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SHAPE ISOMER EXCITATION BY MU-MINUS CAPTURE? *

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ABSTRACT

In a search for back-decay gamma rays from the shape isomer in ^{238}U following mu-minus capture, no candidates have been found with yields greater than 2% of the muon stoppings. The intensities of the gamma rays are insufficient to permit definitive lifetime measurements of individual peaks; however, for 500-keV energy ranges of gamma ray pulses, lifetimes have been determined that give results consistent with recent electron lifetime measurements.

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Recently, S. D. Bloom[1] proposed a rather intriguing alternative to the normal picture of nuclear fission following mu-minus capture in ^{238}U to explain an apparent discrepancy between the electron (T_e)[2] and fission (T_f)[3] measurements of the mu-minus lifetime. His hypothesis is as follows: During the atomic cascade a significant fraction of the 2p-1s muonic transitions excite, non-radiatively, the shape isomeric state. Thus, at time zero (signalled by the arrival of the muon in the 1s orbit), there exist two distinct muon-nuclear states. The subsequent behavior of the ground-state—muon system is the ordinary one. However, for the isomeric-state—muon system the situation is somewhat different; the isomer may capture the muon, spontaneously fission, or back-decay to the ground state by gamma emission, as shown in fig. 1.

The principal bases for Bloom's proposal are a) the existence of an isomeric state that can be dipole excited at the available energy[4]; b) the established fact of missing mu-mesic x rays[5]; and c) the possible discrepancies between T_e and T_f in the mu-minus lifetime measurements. The previous mu-minus lifetime measurements known to the authors are shown in Table 1. The possible discrepancy lies in the somewhat higher average of the electron measurements compared to the fission measurements.

Decays or captures associated with the stopping muon may be characterized by two distinct lifetimes: that of the muon in its K shell, T_μ, and that of the isomeric state, T_i. Expressed in terms of the various capture and decay rates, the reciprocal muon lifetime is,

$$1/T_\mu = w_e + w_c \quad (1)$$

$$= w_e + w_{cf} + w_{cn}, \quad (2)$$

where w_e is the muon decay rate in free space and w_c is the muon capture rate (which may be expanded as the sum of the capture rate leading to fission, w_{cf}, and the capture rate which does not lead to fission, w_{cn}). The reciprocal lifetime of the isomer may be expressed as,

$$1/T_i = w_{ic} + w_{i\gamma} + w_{if}, \quad (3)$$

where w_{ic} is the muon capture rate by the isomer, $w_{i\gamma}$ is the decay rate of the isomer to the ground state (back-decay rate), and w_{if} is the rate of isomeric fission. If we neglect the contribution of the fission rates to the total lifetimes (assume that $1/T_\mu \gg w_{cf}$ and $1/T_i \gg w_{if}$) and make the approximation that the capture rates by the isomer and the ground state are the same ($w_{ic} = w_c$), then we obtain for the rate of electron emission,

$$\dot{n}_e = w_e \exp(-t/T_\mu); \qquad (4)$$

and for the fission rate,

$$\dot{n}_f = w_{cf} \exp(-t/T_\mu) + \varepsilon w_{if} \exp(-t/T_i), \qquad (5)$$

where ε is the fractional isomer production.

According to Bloom, the admixture of the shorter lifetime T_i (shorter because $w_{i\gamma} \gg w_e$) in the rate equation for the emission of fission products gives the appearance of a single shorter exponential. We are unable to state whether or not any of the fission measurements[3] have sufficient precision to exclude this possibility. Extending Bloom's arguments, it follows that the non-fission, muon-capture gamma rays would be produced at the rate

$$\dot{n}_{cn\gamma} = w_{cn} \exp(-t/T_\mu), \qquad (6)$$

and the isomer, back-decay gamma rays would be produced at the rate,

$$\dot{n}_{i\gamma} = \varepsilon w_{i\gamma} \exp(-t/T_i) \cdot \qquad (7)$$

Thus, one could hope to observe two distinct types of gamma rays: those from non-fission capture with a pure lifetime, T_μ, and those from isomer back-decay with a pure lifetime, T_i. Furthermore, if the isomer is copiously excited and its back-decay gamma rays can be easily identified, then such measurements can provide a means of studying the interior fission barrier as perturbed by the Coulomb field of the muon.

