Uranium Liquid-Argon Calorimeters: A Computational Investigation

T. A. Gabriel

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A Calculational Investigation*

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URANIUM LIQUID-ARGON CALORIMETERS:
A CALCULATIONAL INVESTIGATION

T. A. Gabriel

ABSTRACT

A detailed calculational study has been performed to determine the response of uranium liquid-argon calorimeters to high energy (≤ 20 GeV) incident protons. The results obtained are consistent with the recently published experimental data of Fabjan *et al.* This experimental data and the calculations indicate that "nuclear fluctuations", which limit the resolution of calorimeters containing ordinary materials, can be effectively reduced by the fissioning and capture characteristics of ^{238}U .

I. Introduction

Due to the fissioning and capture characteristics of natural uranium, "nuclear fluctuations" which usually dominate the resolution in total absorption calorimeters containing ordinary materials can be reduced substantially.^{1,2} This reduction can be explained in the following way. If the particle cascade generated in the calorimeter is strongly electromagnetic through the production of π^0 's, etc., there will be only a slight amplification of the signal due to the small photo-fission cross section and due to the reasonably small number of secondary hadronic particles, especially neutrons. For a fixed incident energy, the signal received from largely electromagnetic cascades normally represent the upper part of the pulse height distribution, i.e., the larger signals. However, if the particle cascade is strongly hadronic, there will be a reasonably large amplification of the signal due to hadronic induced fission and neutron capture. Without the amplification the signal would normally represent the lower part of the pulse height distribution, i.e., the smaller signals. Since the normally smaller signal receives the greater amplification, this leads to a narrowing of the pulse height distribution as well as an increase in the value of the most probable pulse. Both of these effects reduce the resolution. It should be noted that most of the fission energy, ~ 170 MeV/fission, results from heavy fragment recoil. This energy is deposited within the uranium and therefore is not detectable. It is the fission neutrons and gammas which are of interest and that can be detected.

In this paper, calculations are presented in which fission amplification of calorimeter signals are investigated. The design of the

calorimeter chosen for consideration is similar to that employed in Ref. 1. This will allow some comparisons with experimental data. It will be shown that it is possible calculationally to predict with reasonable accuracy the performance of uranium-loaded calorimeters. Presented in Section II is the geometry of the calorimeter and the methods of calculation, and, in Section III, the results are presented and discussed.

II. Description of Calorimeter and Computational Procedures

The geometry and materials of the calorimeter are given in Fig. 1. In most of the calculations this was the arrangement. For some calculations the uranium was replaced by iron making the device totally iron and liquid argon. Also for some calculations the iron was replaced by uranium making the device totally uranium and liquid argon. In all cases, the radii, dead spots, gaps, plates, etc. all remained the same dimensional size as given in Fig. 1. The naturally occurring isotopic composition of U, Fe and A was used.

Except for the more detailed treatment of the low-energy ($E < 20$ MeV) neutrons and excitation gammas, and the inclusion of high energy ($E > 0$ for protons, $\pi^\pm$, and $E \geq 20$ MeV for neutrons) particle-induced fission, the calculations are the same as those described in Ref. 3. The fission cross sections used in the calculation for high-energy particle-induced fission were taken from Ref. 4. (See p. 666, Fig. 7, $Z_f = 90$.) The lowest energy point where a fission cross section was given was ~ 100 MeV. Below this energy to 20 MeV, the fission data needed was obtained by linear extrapolation using the 20-MeV neutron fission cross section obtained from ENDFB/4^{5//} to define the lower energy point. These

A_{CENT}: 75 GAPS, 75 U PLATES
 GAP WIDTH = 0.19 cm, THICKNESS OF PLATES = 0.16 cm

B_{CENT}: SAME AS A_{CENT}

C_{CENT}: 100 GAPS, 100 U PLATES
 GAP WIDTHS = 0.19 cm THICKNESS OF PLATES = 0.16 cm

D_{CENT}: 100 GAPS, 100 Fe PLATES
 GAP WIDTH = 0.195 cm, THICKNESS OF PLATES = 0.15 cm

A_{OUT}: 75 GAPS, 75 Fe PLATES
 GAP WIDTH = 0.19 cm, THICKNESS OF PLATES = 0.16 cm

B_{OUT}: SAME AS A_{OUT}

C_{OUT}: 100 GAPS, 100 Fe PLATES
 GAP WIDTH = 0.19 cm, THICKNESS OF PLATES = 0.16 cm

D_{OUT}: SAME AS D_{CENT}

$\rho_U = 18.95$ g/cm³, $\rho_{Fe} = 7.86$ g/cm³, $\rho_A = 1.4$ g/cm³

ALL GAPS ARE FILLED WITH LIQUID ARGON

Fig. 1. Geometry and Composition of the Calorimeter.

