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SIMULATION OF THE TRANSITION EFFECT IN LIQUID ARGON CALORIMETERS

W. FLAUGER

Deutsches Elektronen-Synchrotron DESY, Hamburg, FRG

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The transition effect was calculated from EGS3 shower Monte Carlo simulations for a liquid argon calorimeter. The transition effect was found to be energy independent and can easily reduce the signal of electromagnetic showers to 70%. The effect on the e/h ratio of liquid argon calorimeters is discussed.

1. Introduction

In electromagnetic showers the energy spectra of the produced electrons and photons depend on the critical energy of the showering material and on the age of the shower. Showers developing from one medium into another will therefore change their properties at the boundary. The magnitude of this transition effect was firstly calculated analytically [1] and later also with Monte Carlo techniques [2]. For liquid argon (LAr) sampling calorimeters it was always clear that the transition effect must be taken into account [3], especially if the response is intercalibrated with minimum ionizing particles like muons [4]. As the detector medium normally has a higher critical energy than the converter medium, the fraction of the total energy which gets samples was found to be considerably smaller for electromagnetic showers than for penetrating muons. This reduction in pulse high for electromagnetic showers also effects the relative response e/h of a sampling calorimeter to electrons and pions respectively. Mainly due to the large losses of binding energy in hadronic showers this relative response is larger than 1, unless one takes advantage of the nuclear fission amplification from uranium. For uranium however the transition effect is large, which also will result in a significant reduction of e/h.

Recently extensive EGS Monte Carlo calculations were performed [5] for LAr calorimeters with U, Pb and Fe as converter plates. It was pointed out that within a crude model of hadronic showers $e/h \simeq 1$ can be reached for U, LAr calorimeters with the transition effect only, neglecting nuclear fission.

Our calculations are mainly concentrated on the question, how rapid is the change at the boundary of the different media and is it possible to tune e/h with the contribution of the transition effect for an optimized hadron calorimeter?

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2. Monte Carlo simulations

We have performed EGS3 Monte Carlo simulations for Al, Fe, Pb and U as converter material and LAr as the detector medium. The incident particles were electrons of 1, 3, 10 and 20 GeV. The cutoff energies were set to 1.5 MeV for electrons and 0.1 MeV for photons respectively. Particles with energies below the cutoff energy are no longer treated and their energy is immediately deposited. The thickness of the converter plates were compatible with 3 mm of Pb in units of radiation lengths. Table 1 gives the exact dimensions used for the calculations together with some material properties.

To study the effects at the boundaries in more detail, each converter plate and each detector gap was subdivided in four slices each. The deposited energy was treated for each slice separately. The whole detector consisted of 400 slices, resulting in a total radiation length of $27.8 X_0$.

The transition curve for 10 GeV electrons on Pb/LAr is shown in fig. 1. For each slice the deposited energy of an average 10 GeV shower was divided by the mean dE/dx of a minimum ionizing particle in the same

Table 1
Dimensions used for the calculations and some material properties

	X_0 [cm]	Thickness [mm]	Thickness X_0	dE/dx [MeV/cm]	Critical energy [MeV]
Al	8.872	47.35	0.534	4.37	39.3
Fe	1.760	9.39	0.534	11.6	20.5
Pb	0.562	3.00	0.534	12.8	7.2
U	0.318	1.70	0.534	20.7	6.6
LAr	13.952	3.00	0.022	2.11	29.8

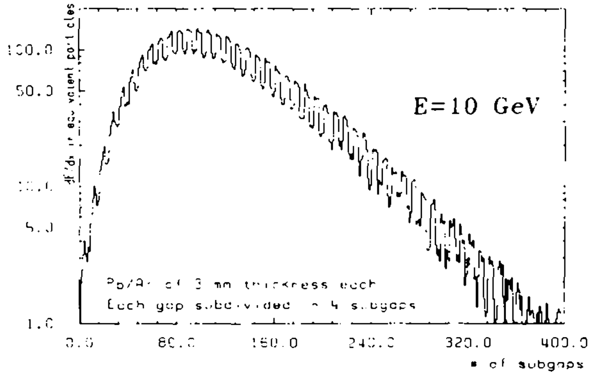

Fig. 1. Response of a sampling Pb, LAr calorimeter to electrons. The calorimeter starts with 4 Pb subgaps.

slice. This ratio then represents the deposited energy in units of minimum ionizing particles. From fig. 1 one can see that the transition effect is strongly shower age dependent. In the front part the relative response of the LAr is about 80%, whereas in the back part, where the bulk of the shower particles are below the critical energy of argon, the relative response drops to 60%. Within one converter plate or detector gap the deposited energy is distributed quite uniformly over the subgaps. This means that the transition occurs quite fast at the boundary. To study this effect in more detail, the deposited energies in the corresponding subgaps of the converter and the detector were added up along the shower. The result is shown in figs. 2a–2c for Fe, Pb and U and different energies. For Pb and U the signal decreases by 6% from the outer to the central LAr slices. The deposited energy in the first slice is equal within 1% to the deposited energy in the last slice.

