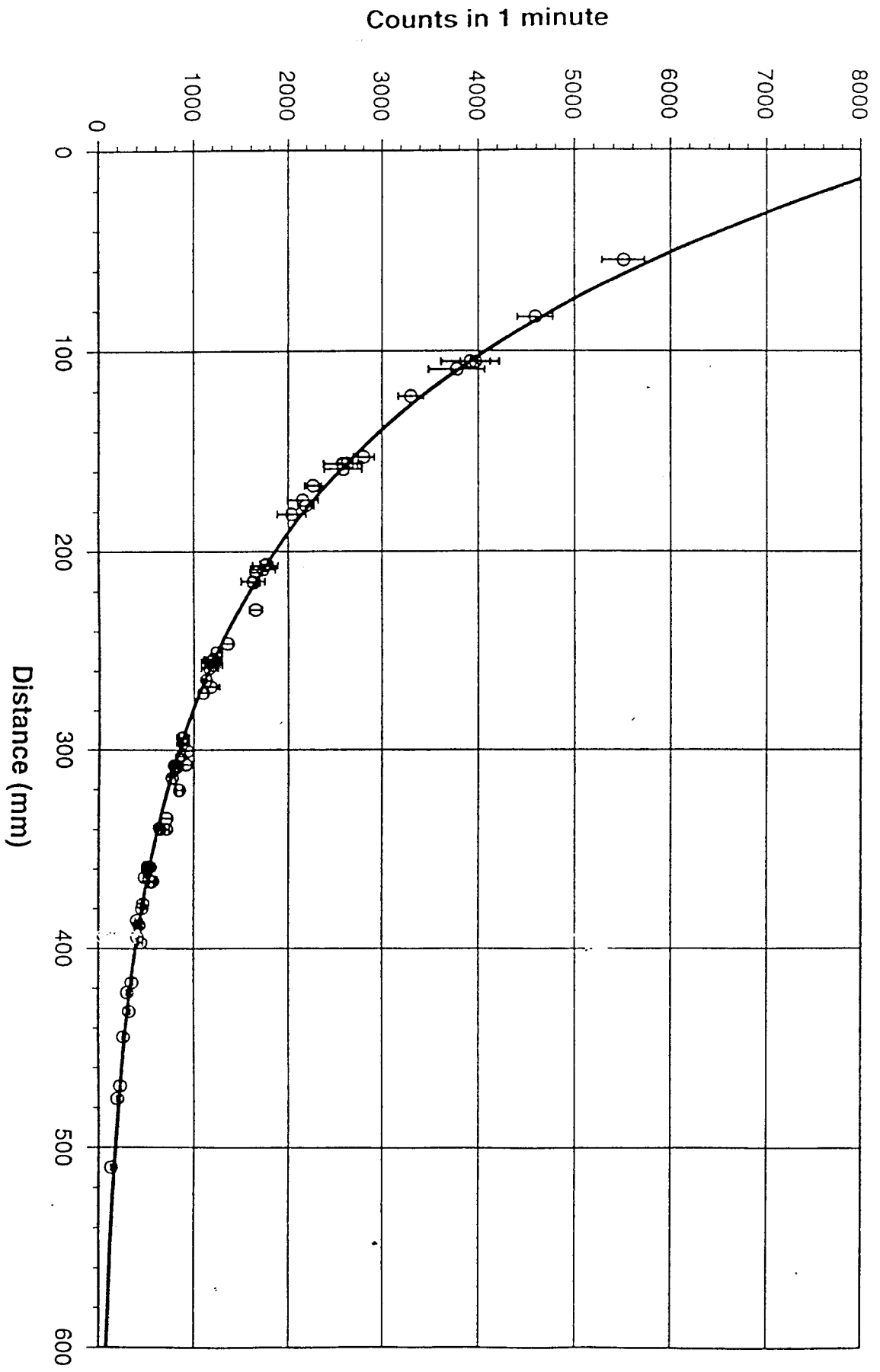