In order to look for these gamma rays with a Ge(Li) detector, we have stopped 2.5 x 10^9 muons in a ^{238}U target using 1024 energy channels and 16 time channels. To date we have learned (fig. 2): prominent, non-background gamma rays of any kind are conspicuous by their absence. No single, unambiguous gamma ray with a yield greater than 1% of the muon stoppings has been observed.

An energy region of particular interest is the neighborhood of 2.5 MeV where Russo, Pedersen, and Vandenbosch[6] have reported a prominent gamma-ray transition at 2.514 MeV that is attributed to the back-decay of the ^{238}U fission isomer. Unfortunately, because of Coulomb perturbations of the barrier due to the presence of the muon (fig. 3), the energy of the back-decay gamma ray is not expected to be identical to that listed in ref. 6; and, Bloom[7] has suggested that the muon could increase this energy by as much as 400 keV. Near and above 2.5 MeV, the significant spectral features are as shown in fig. 4. The peak at approximately 2614 keV corresponds to a net gamma-ray yield of 2.0 ± 0.5% of the muon stoppings. The time correlations show that the peak occurs within a reasonable delay range following the muon stopping signal, but the data are insufficient to permit calculation of a meaningful, precise lifetime value. It is also unfortunate that the observed energy of 2614 keV is within experimental precision (±2 keV) equal to that of the well-known first excited state of ^{208}Pb (2614.5 keV). It is possible that time-correlated, inelastic excitation of this level in the ever-present lead shielding could occur to the extent observed, and cannot yet be excluded. (A priori, of course, the possibility of an accidental energy overlap is on the order of 1%.)

Although single gamma-ray intensities are not sufficient to permit lifetime measurements, they can be made for ranges of gamma-ray pulses in the Ge(Li) detector. The only presently reportable values were made in several short runs using 128 time channels. An example of such a time spectrum is shown in fig. 5. The periodic, beam-associated background is evident both in the prompt and the delayed times. After subtraction of the periodic background measured at negative times, the delayed counts can be fitted (with excellent χ^2) to a single exponential as shown in fig. 6. A single-run example of the experimental lifetimes measured in this manner is shown in Table 2. The increase in the lifetime at the higher energy ranges is attributed to an increased relative background from electron bremsstrahlung; however, at the present time, we have not yet tried to fit these data to other than a single exponential.

In conclusion, our lifetime measurements are in excellent agreement with the electron measurement of Hashimoto et al.[2] and several standard errors larger than the results from fission measurements[3], thereby adding some weight to Bloom's hypothesis, despite our inability to obtain definitive lifetime measurements on individual gamma rays.

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[6] P. A. Russo, J. Pedersen and R. Vandenbosch, Nucl. Phys. A240 (1975) 170.

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Table 1. Previously measured mu-minus lifetimes in ^{238}U.

Lifetimes	References	
τ_e = 88 ±4	1959	(Sens, ref. 2)
τ_f = 75.6±2.9	1963	(Diaz *et al.*, ref. 3)
τ_f = 74.1±2.8	1970	(Budick *et al.*, ref. 3)
τ_f = 76.1±1.0	1974	(Chultem *et al.*, ref. 3)
τ_e = 81.5±3.0	1975	(Hashimoto *et al.*, ref. 2)

Table 2. Measured mu-minus lifetimes in ^{238}U, this experiment.

Energy Range (MeV)	τ (ns)	χ^2/degree of freedom
0.5 - 1	80.2±1.9	59/64
1 - 1.5	81.5±1.8	72/64
1.5 - 2	80.2±2.6	56/64
2 - 2.5	91.0±4.9	51/64
2.5 - 3	96.6±8.9	29/64

FIGURE CAPTIONS

Fig. 1. Decay of the shape isomer in muonic ^{238}U.