The size of the transition effect was found to be independent of energy within 0.8% for incident energies of 1–20 GeV for Fe, Pb and U respectively. Fig. 2d and the first part of table 2 show the transition effect as a function of Z of the converter material for 10 GeV showers. In this plot R_e and R_μ are the fractions of the deposited energy in the liquid argon relative to the total deposited energy in the calorimeter for electrons and minimum ionizing particles respectively. For comparison the results of ref. [5] are shown which had a different sampling of $1 X_0$ compared to $0.556 X_0$ of this simulation. The Z dependence is quite similar, but there

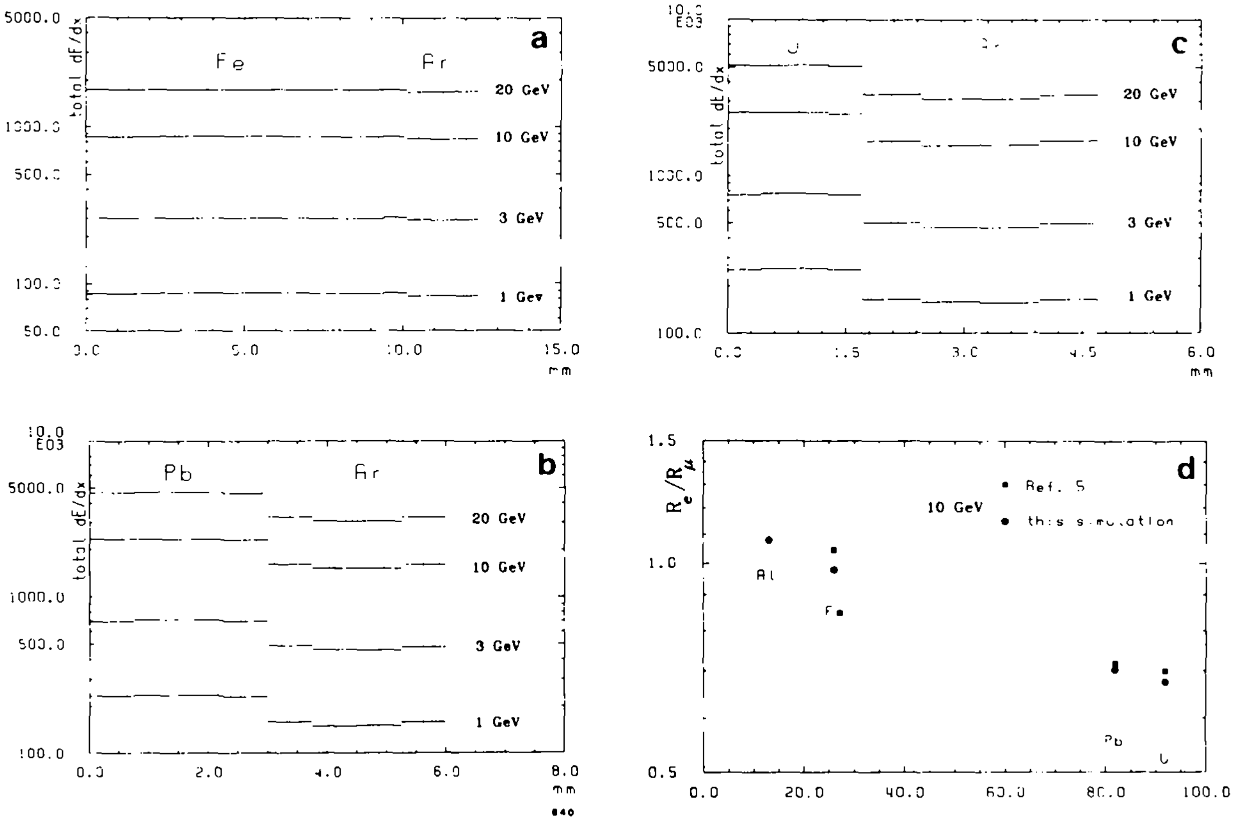

Fig. 2. Total dE/dx in equivalent particles for different converters and different energies. The deposited energies are summed up along the shower. ((a) Fe, (b) Pb, and (c) U.) (d) The transition effect for a LAr calorimeter as a function of Z for the converter material.