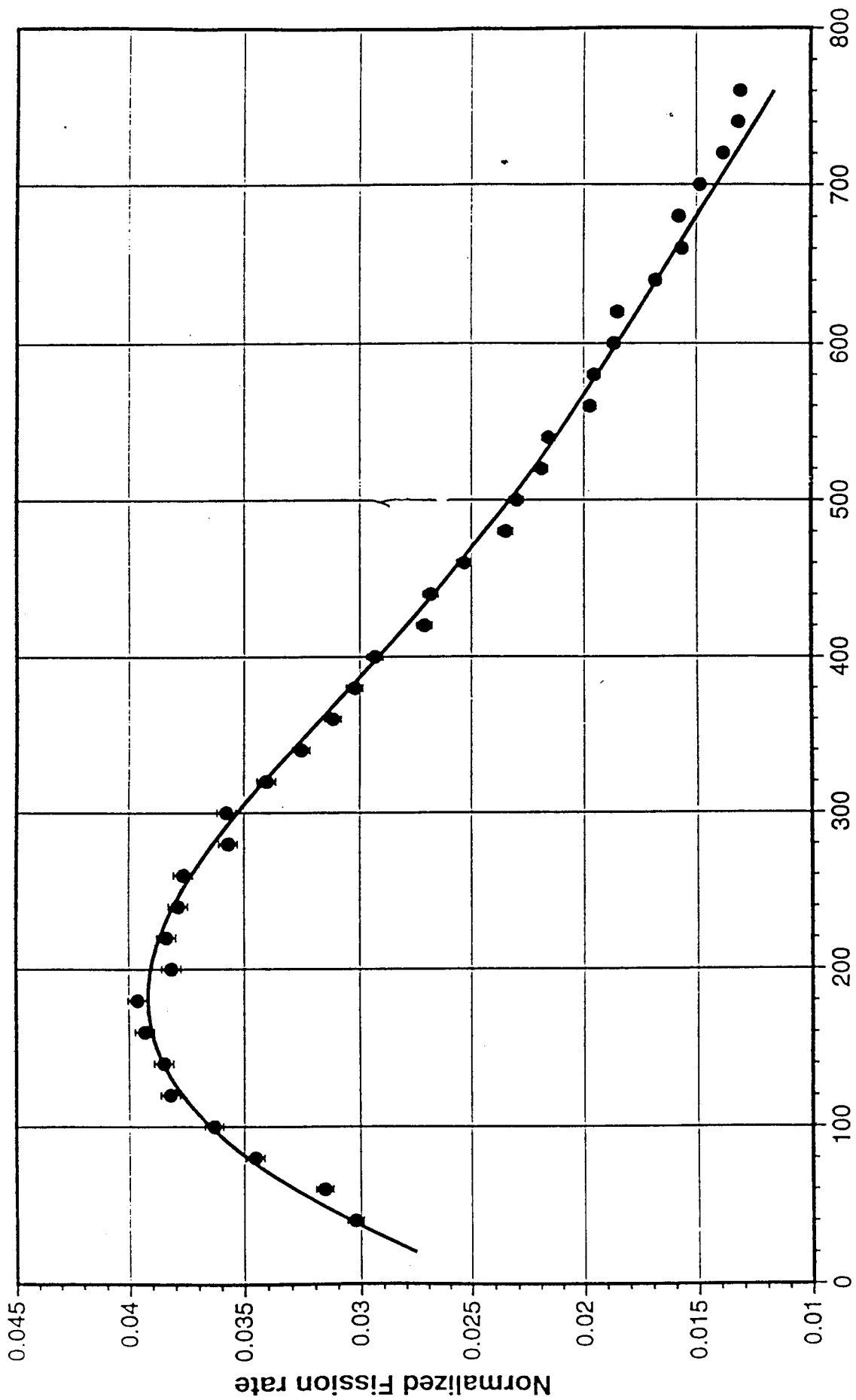


Figure 2



Time ( $\mu\text{s}$ )  