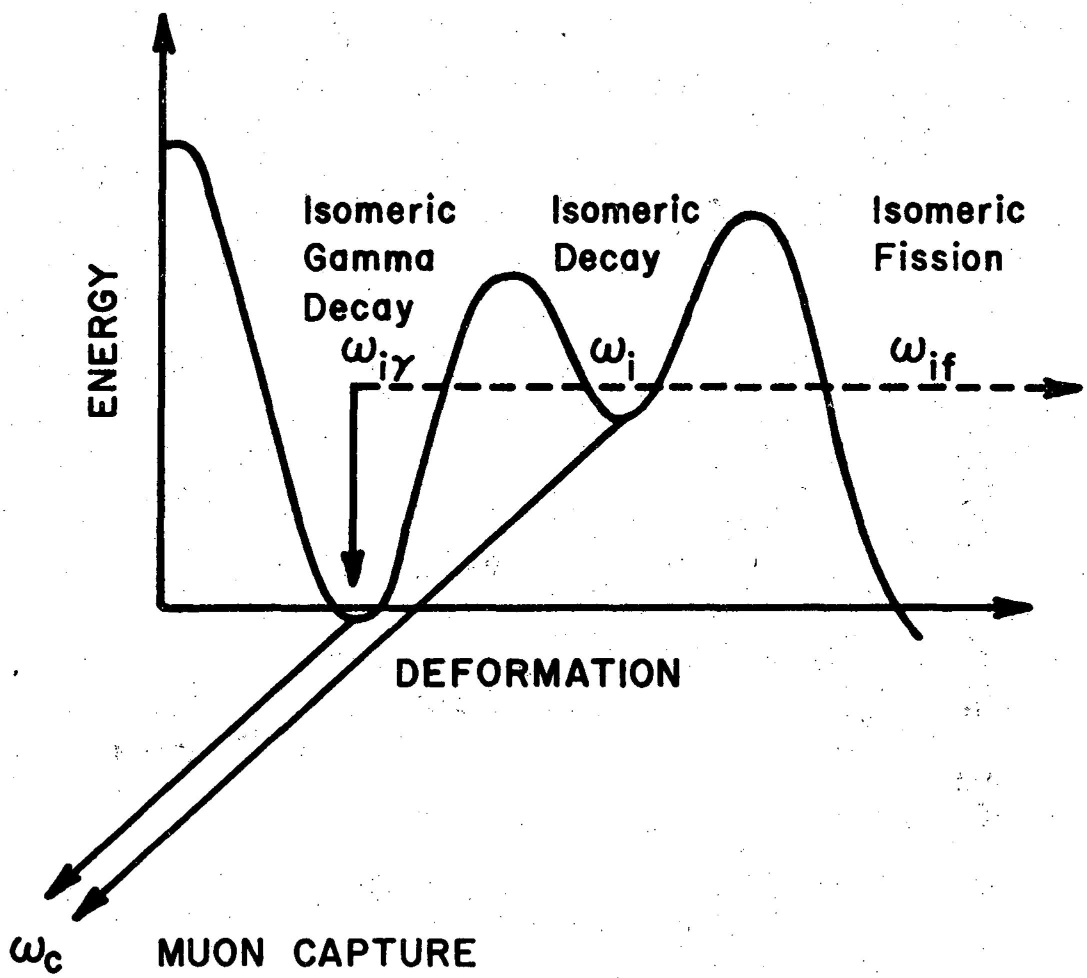
Fig. 2. Approximately 700 channels of a 1024-channel spectrum representing background gamma rays, prompt x rays, and delayed nuclear gamma rays following mu-minus capture in ^{238}U.

Fig. 3. Perturbation of the barrier potential as a function of the distortion parameter, β, due to the presence of the muon in the 1s state. The back-decay gamma ray is indicated by γ_D. (After ref. 7.)

Fig. 4. An expanded version of fig. 2 in the energy region near and above 2500 keV.