fission cross sections were assumed to apply for neutrons, protons, and charged pions. For the charged pions, the energy used for the cross section determination was the total energy. One nice feature of the high energy particle collision model^{6//} used in the calculation is that the neutron multiplicities associated with high energy fission are automatically taken into account without any additions to the model. (See p. 667, Fig. 8 of Ref. 4) Fission gammas from the high-energy particle-induced fissions were assumed to have the same spectral distribution⁵ as those from low-energy neutron-induced fissions. These fission gammas, as well as neutrons below 20 MeV and deexcitation gammas were transported using a modified version of MØRSE^{a)7///}. The neutron- and gamma-cross sections used by MØRSE were obtained from ENDFB/4^{5///} and were processed using AMPX^{8///}.

III. Results

A. Pure Uranium Case

Results are presented in Fig. 2 of an idealized case in which protons of various energies are incident on an infinite natural uranium system. No particle leakage has been allowed. Fig. 2a indicates that ~ 24 fissions/1 GeV of proton energy results (5 from ^{235}U , and 19 from ^{238}U). Of these, 19 fissions/1 GeV of proton energy results from neutrons with energy ≤ 20 MeV (5 from ^{235}U , and 14 from ^{238}U). The number of captures that occur are given in Fig. 2b. Approximately 82 captures/1 GeV of proton energy results. The majority ($\sim 99\%$) of the

^aThe main modification of the MØRSE code was to explicitly account for Compton, pair production and photoabsorption-type processes associated with the transport of the gammas. The electrons produced were transported using the straight ahead approximation and the associated stopping power formula.

Fig. 2. Fissions, Captures, Energy Deposition and Effective Energy Deposition in an Infinite Uranium System Produced by Protons of Various Energies.

captures occur with ^{238}U . Fig. 2c shows the total energy deposition. This yield amounts to ~ 5.4 GeV/1 GeV of incident proton energy. However, for calorimeter applications the majority of the energy (~ 170 MeV/fission) is not available for detection. The energy that is available for detection is shown in Fig. 2d (upper curve). The lower curve in this figure indicates the available energy if fission and capture are omitted. As can be seen, there is a substantial increase in the "effective energy" due to fission and capture. The "error bars" for the 5-GeV energy case given in the figure represent upper and lower bounds of uncertainty associated with the calculational model. They are not error bars for statistical fluctuations associated with the calculations. Similar uncertainties can be applied to the other energies.

Shown in Fig. 3 is the time scale associated with fission, capture, energy deposition and effective energy deposition for 5-GeV incident protons. Since the high energy transport code⁹ and the electron-photon transport code¹⁰ do not have a timing scheme incorporated, it has been assumed that no time has passed for this phase of the particle cascade. Therefore, all energy deposited from this phase of the calculation is deposited at $t = 0$ and all low-energy ($E \leq 20$ MeV) neutrons, high-energy particle-produced fission gamma-rays, and deexcitation gamma-rays are born at time = 0. In actuality, these particles are usually born and the energy deposited in a time window from 0 to ~ 30 nsec. Therefore, the time scale shown must be considered an absolute lower limit for the processes indicated. Although these curves are for a total uranium system, they should be approximately applicable for calorimeter systems in which there is negligible leakage since the uranium will constitute

Fig. 3. Fissions, Captures, Energy Deposition and Effective Energy Deposition in an Infinite Uranium System as a Function of Time for Incident 5-GeV Protons.

a large fraction of the total mass in calorimeters. As can be seen, a substantial amount of time is required before the entire "effective" energy is deposited. This may present a possible problem due to pileup for a large nonleaking calorimeter system if they are to be used in a beam which has a high current ($\sim > 10^6$ particles/sec) or when two particles enter the device with a Δt of $< 1 \times 10^{-6}$ sec.