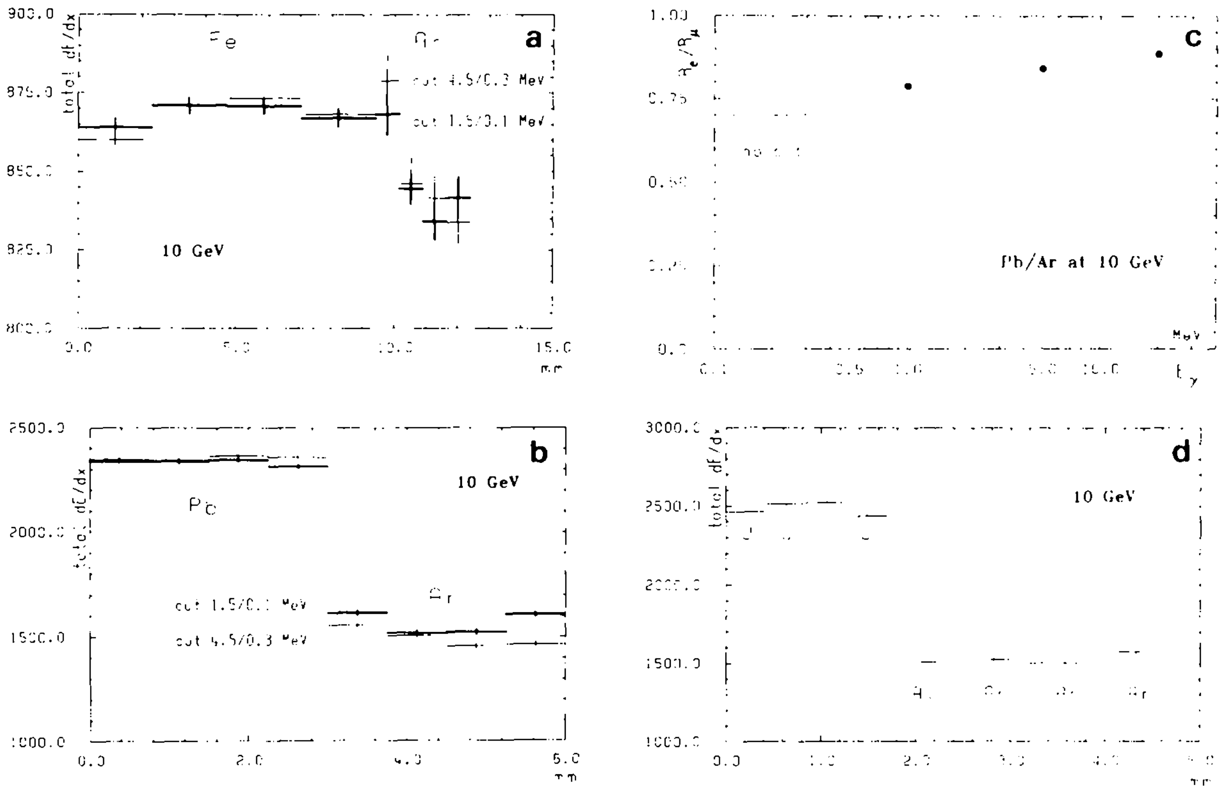

Fig. 3. Effect of the cutoff energy on the total deposited energy. The heavy lines are for the normal cut of 1.5/0.1 MeV. ((a) Fe, (b) Pb.) (c) The transition effect as a function of the threshold energy E_γ. All photons with smaller energies than E_γ are deleted immediately in the shower development. (d) Total dE/dx in equivalent particles for the first LAr gap replaced by aluminium.

is an absolute difference between the two simulations by 4%.

To check the effect of the cutoff energies we have increased the cutoff energy by a factor of 3 to 4.5 MeV for electrons and to 0.3 MeV for photons respectively. The result is shown in figs. 3a and 3b for Fe and Pb. The errors shown are the errors from the Monte Carlo statistics. For Fe the anyhow small transition effect is independent from the cutoff energies within the statistical errors, whereas for Pb converters a significant reduction of the response by 4.8% is observed. This reduced response may be explained with the relative increase of deposited photon energy in Pb, as the creation of photons is much larger in Pb compared to LAr. Further information on this explanation can be obtained if the photons are deleted (energy not deposited) immediately, if they are produced below a certain energy E_γ. For E_γ of 1, 5 and 20 GeV the size of the transition effect is shown in fig. 3c together with the size of the transition effect if no photons are deleted. For the 20 MeV cut $R_e/R_\mu = 0.886$ compared to $R_e/R_\mu = 0.702$ if no photons are removed.