Figure 3

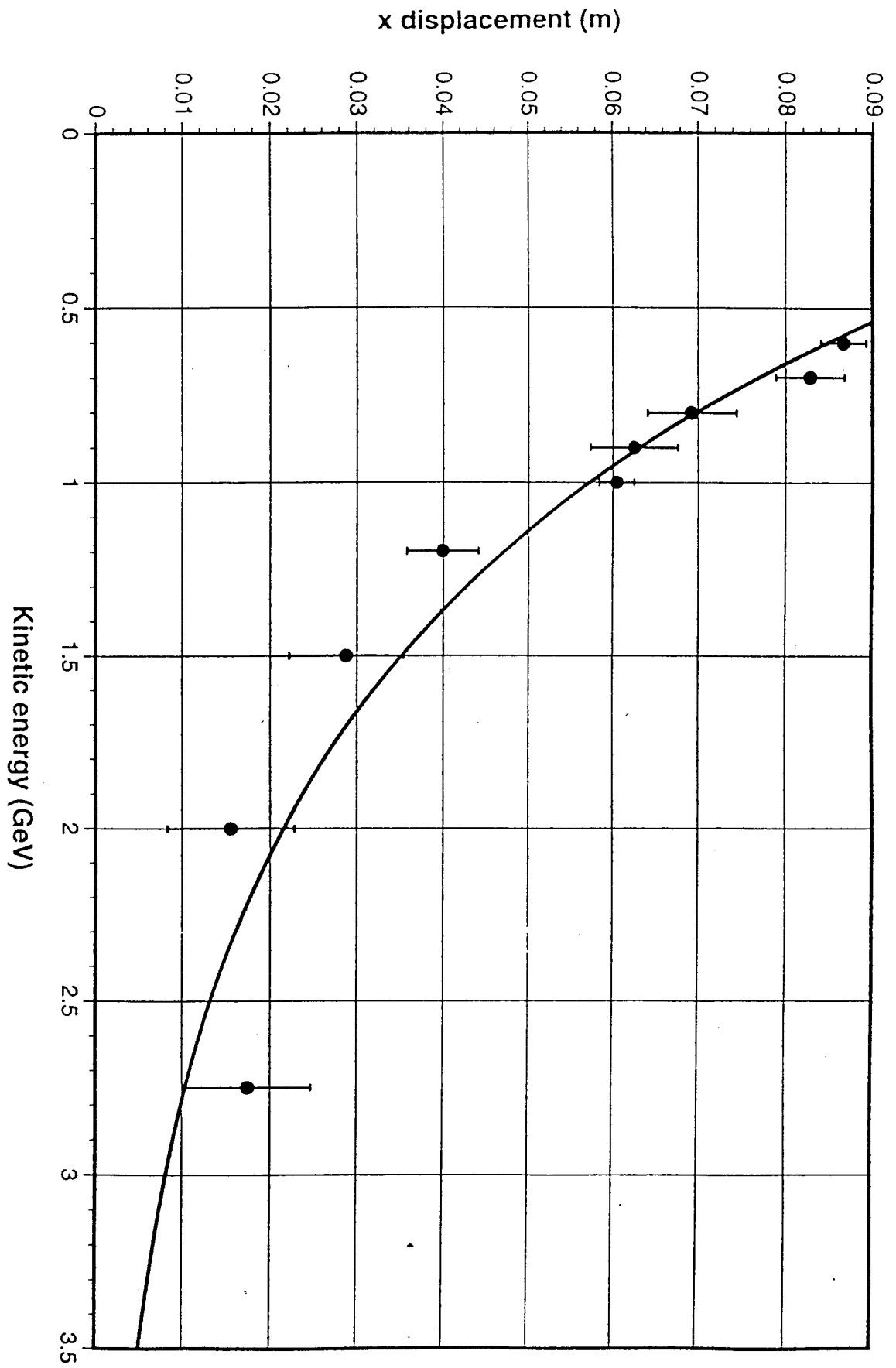


