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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 ≥ 1 GeV, below which G decreases but is still acceptable in the energy range explored.

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Nuclear reactors produce today a significant fraction (≈ 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 (≈ 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 to 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_∞, defined as the average 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 (δ-function), the neutron population decreases exponentially with a time constant which grows linearly with $1/(1-k)$, where k is the *effective multiplication coefficient* [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 ≤ 1.0 cm radius focal spot, in the form of a sharp (≤ 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}U.

The neutronic behaviour of the assembly has been calibrated with the help of a 58 GBq 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 (styrofaoam, target etc.) have been introduced. The calculated reduction is $\Delta k = -0.02$, leading to an expected value for the beam configuration of $k = 0.895 \pm 0.010$.

The parameters of the detectors are listed in Table 2. The power produced by the beam in the device, typically ≈ 1 watt, has been measured by the temperature rise of small sampling blocks of Uranium [11] moved at different positions inside the device (Table 3). In practice the temperature behaviour in a succession of beam-on beam-off cycles (typically 1-$1^1/_2$ hours and two cycles per position/beam energy) has been measured. The specific power produced inside the Uranium probes of the thermometer was obtained by applying two methods of analysis: the usual calorimetric method and a five parameters method based on an equivalent electrical model, which allows to predict the temperature evolution outside the thermometer. A "zero" measurement has also been performed, with a lead block which is known to be largely transparent to low energy neutrons. Figs. 3a and 3b show an example of a temperature measurement and the description obtained by the two methods of analysis. In Fig. 3b the behaviour of the temperature outside the thermometer, measured with Pt resistors (more than one order of magnitude less accurate than the NTC thermistors used in the themometer's probes), is compared with the prediction from the electrical model. The results from both methods were always compatible and the typical accuracy, for 10^9 protons each 14.4 s, is ≈ 10 nW/gr, equivalent to ≈ 0.3 mK in the temperature variation. The specific heat of the ensemble Uranium sample-thermal insulator-supports (close to the Uranium specific heat) was determined by heating with the thermistors, injecting 1 mA during 80 s and measuring the temperature change. To calibrate, the same method was used [12], in particular by a simulation of the experimental conditions injecting 1 mA during 10 s, each 120 s, for periods of $1^1/_2$ hours. The heat measured by the analysis of the temperature evolution, using the above referred methods, are in agreement with the heat injected within 1%. Results of the power generated, normalized to the beam intensity, for different positions and energies, are listed in Table 3. The major contribution to the gain is expected from fission. This has been demonstrated counting the fissions in thin (≈ 1 mg/cm^2) 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 (≈ 1 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 μs 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 (≈ 5%) because of saturation around $t = 0$ and to delayed neutrons (≈ 7%), but they allow to observe exponential decay of the activity. A typical distribution is shown in Fig. 4 and shows good agreement with the (asymptotic) exponential behaviour predicted by the theory. The value of the multiplication coefficient 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 [16]. For that purpose, using one of the counters, a short test (35 minutes) was done counting fissions at all times except for a gate 100 μs before the beam pulse and 10 ms after the beam pulse. The result was 398 fissions in that delayed gate as compared to the 5649 fissions occurring simultaneously in the prompt gate. Taking a value of β, the delayed neutron branching ration of 0.0065, the ratio between the counts in the two scalers led to a value of k=0.915±0.005. The result is in good agreement with the other method but we point out that the quoted error is of purely statistical origin, since we have not evaluated the possible systematic errors. The preferred value, used in the analysis, is therefore based on the detemination from the source method as k= 0.895±0.010.

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 ≤ 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 $\phi(x,y,z) = const \times \exp(-d/\lambda)$, where $d = \sqrt{(\alpha x + \delta)^2 + y^2 + z^2}$ (x-axis along the beam line, z-axis vertical) with the (fudge) parameters δ and α 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 λ the common exponential decay length. Such a paramatrization 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, with $\lambda = 0.074$, as expected by the behaviour of the subcritical device and (3) a progressive movement of the centroid of the beam source δ as shown in Fig. 5. The experimental dependence of the fission rate as a function of the distance d is shown in Fig. 6a 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. 6b. 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. 7. 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 [17].

Results (Fig. 7) 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 [18] 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 average gain for 1 GeV proton energy, G = 29 ± 2, 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* [17] 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 [17], a suitable EA should deliver a net power of 545±80 MW thermal or about 181±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 (Th^{232}) or depleted Uranium (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) 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; (2) topped with fresh Th^{232} or U^{238} 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 [19] and others [20]. 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 U^{238} and it is used very efficiently (750 kg of natural Th^{232} deliver the same useful energy (800 MWatt × 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 [21] and (4) diversion of the spent fuel to military applications can be made practically impossible or extraordinarily difficult [8][22].

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 [23], 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.

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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 line corresponds to the Monte Carlo simulation data.

Fig. 3 Analysis of the temperature evolution of one cycle beam off - beam on a) using the calorimetric method, b) using the equivalent electrical method.

Fig. 4 Time dependence of fission rate. The line corresponds to the MonteCarlo simulation.

Fig. 5 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. 6a 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. 6b Residuals (ratio between experimental data and fit) as a function of cos(θ), θ being the polar angle of the detector position respect to the beam direction. It shows no forward/backward asymmetries in the fission rate.