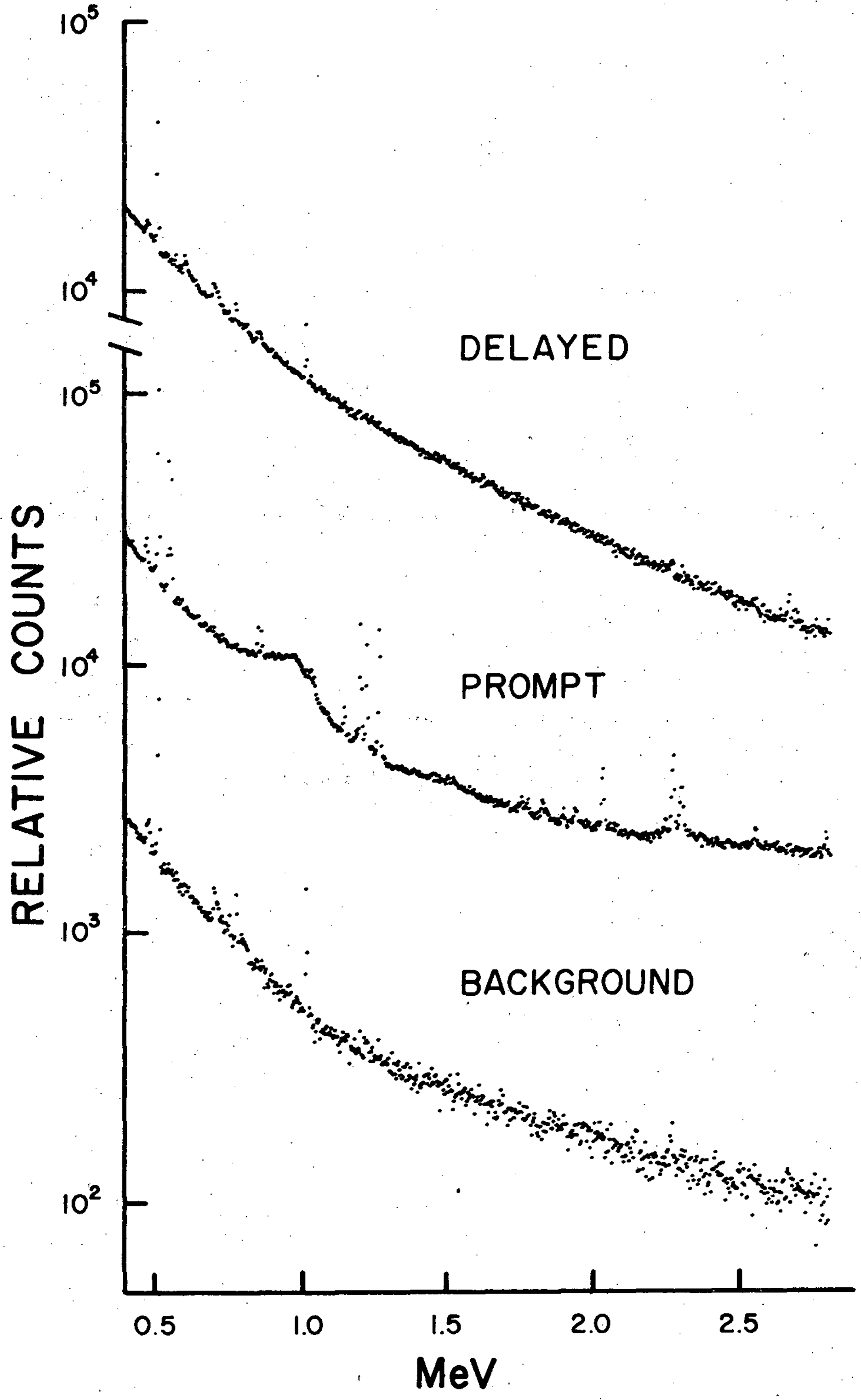
Fig. 5. A time spectrum of 128 channels in the energy range from 1.0 to 1.5 MeV. The unlabeled abscissa represents units of 16 channels: The first three units represent the background, the next two units represent prompt times, and the remaining units represent delayed times.

Fig. 6. A delayed time spectrum of approximately 65 channels after subtraction of the periodic, beam-associated background.