In U, LAr calorimeters the uranium plates may be covered by other materials to shield the uranium radioactivity and to tune the e/h ratio. The effect of such a layer on the transition effect was investigated by replacing the first LAr subgap by Al of the same thickness. The result of a 10 GeV simulation shows fig. 3d. The transition effect to the 3 LAr subgaps in fig. 3d is very similar to the corresponding 3 LAr subgaps of fig. 2c. For these 3 LAr subgaps the ratio $R_e/R_\mu = 0.665$ without Al and $R_e/R_\mu = 0.661$ with Al shielding.

Table 2
Transition effect as a function of Z of the converter material for 10 GeV showers

	Al/LAr	Fe/LAr	Pb/LAr	U/LAr	Fe/C	Pb/C
R_e	0.0320	0.0537	0.0994	0.1030	0.0844	0.149
R_μ	0.0297	0.0549	0.1415	0.1526	0.0999	0.240
R_e/R_μ	1.079	0.978	0.702	0.675	0.845	0.621

3. Comparison with experiment

Dedicated experiments to measure the transition effect exist only for one transition between media of different critical energy [6]. As in high energy physics experiments LAr calorimeters are mainly used to measure electrons and photons, the energy calibration is normally done with electrons. This calibration is then not affected by the transition effect. However comparing the measured charge of electromagnetic showers with the expected charge from the ionization it was found [4] that for a sampling of 1.5 mm Pb and 2.05 mm LAr only 70% of the signal was detected, whereas for penetrating muons the measured signal was consistent with the expected one. This result is in good agreement with our value of $R_e/R_\mu = 0.702$ for Pb/LAr.

Sandwich calorimeters with silicon detector readout are well suited to study the transition effect experimentally. The silicon detectors are stable in response and the calorimeters can be reassembled easily. A comparison was made between U and W as converter plates for a calorimeter with silicon detector readout [7]. It was found that for an equal sampling of $2X_0$ the response R_e of the calorimeter to electrons is 11% higher for U compared to W. From the values of dE/dx per radiation length the calculated muon response R_μ is 20% higher for U than for W. This means that R_e/R_μ is larger for W by 8%. This is quite compatible with our simulations. If we take R_e/R_μ for W by interpolation in fig. 2d we find that this value is 11% higher for W than for U.

4. Conclusions

From our Monte Carlo simulations the following results can be summarized.

1) In electromagnetic showers the transition effect can easily reduce the signal to 70%.
2) The transition effect increases strongly with shower age.
3) The transition effect is not energy dependent.
4) The steps at the boundary are fast.
5) Calorimeters with U plates covered by Al show very similar electromagnetic response as calorimeters with uncovered plates.

From the last two points it looks quite difficult to tune the e/h ratio to be close to one for a compensating U, LAr hadron calorimeter, as easily accessible parameters like sampling thickness and the insertion of plates from light materials have only a small effect on the electron response. In ref. [5] it was concluded that $e/h \simeq 1$ can be reached for U, LAr calorimeters with the transition effect only. This however seems to be in contradiction with experimental results for scintillator readout [8,9]. In [8] the relative response e/h was measured for Fe and Pb at different energies. Around 10 GeV it was found that the e/h ratio for Pb was 1.34 times larger than for Fe. This result is not in good agreement with a similar measurement on Pb and Cu [9], where the e/h ratio for Pb was extracted to be only 0.96 times the e/h ratio of Cu. Combining these two measurements we conclude that for scintillator readout a hadron calorimeter with Pb plates will have no smaller e/h ratio due to the transition effect than a Fe/Cu calorimeter has. This must be due to the much higher losses in binding energy for Pb.

To compare the scintillator readout with a LAr readout we replaced the argon gap by carbon of the same thickness to simulate the scintillator. The obtained R_e/R_μ values at 10 GeV are also included in table 2. For the scintillator readout the response is found to be smaller than for the LAr readout, but the relative response between an Fe or Pb calorimeter to electrons is quite similar for the scintillator and LAr readout. From this result together with refs. [8,9] we conclude that a Pb, LAr calorimeter will have no better compensation due to the enhanced transition effect than a Fe (or Cu), LAr calorimeter has. We think that it will not be possible to build a compensating U, LAr calorimeter without a significant contribution from nuclear fission amplification.

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