Fig. 7 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. The error bars include quadratically both statistical and systematic errors although the biggest contribution has a statistical origin. Among the systematic contributions, the beam intensity accuracy and the error on the integral power due to the shape of the spatial distribution (both of the order of 2%) are the most important.

Table 1: Parameters of the sub-critical assembly.

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

Table 2.- Summary of detector parameters.

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

Table 3: Positions of the Thermometers and measurements of the specific power normalized to 10^9 protons/pulse each 14.4 s. For the radial dependence measurements only one thermometer (T1) was available. For the beam energy measurements three thermometers (T1, T2, T3) were used.

RADIAL DEPENDENCE MEASUREMENTS								
	Position 1		*Position 2*		*Position 3*		*Position 4*	
T1:	*U1*	*U2*	*U1*	*U2*	*U1*	*U2*	*U1*	*U2*
x (mm)	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4
y (mm)	- 102.7	- 102.7	- 190.6	- 190.6	- 278.6	- 278.6	- 366.6	- 366.6
z (mm)	29.6	- 150.4	29.6	- 150.4	29.6	- 150.4	29.6	- 150.4
Power density (nW/g)	1120 ± 65	726 ± 42	698 ± 52	504 ± 37	365 ± 20	308 ± 17	187 ± 12	165 ± 11

BEAM ENERGY DEPENDENCE MEASUREMENTS						
	T1		*T2*		*T3*	
Position:	*U1*	*U2*	*U1*	*U2*	*U1*	*U2*
x (mm)	25.4	25.4	0	0	228.6	228.6
y (mm)	102.7	102.7	293.3	293.3	102.7	102.7
z (mm)	29.6	-150.4	-10.4	-155.4	-25.4	-180.4
E_{beam}(GeV):	*Power density (nW/g)*					
0.60	171±6	116±5	51±3	46±4	62±3	48±3
0.70	233±14	147±15	66±9	52±9	72±8	58±8
0.80	294±21	192±19	98±13	74±13	103±8	72±8
0.90	335±10	216±9	96±5	91±4	121±8	91±5
1.00	390±10	256±9	113±5	102±4	150±5	107±4
1.20	482±38	305±28	136±9	119±7	194±14	144±11
1.50	601±30	364±16	188±10	165±9	254±10	172±7
2.00	842±29	532±19	238±10	200±9	360±17	248±14
2.75	1042±80	687±53			510±42	366±31