Figure 4a

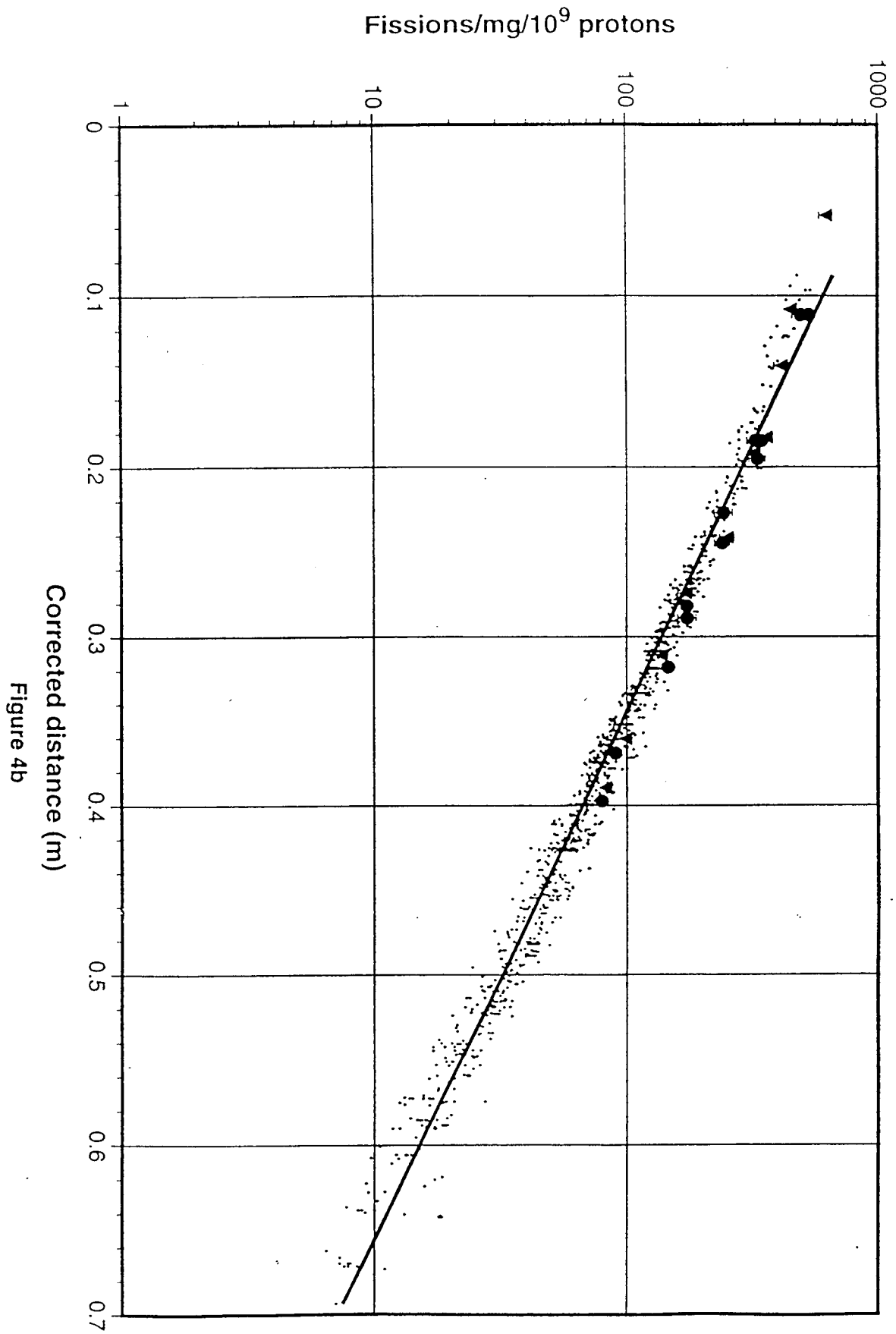