B. Iron-Argon Calorimeter Results

Since a detailed treatment of the low-energy ($E \lesssim 20$ -MeV) neutrons and excitation gamma rays had not been included in obtaining previous calorimeter results, a calculation was carried out for a total iron-argon (Fe-A) system for incident 5-GeV protons. The purpose of this calculation is two-fold. First, this calculation will partly validate the more detailed treatment of the low-energy neutrons and excitation gamma rays and will also give an indication of the magnitude of any nonlinear effects (i.e., the charge collected is not linearly related to the energy deposited) associated with heavily ionizing particles.¹¹ The results of the calculation are given in Fig. 4 and Table 1. As can be seen in Table 1, the approximation used in previous calculations to determine the energy deposition of low-energy neutrons and deexcitation gamma rays is quite good. The sampling fluctuation distribution was obtained by taking the difference in the signal obtained from alternating pairs of argon gaps for each incident particle; i.e., $\text{gap}_1 + \text{gap}_2 - \text{gap}_3 - \text{gap}_4 + \text{gap}_5 + \text{gap}_6 - \text{gap}_7 - \text{gap}_8 + \text{etc.}$ $= I_1 - I_2$. Both the resolution and the sampling fluctuation are in excellent agreement with experimental data¹.

Fig. 4. Pulse Height and Sampling Distributions Expected from an Iron-Argon Calorimeter When 5-GeV Protons are Incident.

Table 1

Energy Deposition and Leakage Produced by the Interaction
of 5-GeV Protons in an Iron-Argon Calorimeter^a

Energy Deposition ^b (MeV)		
	<u>Iron plus Argon</u>	<u>Active Argon</u>
1. Primary ionization	187.	27.1
2. Secondary proton ionization	1424.	234.
3. Secondary $\pi^{\pm}$ ionization	362.	60.7
4. Secondary $\mu^{\pm}$ ionization	8.9	1.5
5. Nuclear-recoil and evaporated-charged particles other than protons produced by p and $\pi^{\pm}$ and neutrons with $E > 20$ MeV	112.	19.6
6. Neutrons with energy < 20 MeV and deexcitation gamma-rays	298.	88.8(75.4) ^e
7. Electromagnetic from π^0 decay	<u>817.</u>	<u>145.</u>
Total	3209.	577.

Leakage Energy ^b (MeV)			
	<u>Front</u>	<u>Side</u>	<u>Back</u>
p	2.3	9.8	141.
n	44.6	304.	213.
$\pi^{\pm c}$	11.5	26.8	38.0
$\mu^{\pm 0}$	0.	1.6	1.1
γ	13.8	26.9	14.5
$e^{\pm c}$	<u>1.4</u>	<u>1.8</u>	<u>1.8</u>
Total	73.6	371.	409.

Total leakage energy = 854. MeV

Binding plus ν energy^d = 937. MeV

Electromagnetic source energy (π^0) = 854. MeV

^aSee description of calorimeter

^b50 nsec time cut

^cIncludes rest mass

^dIncludes some energy lost due to b)

^eValue obtained by prorating neutron and gamma-ray source energy on a gm thickness basis

If the initial interaction of the incident proton is restricted so that the amount of leakage energy is reduced the e/p ratio decreases to 1.40. The experimental value obtained under similar conditions is 1.52¹. This implies an 8% nonlinear effect if it is assumed that there are no other contributing factors. This 8% nonlinear effect for argon devices is approximately 1/2 that which is expected for plastic or liquid scintillators.³ Average pulses were used to calculate the e/p ratio. If the most probable proton pulse had been used the nonlinear effect would have been larger. Therefore, the 8% will be taken to represent a lower estimate for 5-GeV protons incident on the Fe-A calorimeter.

Increasing the cascade transport time upwards from 50 nsec does not yield a much larger signal. In the calculations given here no time has been allowed for the drift time of the electrons across the argon gaps.

C. Uranium-Iron-Argon and Uranium-Argon Calorimeter Results

The number of ²³⁸U fissions that can be expected in a realistic calorimeter are given in Fig. 5 as a function of incident proton energy. Even for the uranium-argon (U-A) results, the number of fissions are substantially less than the number obtained for the infinite uranium system. This decrease is due to leakage energy and energy loss in the iron and/or argon.