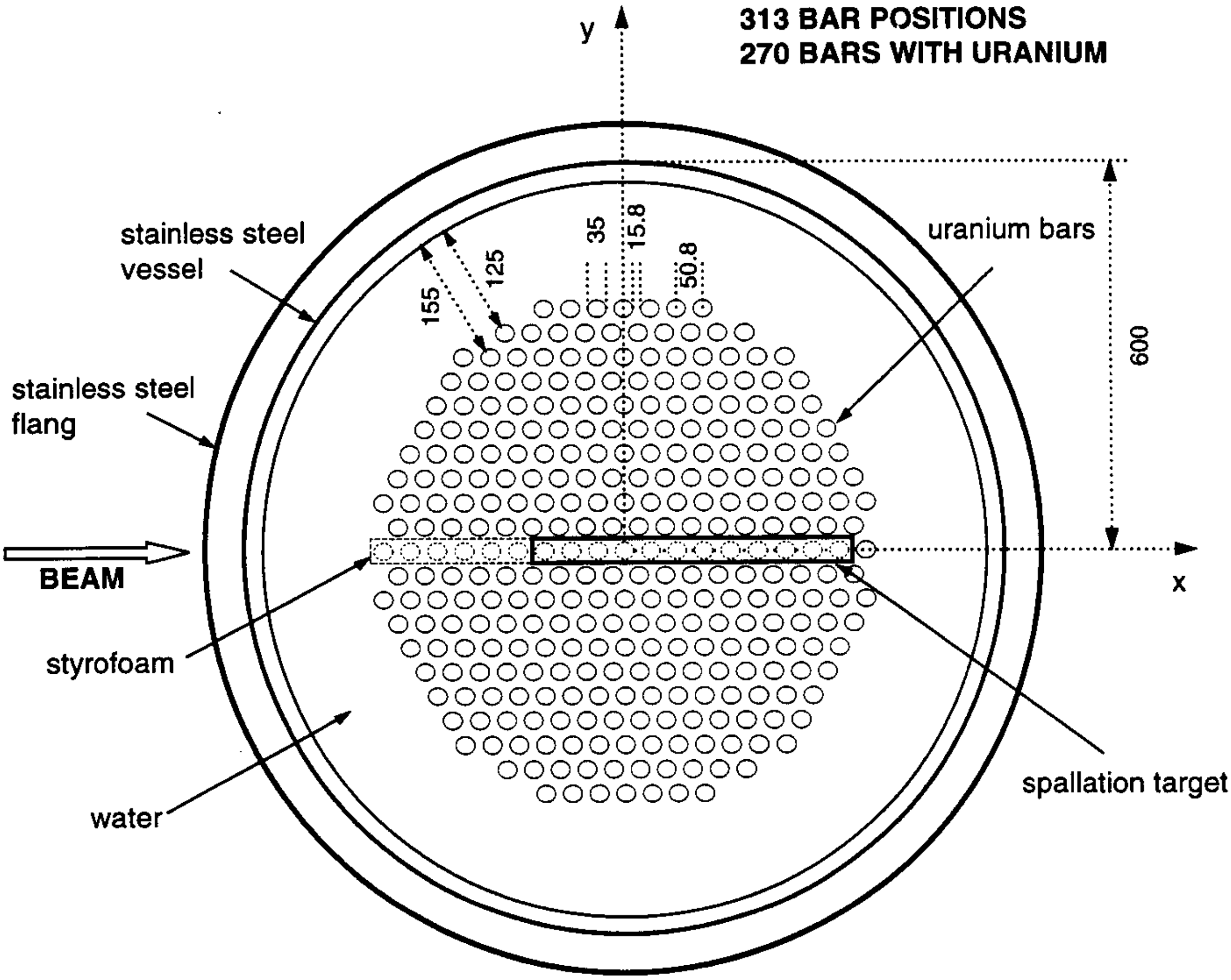
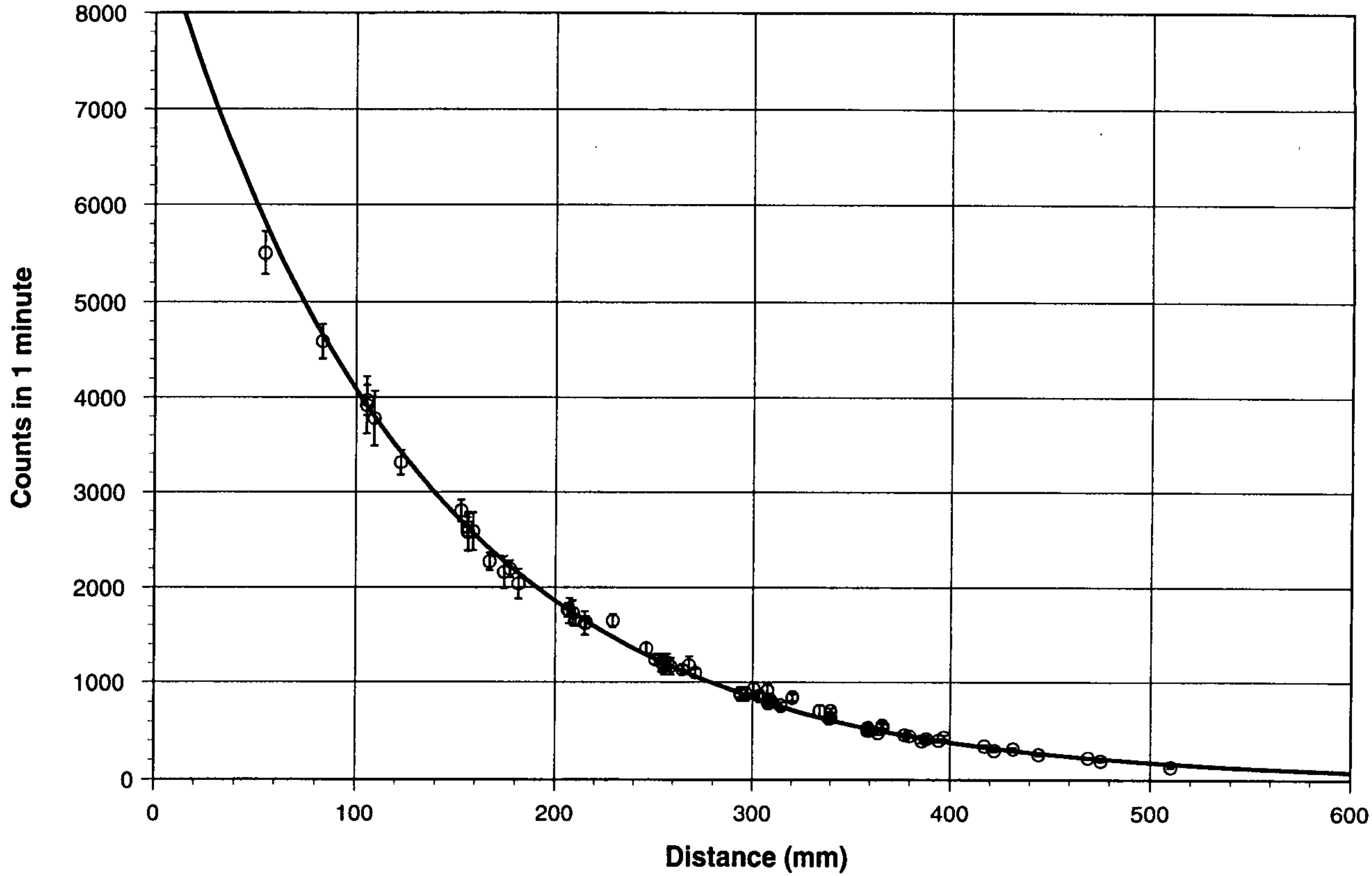

313 BAR POSITIONS
270 BARS WITH URANIUM
y
x
stainless steel
vessel
stainless steel
flang
BEAM
styrofoam
water
uranium bars
spallation target
155
125
35
15.8
50.8
600

Figure 1



Counts in 1 minute
8000
7000
6000
5000
4000
3000
2000
1000
0
0
100
200
300
400
500
600
Distance (mm)