Figure 4b

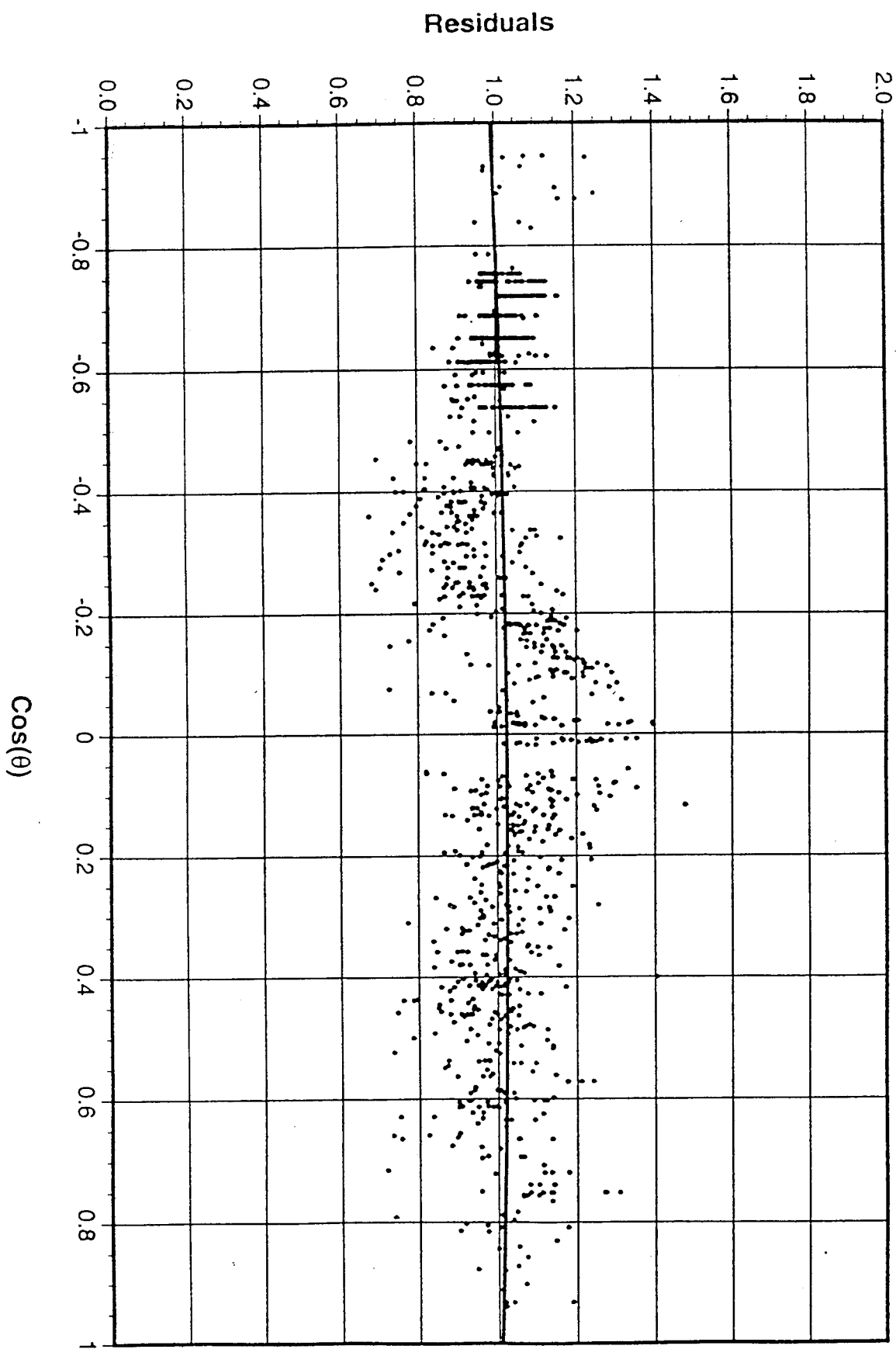