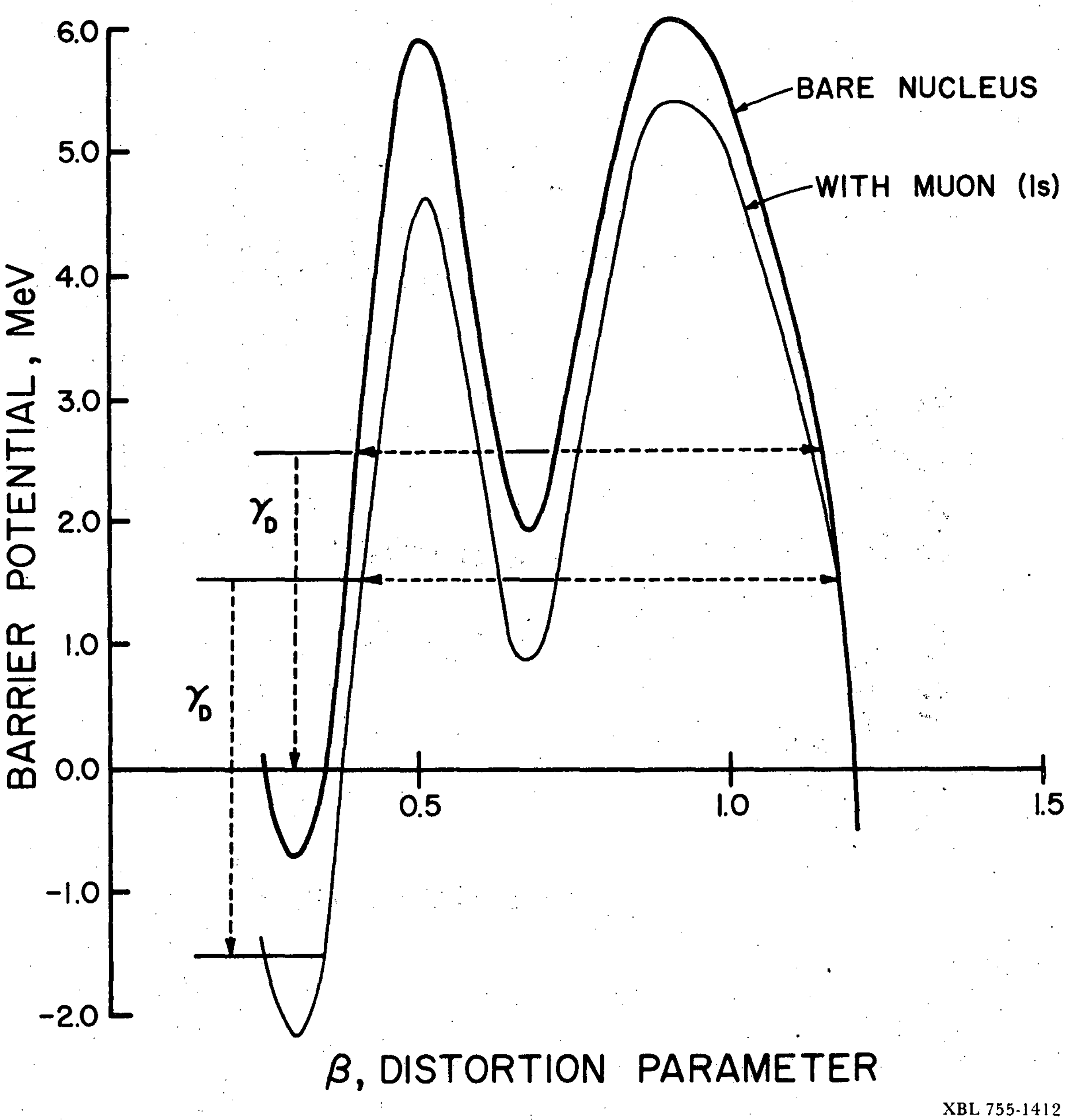
XBL 755-1392

Fig. 1



XBL 755-1389

Fig. 2



6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
BARRIER POTENTIAL, MeV
BARE NUCLEUS
WITH MUON (ls)
γ_D
γ_D
0.5
1.0
1.5
β, DISTORTION PARAMETER
XBL 755-1412