Figure 2

Temperature measurement at 900MeV

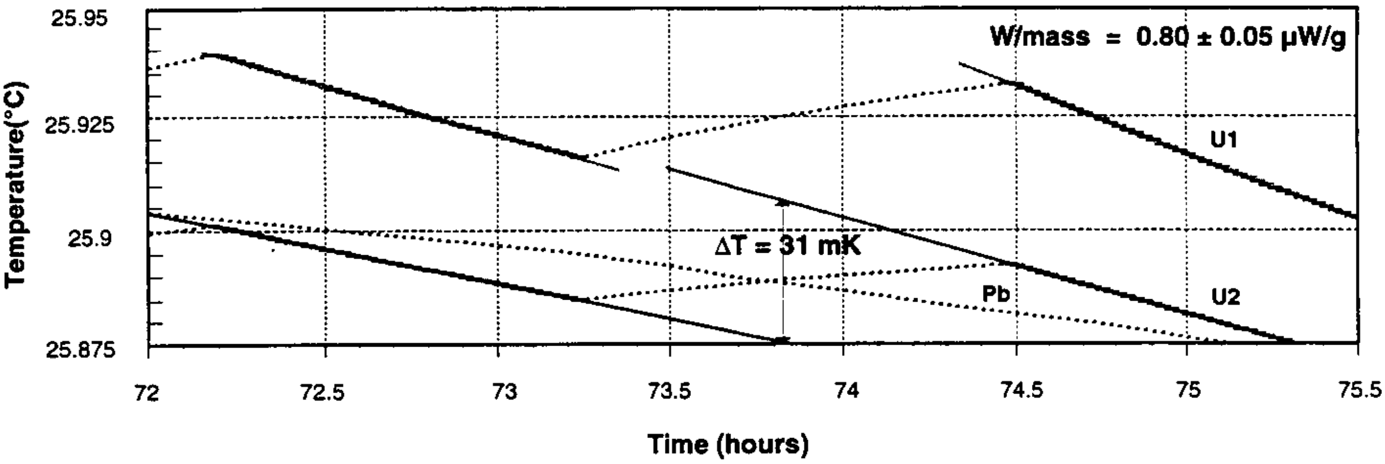