The energy deposition and leakage summary sheets for the proton energies considered are given in Tables 2 and 3 for the uranium-iron-argon (U-Fe-A) calorimeter, and Table 4 for the U-A calorimeter. To obtain the energy deposition for the entire system, the heavy ion recoil energy associated with fission has been taken to be 170 MeV. Even for this relatively large device the energy leakage is $\sim 15\%$.

Fig. 5. Number of ^{238}U Fissions Expected in a U-Fe-A and a U-A Calorimeter as a Function of Proton Energy.

Table 2
Energy Deposition and Leakage Produced by the Interaction of
2- and 5-GeV Protons in a Uranium-Iron-Argon Calorimeter^{a,e}

2-GeV Protons		
	Energy Deposition ^b (MeV)	
	Entire System	Active Argon
1. Primary ionization	215.	20.1
2. Secondary proton ionization	530.	60.5
3. Secondary $\pi^\pm$ ionization	82.2	8.8
4. Secondary $\mu^\pm$ ionization	1.9	0.23
5. Nuclear-recoil and evaporated-charged particles other than protons produced by p and $\pi^\pm$ and neutrons with E > 20 MeV	65.7	4.6
6. Neutrons with energy < 20 MeV, deexcitation gamma-rays, and fission	2748.(265.) ^d	57.7(27.3) ^d
7. Electromagnetic from π^0 decay	138.	13.0
Total	3781.(1298.) ^d	165.(135.) ^d

	Leakage Energy ^b (MeV) (with fission, capture, etc.)		
	Front	Side	Back
p	0.70	3.9	5.9
n	31.4	121.	17.6
$\pi^\pm$ ^c	4.4	2.5	0.48
$\mu^\pm$ ^c	0.	0.28	0.
γ	6.4	5.7	0.28
$e^\pm$ ^c	1.3	0.17 ^c	~ 0.
Total	44.2	134.	24.3.

Number of fissions/incident particle = 12.9
Total leakage energy = 203. MeV
Electromagnetic source energy (π^0) = 145. MeV

(continued)

Table 2 (Cont'd)

5-GeV Protons

	Energy Deposition ^b (MeV)	
	Entire System	Active Argon
1. Primary ionization	225.	20.7
2. Secondary proton ionization	1234.	149.
3. Secondary $\pi^{\pm}$ ionization	308.	34.5
4. Secondary $\mu^{\pm}$ ionization	4.6	0.6
5. Nuclear-recoil and evaporated-charged particles other than protons produced by p and $\pi^{\pm}$ and neutrons with E > 20 MeV	175.	12.4
6. Neutrons with energy < 20 MeV, deexcitation gamma-rays, and fission	6541.(641.) ^d	141.(67.0) ^d
7. Electromagnetic from π^0 decay	637.	62.8
Total	9125.(3225.) ^d	421.(347.) ^d

Leakage Energy^b (MeV)
(with fission, capture, etc.)

	Front	Side	Back
p	5.1	7.3	53.9
n	90.4	273.	65.9
$\pi^{\pm c}$	14.0	7.5	8.5
$\mu^{\pm c}$	0.1	0.3	0.
γ	12.9	10.8	2.2
$e^{\pm c}$	2.0	0.9	1.8
Total	125.	300.	132.

Number of fissions/incident particle = 30.5

Total leakage energy = 557. MeV

Electromagnetic source energy (π^0) = 655. MeV^aSee description of calorimeter^b50 nsec time cut^cIncludes rest mass^dWithout fission and capture^eNo restriction on initial interaction

Table 3

Energy Deposition and Leakage Produced by the Interaction of
10- and 20-GeV Protons in a Uranium-Iron-Argon Calorimeter^{a,e}