Fig. 3

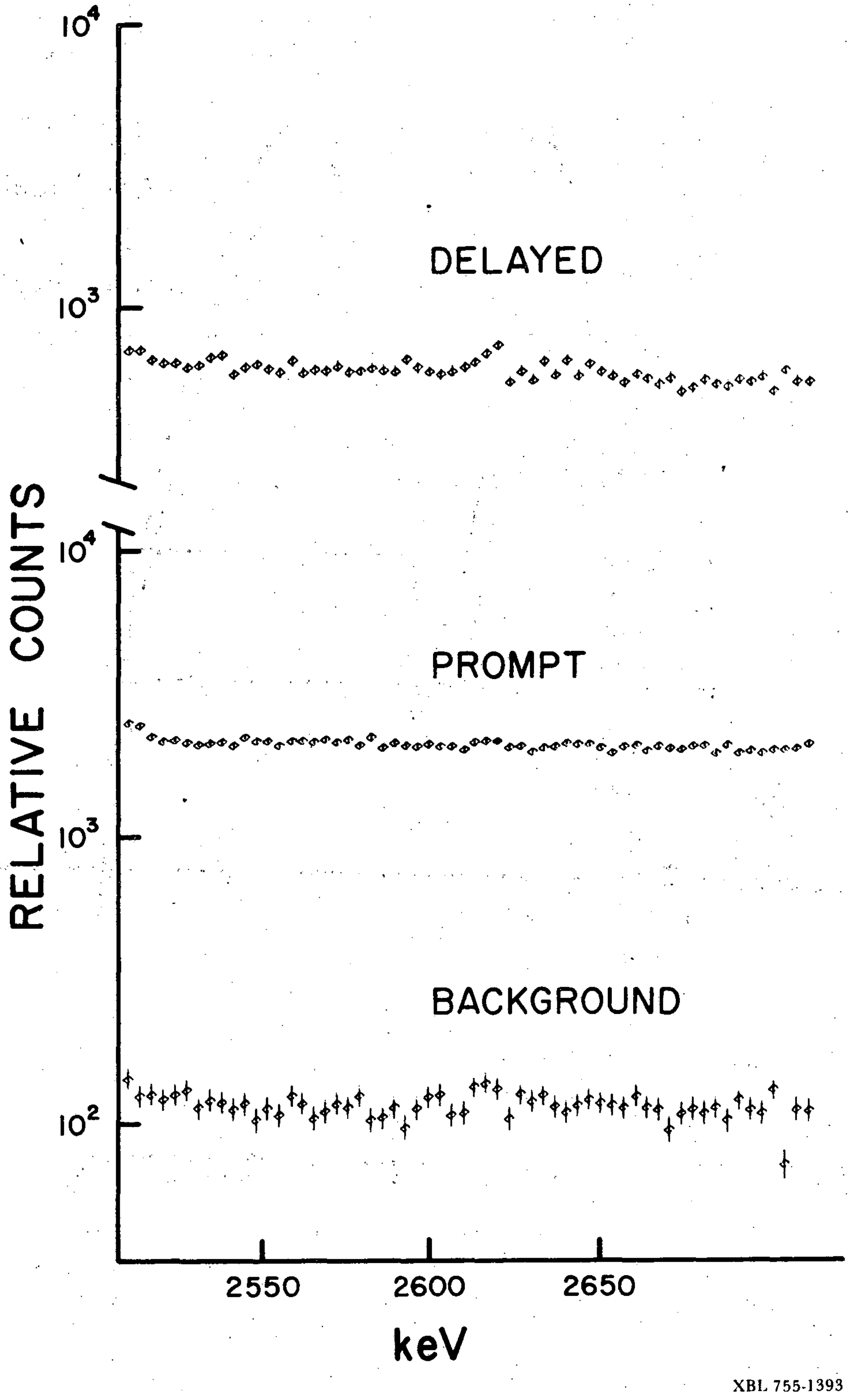

10⁴
10³
DELAYED
RELATIVE COUNTS
10⁴
PROMPT
10³
BACKGROUND
10²
2550
2600
2650
keV
XBL 755-1393

Fig. 4