Figure 3a

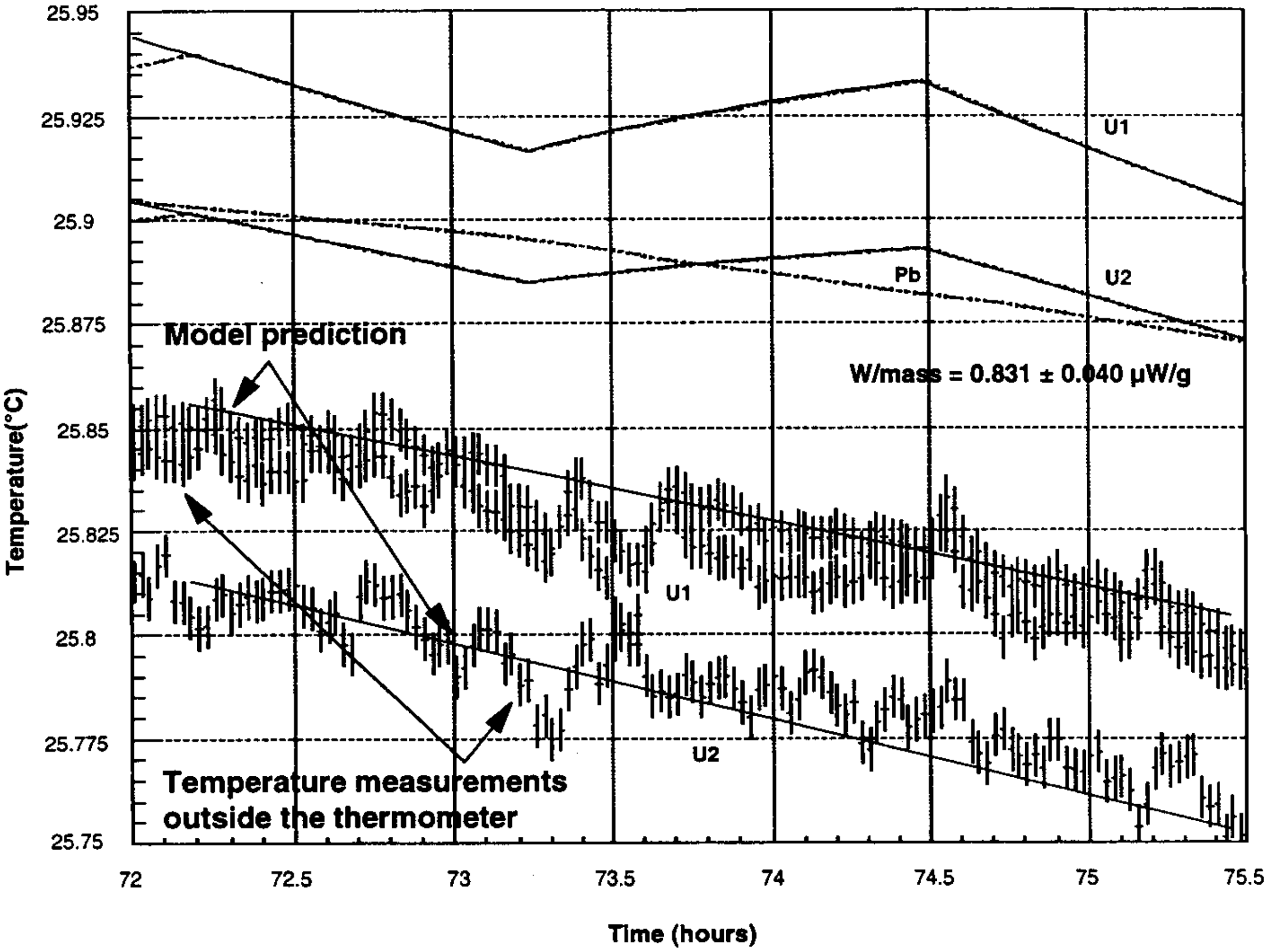


Figure 3b

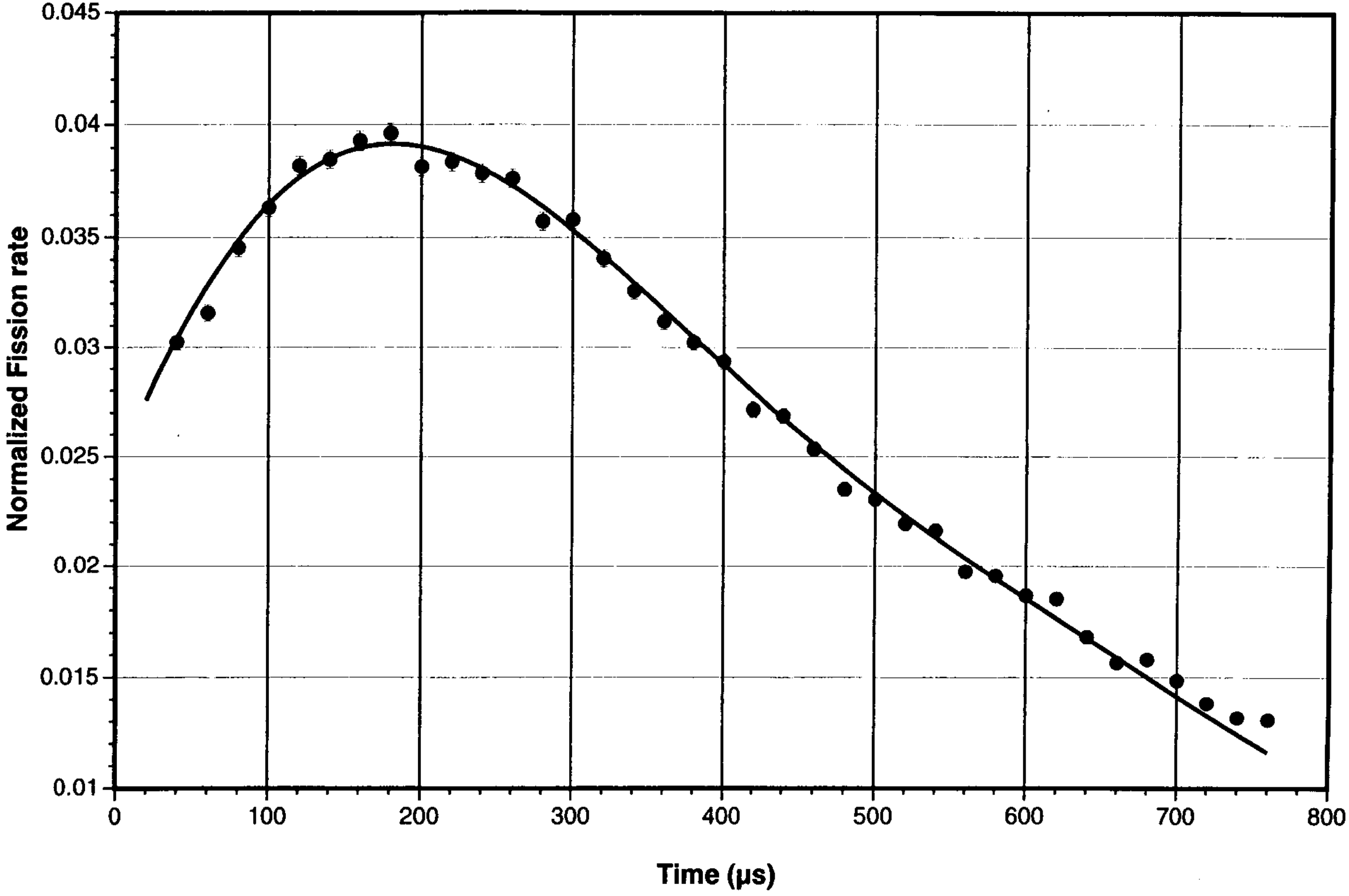