10-GeV Protons			
Energy Deposition ^b (MeV)			
	<u>Entire System</u>	<u>Active Argon</u>	
1. Primary ionization	242.	21.9	
2. Secondary proton ionization	2472.	304.	
3. Secondary $\pi^{\pm}$ ionization	671.	75.	
4. Secondary $\mu^{\pm}$ ionization	5.5	0.69	
5. Nuclear-recoil and evaporated-charged particles other than protons produced by p and $\pi^{\pm}$ and neutrons with E > 20 MeV	295.	32.5	
6. Neutrons with energy < 20 MeV, deexcitation gamma-rays, and fission	12637.(1198.) ^d	271.(127.) ^d	
7. Electromagnetic from π^0 decay	1483.	148.	
Total	17806.(6367) ^d	853.(709) ^d	
Leakage Energy ^b (MeV) (with fission, capture, etc.)			
	<u>Front</u>	<u>Side</u>	<u>Back</u>
p	16.6	17.5	89.5
n	225.	515.	198.
$\pi^{\pm c}$	75.2	16.5	48.5
$\mu^{\pm c}$	0.	0.	1.1
γ	37.9	19.1	5.2
$e^{\pm c}$	6.6	1.3	1.7
Total	361.	569.	344.
Number of fissions/incident particle = 59.3			
Total leakage energy = 1274. MeV			
Electromagnetic source energy (π^0) = 1533. MeV			

(continued)

Table 3 (Cont'd)

20-GeV Protons

Energy Deposition^b (MeV)

	<u>Entire System</u>	<u>Active Argon</u>
1. Primary ionization	275.	25.5
2. Secondary proton ionization	4702.	583.
3. Secondary $\pi^{\pm}$ ionization	1325.	147.
4. Secondary $\mu^{\pm}$ ionization	16.8	2.3
5. Nuclear-recoil and evaporated-charged particles other than protons produced by p and $\pi^{\pm}$ and neutrons with E > 20 MeV	537.	49.9
6. Neutrons with energy < 20 MeV, deexcitation gamma-rays, and fission	24247.(2283.) ^d	518.(243.)
7. Electromagnetic from π^0 decay	<u>3686.</u>	<u>372.</u>
Total	34789.(12825) ^d	1698.(1423.)

Leakage Energy^b (MeV)
(with fission, capture, etc.)

	<u>Front</u>	<u>Side</u>	<u>Back</u>
p	50.3	15.7	230.
n	448.	869.	595.
$\pi^{\pm c}$	217.	11.1	139.
$\mu^{\pm c}$	0.	0.	7.0
γ	27.5	34.5	9.6
$e^{\pm c}$	<u>6.7</u>	<u>2.0</u>	<u>13.1</u>
Total	750.	932.	994.

Number of fissions/incident particle = 114

Total leakage energy = 2676. MeV

Electromagnetic source energy (π^0) = 3772. MeV^aSee description of calorimeter^b50 nsec time cut^cIncludes rest mass^dWithout fission and capture^eNo restriction on initial interaction

Table 4

Energy Deposition and Leakage Produced by the Interaction
of 10-GeV Protons in a Uranium-Argon Calorimeter^{a,d}

	Energy Deposition ^b (MeV)	
	Entire System	Active Argon
1. Primary ionization	260.	24.4
2. Secondary proton ionization	2405.	276.
3. Secondary $\pi^{\pm}$ ionization	668.	70.4
4. Secondary $\mu^{\pm}$ ionization	10.	1.2
5. Nuclear-recoil and evaporated-charged particles other than protons produced by p and $\pi^{\pm}$ and neutrons with $E > 20$ MeV	305.	28.7
6. Neutrons with energy < 20 MeV, deexcitation gamma-rays, and fission	20200.	320.
7. Electromagnetic from π^0 decay	1458.	141.
Total	25306.	861.

Leakage Energy^b (MeV)
(with fission, capture, etc.)

	Front	Side	Back
p	12.5	5.0	116.
n	210.	385.	155.
$\pi^{\pm c}$	53.0	4.6	23.1
$\mu^{\pm}$	0.	0.7	0.
γ	41.6	10.2	5.8
$e^{\pm c}$	5.8	0.8	1.5
Total	323.	406.	301.

Number of fissions/incident particle = 99.0

Total leakage energy = 1030. MeV

Electromagnetic source energy (π^0) = 1509. MeV

^aSee description of calorimeter

^b50 nsec time cut

^cIncludes rest mass

^dNo restriction on initial interaction

For the 10-GeV U-Fe-A and U-A cases, calculations were also done in which no time cutoff was imposed. The resulting energy deposition in the active argon increased from 853 MeV to 878 MeV, and 861 MeV to 941 MeV, respectively. Note that for the U-A calorimeter, the signal increase is larger (9% compared to 3%) and would require a longer collection time.