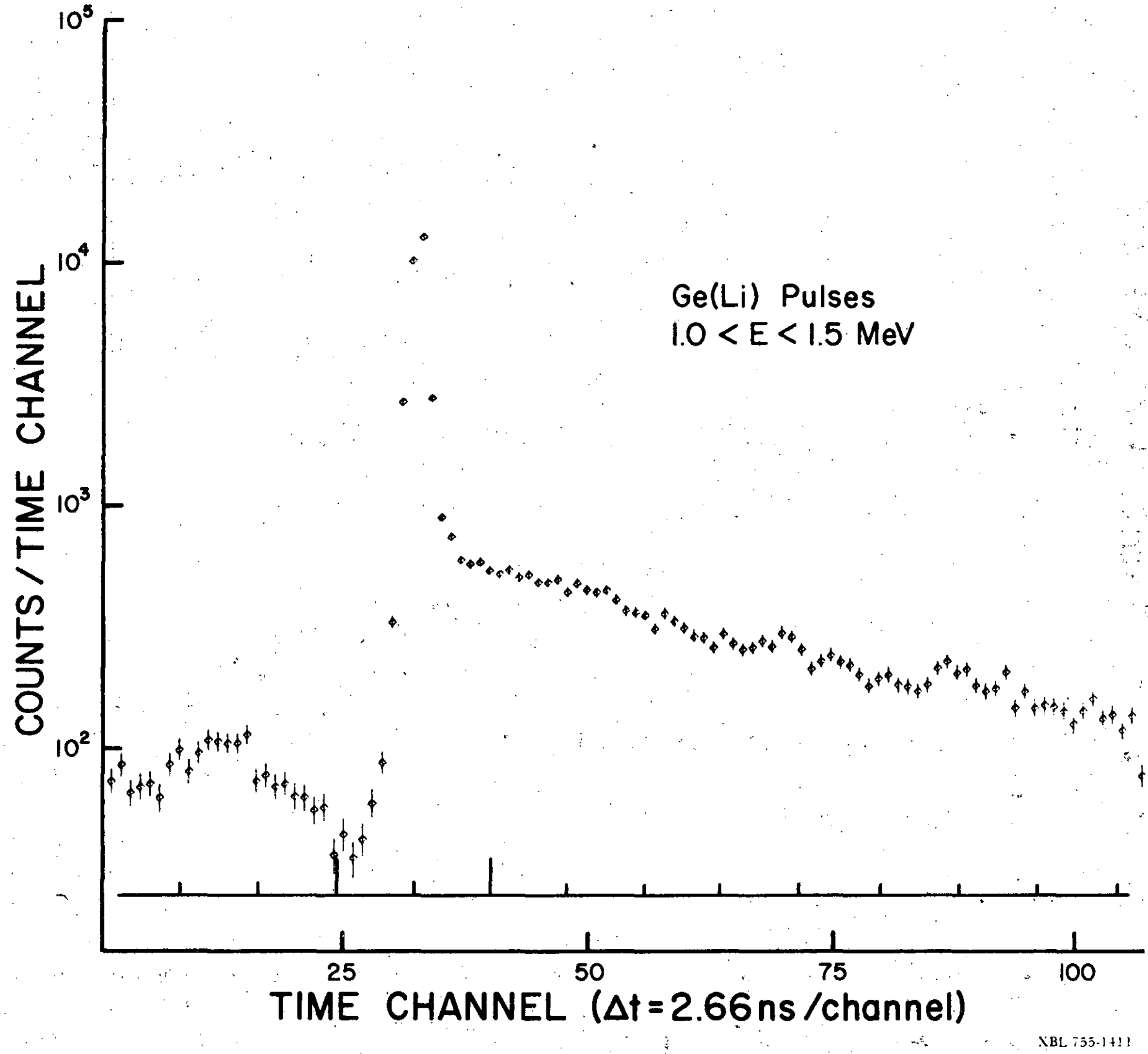

Ge(Li) Pulses
1.0 < E < 1.5 MeV
COUNTS / TIME CHANNEL
10^5
10^4
10^3
10^2
25
50
75
100
TIME CHANNEL (Δt = 2.66 ns / channel)
XBL 755-1411