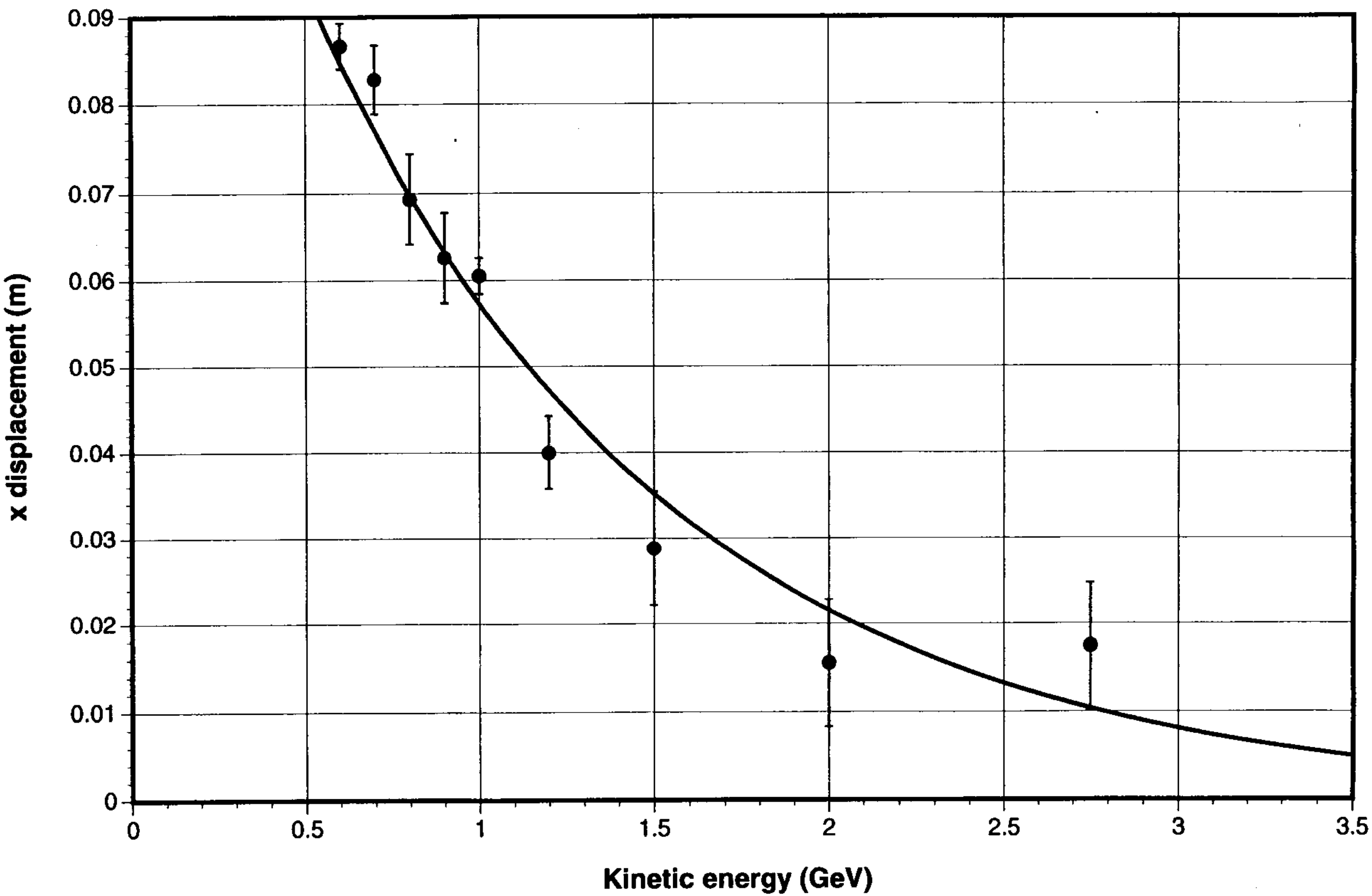
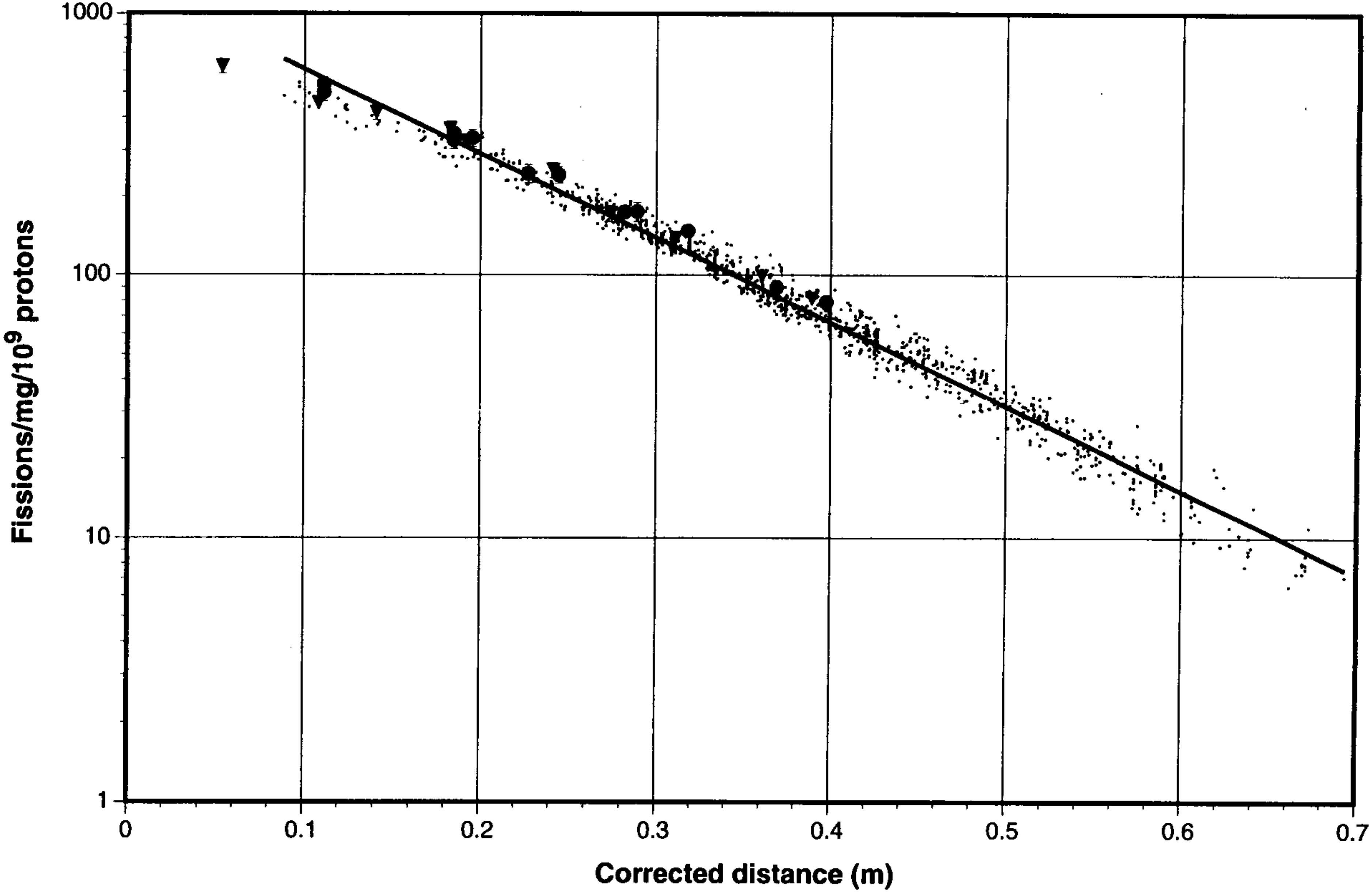