Figure 4c

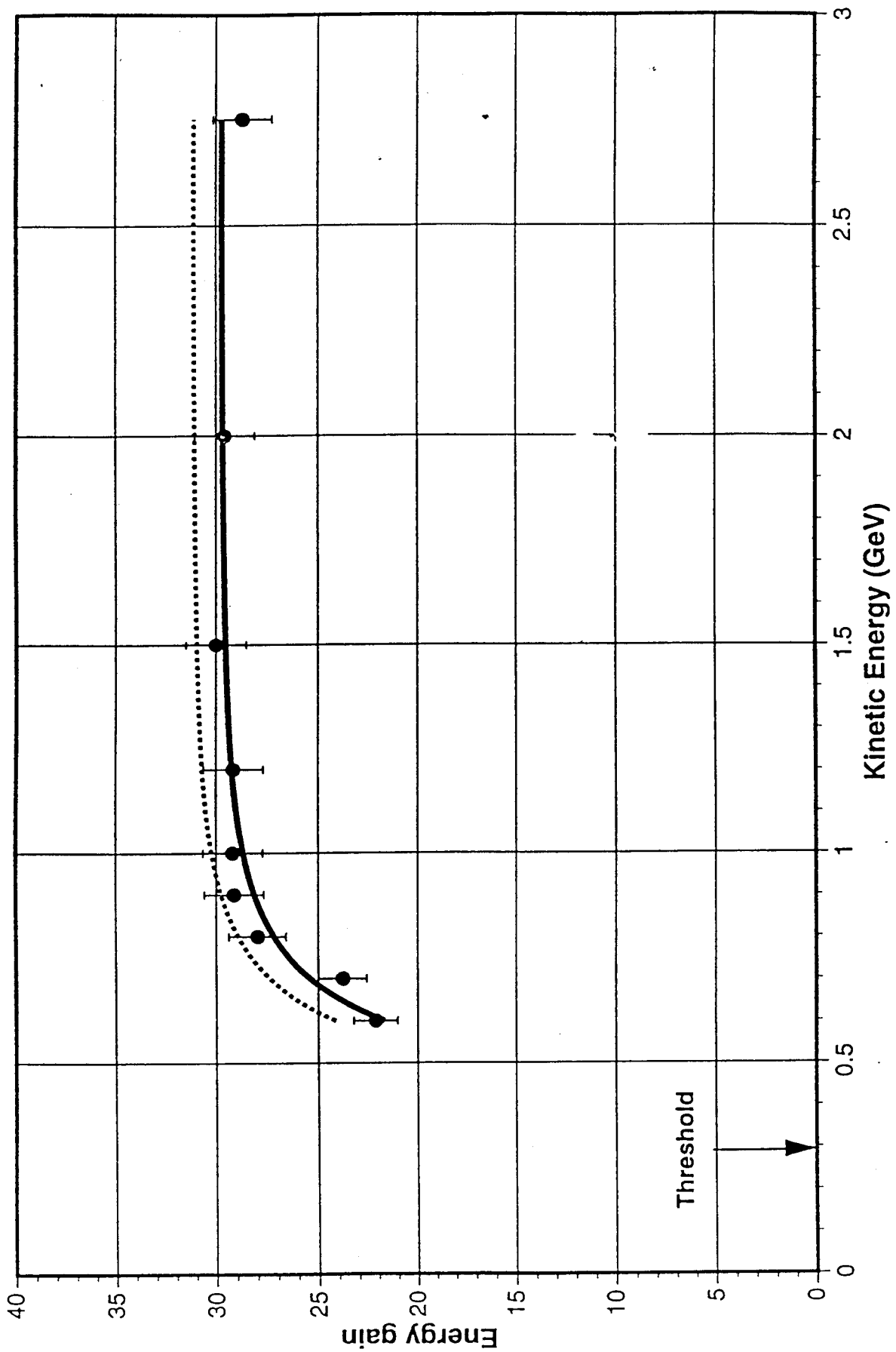


Figure 5