Fig. 5

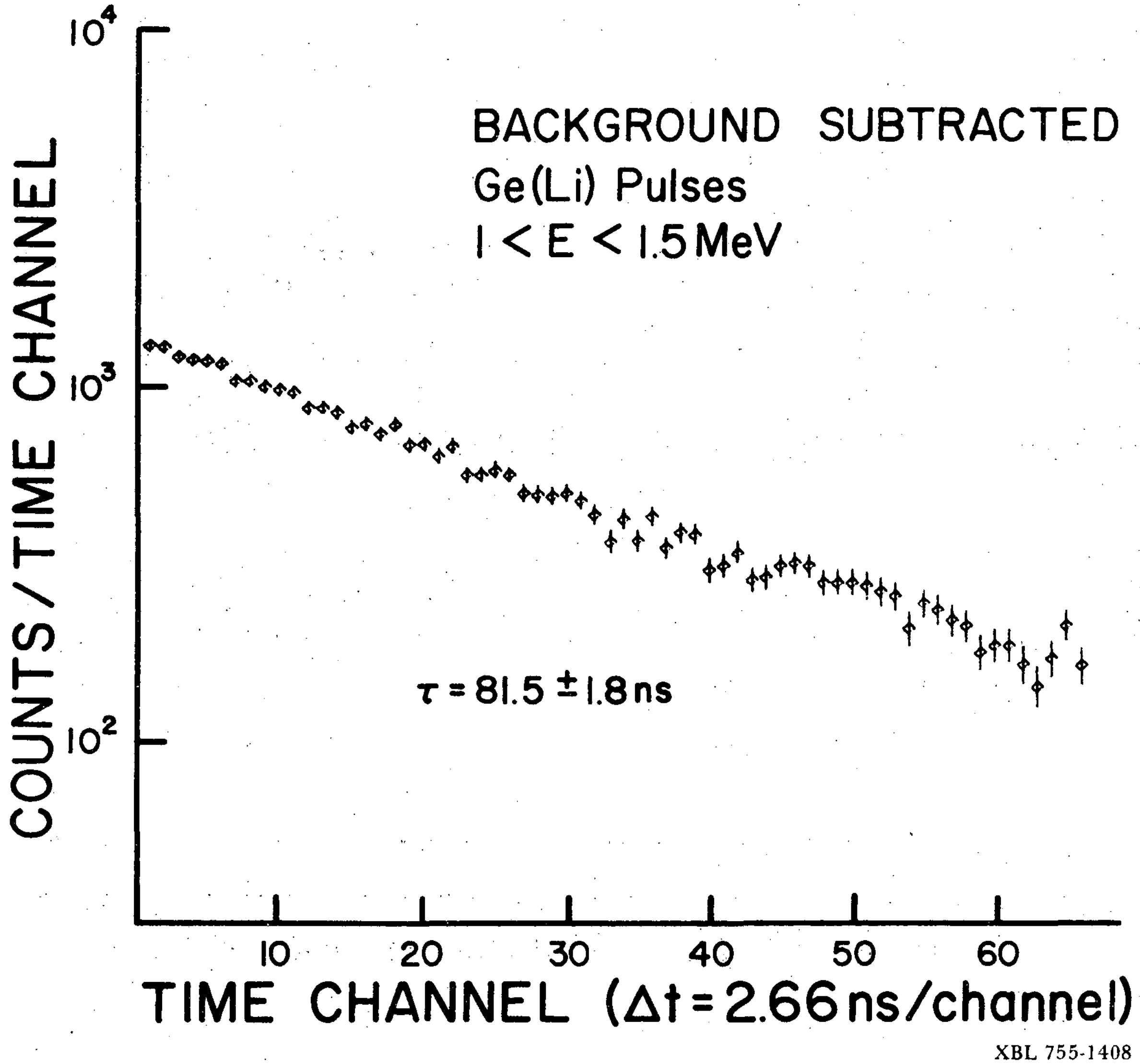

BACKGROUND SUBTRACTED
Ge(Li) Pulses
1 < E < 1.5 MeV
τ = 81.5 ± 1.8 ns
COUNTS / TIME CHANNEL
10⁴
10³
10²
10
20
30
40
50
60
TIME CHANNEL (Δt = 2.66 ns/channel)
XBL 755-1408

Fig. 6

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