0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
Normalized Fission rate
0
100
200
300
400
500
600
700
800
Time (µs)

Figure 4



x displacement (m)
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
0.5
1
1.5
2
2.5
3
3.5
Kinetic energy (GeV)

Figure 5



1000
100
10
1
Fissions/mg/10^9 protons
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Corrected distance (m)

Figure 6a

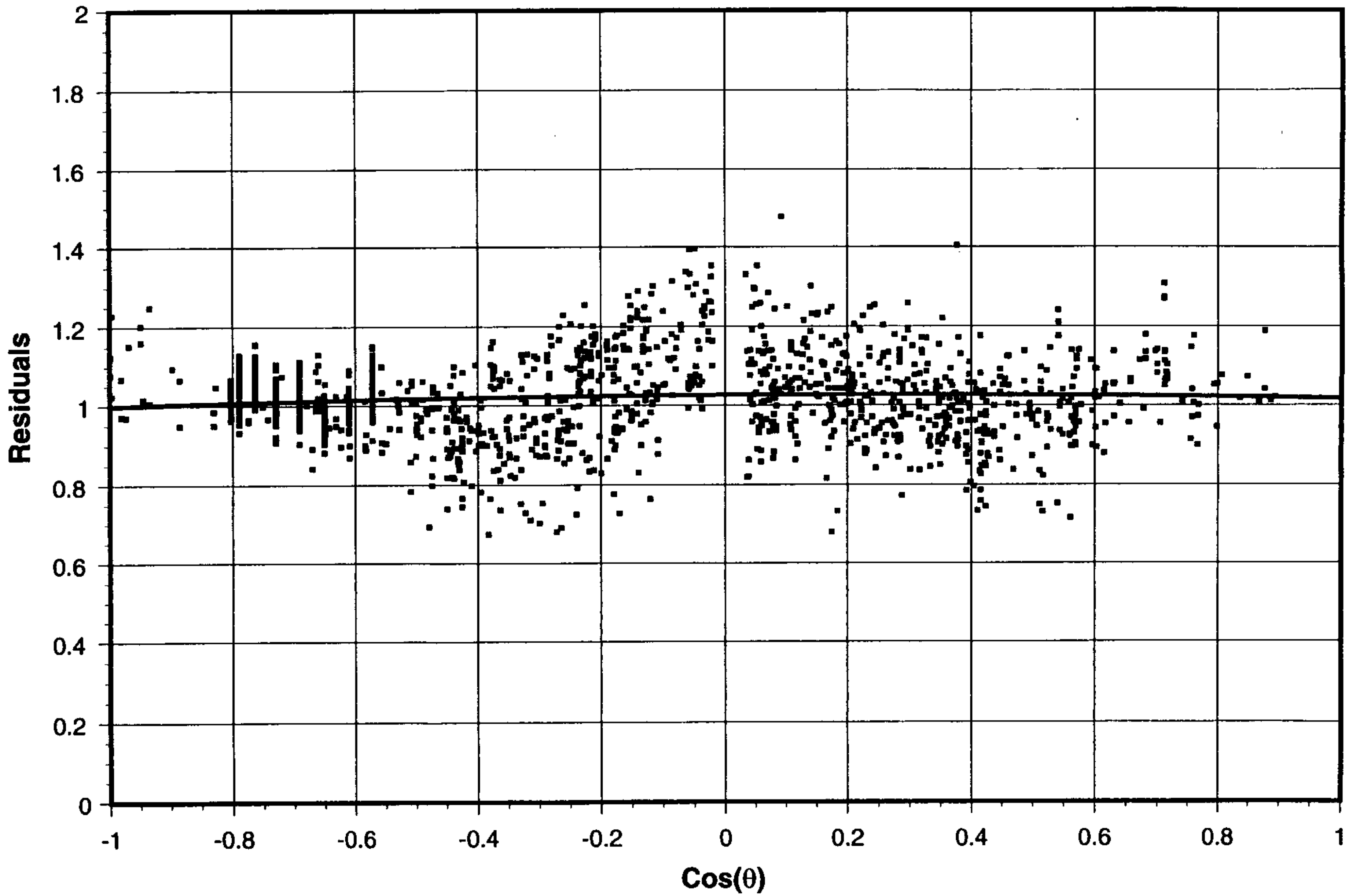
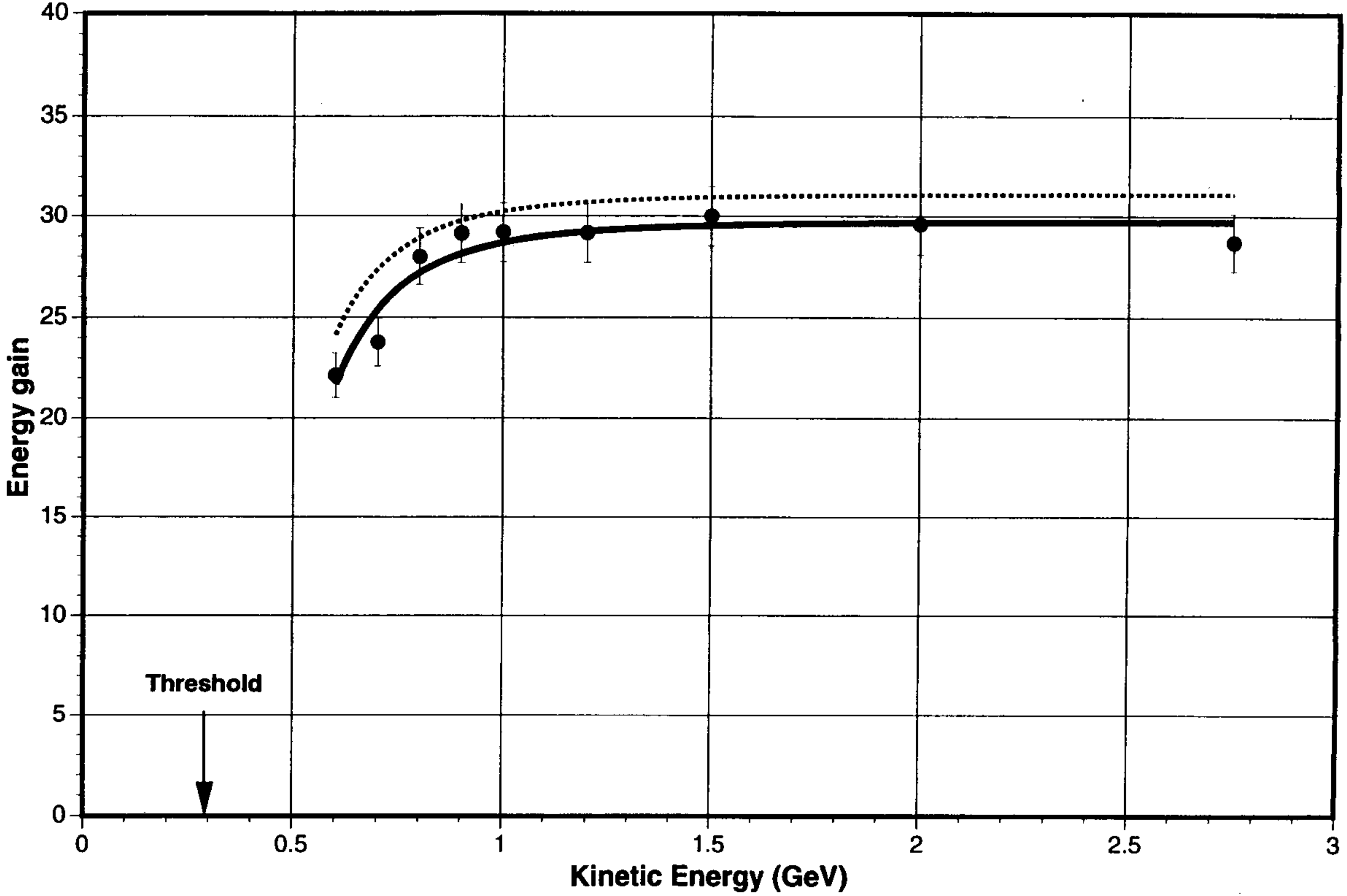

Residuals
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Cos(θ)

Figure 6b



Energy gain
40
35
30
25
20
15
10
5
0
Threshold
0
0.5
1
1.5
2
2.5
3
Kinetic Energy (GeV)

Figure 7