The pulse height distributions with and without fission, etc., and the sampling distributions are given in Figs. 6, 7, and 8.* The narrowing of the pulse height distributions as well as the shift in the location of the most probable pulse are quite apparent due to the amplification of the signal due to fissioning and capture.

The resolution of the U-Fe-A calorimeter as a function of proton energy is given in Fig. 9a. Since a large part of the nuclear fluctuations have been removed due to the use of uranium, the sampling fluctuation now represents a larger fraction of the total resolution. By quadratically subtracting the sampling fluctuations, the intrinsic resolution of the device can be obtained. The remaining fluctuations for this device are attributed to leakage and fluctuations in the fission and capture processes. In Fig. 9b the results of the resolution and sampling fluctuation calculations are compared to the data given in Ref. 1. The agreement is quite good.

The ratio of the average electronic energy deposition to the average hadronic energy deposition is given in Fig. 10 as a function of particle energy and as a function of several different constraints. For the cases in which no restriction has been applied to the initial interaction the e/p ratio decreases at first, but then starts to increase again.

* σ^* shown in the Figs. is the resolution with the sampling fluctuations subtracted.

U-Fe-A CALORIMETER
 NO RESTRICTIONS ON INITIAL INTERACTION 50 nsec TIME CUT

Fig. 6. Pulse Height and Sampling Distributions Expected from a U-Fe-A Calorimeter When 2- and 5-GeV Protons are Incident.

U-Fe-A CALORIMETER

NO RESTRICTIONS ON INITIAL INTERACTION 50 nsec. TIME CUT

Fig. 7. Pulse Height and Sampling Distributions Expected from a U-Fe-A Calorimeter When 5- and 10-GeV Protons are Incident.

Fig. 8. Pulse Height and Sampling Distributions Expected from a U-A Calorimeter When 10-GeV Protons are Incident.

Fig. 9. The Resolution of the U-Fe-A Calorimeter as a Function of Proton Energy.

x PROTONS } EXPERIMENTAL
 + PIONS }

CALCULATED WITH PROTONS INCIDENT

U-Fe-A CALORIMETER

FISSION AND CAPTURE		50 nsec TIME CUT		RESTRICTED COLLISION SITE	
YES	NO	YES	NO	YES	NO

△					
○	X		X		X
●	X		X	X	
□	X				X

U-A CALORIMETER

☆	X		X		X
■	X		X	X	
▲	X			X	X
◆	X			X

Fig. 10. The Ratio of the Average Electronic Energy Deposition to the Average Hadronic Energy Deposition as a Function of Particle Energy.

This increase is due to increased leakage. The increase that results for the restriction collision data is due primarily to the fact that more than 50-nsec collection time is needed. It is quite obvious from the figure that a rather wide spread in e/p ratios can be obtained depending upon the calorimeter and the constraint. The important aspect of this figure is, however, that the e/p ratio can be reduced substantially. The experimental data has been modified to account for a total U-A system.

The individual contributors to the energy deposition have each been boxed separately in Fig. 11 for 2- and 10-GeV protons incident on the U-Fe-A calorimeter. If the calorimeter was only sensitive to secondary protons then the pulse height distribution would be represented by the dashed curves in the figure. It is obvious from the figure that the fluctuations are dominated by correlations between the produced protons, low-energy neutrons and π^0 's (primarily at 10 GeV).

The laterally integrated spatial energy deposition for incident 2-, 5-, 10-, and 20-GeV protons is given in Fig. 12 for the U-Fe-A calorimeter.

IV. Conclusions

The use of uranium in calorimeter application to reduce the "nuclear fluctuations" appears very promising. A factor of $\sim$ two improvement in the resolutions appears possible. However, since the sampling fluctuations are in uranium-loaded calorimeters a larger contributor to the total resolution, their thickness must remain small or the benefits from using uranium will be greatly reduced. In large calorimeters where there is small leakage of low-energy neutrons, pileup effects may occur if the incident particle current is large ($\sim 10^5$ - 10^6 /sec).

Fig. 11. Fluctuations in the Individual Contributors to the Total Pulse Height Distributions from 2- and 10-GeV Incident Protons on the U-Fe-A Calorimeter.

Fig. 12. Spatial Dependence of the Hadron-Induced Cascade in the U-Fe-A Calorimeter.

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