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A METHOD FOR RECONSTRUCTION OF ELECTROMAGNETIC SHOWER PARAMETERS IN A CALORIMETER WITH A RECTANGULAR CELLULAR STRUCTURE

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1. Introduction

To detect electromagnetic showers produced by high-energy gamma-quanta, hodoscopic calorimeters with a cellular structure are used in some experimental facilities (e.g. see Refs /1-3/). The processing of the experimental data from these detectors consists in reconstruction of the released energy values and the coordinates of the electromagnetic shower cores.

In this paper an algorithm is proposed for the processing of the data from an electromagnetic calorimeter with square cells of sufficiently large size (as compared with the transverse size of the shower). The method is based on fitting the given model of the shower energy distribution in the calorimeter cells to the real data. This is a computer programme that is part of the software for the HYPERON facility /4,5/.

Here are general conditions defining the application range of the method proposed:

1. The calorimeter cells have a square section and are tightly joined together to make a "wall" (see Fig. 1).

2. The transverse dimension of the shower does not exceed the size of the cell, so a shower does not hit more than four adjacent cells (a block of 2x2) (see Fig. 2).

3. Let the group of the calorimeter cells where the energy release took place be called a cluster. Each cell of the cluster has at least one common side with any other cell of the cluster, and any two cells of the cluster can be connected by a chain of the cells of the same cluster, the latter cells joined with their sides. Let us suppose the probability of three or more electromagnetic showers hitting one cluster to be negligible.

4. The model distribution of the energy release of a shower produced by a particle with the energy e and coordinates x, y for the point of hitting the wall is as follows:

a) according to item 2, the shower releases energies e_1, e_2, e_3, e_4 in the block of 2x2 adjacent cells;

b) the energies e_i are proportional to the energy e of the incident particle, i.e.

$$e_i = e\, f_i(x,y) \qquad (1)$$

c) the quantities $f_i(x,y)$ from item 4b are related to one another as

$$f_1\, f_4 = f_2\, f_3 \qquad (2)$$

(in accordance with the numeration in Fig. 2);

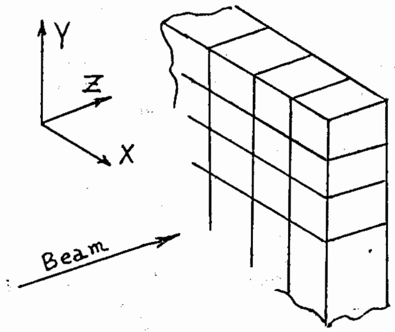

Fig. 1

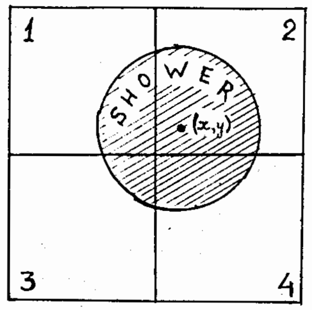

Fig. 2

d) coordinates x, y are unambiguously reconstructed by the ratios $f_i(x,y)/f_j(x,y)$, $1 \leqslant i < j \leqslant 4$.

Of all these assumptions relation (2) from item 4c seems to be least evident. Nevertheless, the model of the form

$$\begin{cases} f_1 = R_1(x)\, R_1(y) \\ f_2 = R_2(x)\, R_1(y) \\ f_3 = R_1(x)\, R_2(y) \\ f_4 = R_2(x)\, R_2(y) \end{cases} \qquad (3)$$

turned to be good for description of the results obtained in the test measurements at the HYPERON facility. The functions R_1 and R_2 were obtained by approximation of the experimental data /5/.

The electromagnetic shower parameter reconstruction technique to be considered below has been developed for processing the data from the Shower Hodoscopic Detector (SHD) of HYPERON. It is mainly based on relation (2) from item 4c, but it also contains several general principles and procedures.

2. General scheme of reconstruction of shower parameters

According to assumption 2 of shower energy release, each shower releases energy in several adjacent cells. On the other hand, according to assumption 3, the maximum of two cell-groups can be combined to make a cluster. So it is convenient to divide all the calorimeter cells, where energy was released, into clusters. Thus every shower is in its cluster, and in one cluster there is no more than two showers.

One must find out, how many showers are in a cluster (one or two), and to reconstruct the parameters of the showers. Division of the cells with the non-zero energy into clusters is a simple combinatoric problem, so we omit its solution. Note, however, that this part of the programme covers up to 20-40% of the total processing time even if there is quite a low density of clusters per event (e.g. 2-5 clusters for 190 cells). Thus, its optimization may also be of importance.

Now we turn to the technique of reconstruction of shower parameters inside a cluster. If C is the set of cells making up a cluster, the model distribution of the energy release is fitted to the really measured values of the energy e_i $(i \in C)$ by the least squares method:

$$\chi^2 = \sum_{i \in C} \frac{(e_i - \hat{e}_i)^2}{d_i} \rightarrow \inf , \qquad (4)$$

where $\hat{e}_i$, $i \in C$ are the "expected" energies, calculated by formula (1) for each cell of the cluster. Formula (4) includes covariances of occasional errors d_i at measurements of the energy e_i . We assume that the expressions of d_i through e_i are known (e.g. $d_i = c_o + c_1 \cdot e_i$).

If the one-shower-per-cluster hypothesis yields a satisfactory fit ($\chi^2 < \chi^2_{lim}$), it is accepted. If not, the parameters of two showers are fitted.

Let us analyse the expression of χ^2 in formula (4). Taking the hypothesis of one shower, one can find a block of 2x2 cells (let it be denoted by B), where the shower released all its energy, for each hypothetical position of the hitting point (x,y). Then

$$\chi^2 = \sum_{i \in B} \frac{(e_i - \hat{e}_i)^2}{d_i} + \sum_{i \in C \setminus B} \frac{e_i^2}{d_i} . \qquad (5)$$

Quantity (5) can be minimized by the following scheme:

a) to look through all blocks of 2x2 cells running across the given cluster;

b) to minimize only the first summand of (5) for each block B, since the second summand does not depend on the shower parameters (e, x, y);

c) to choose the smallest value among all minimal values of the function χ^2, obtained above; it will provide the best fit for the parameters of one shower in the given cluster.

The above scheme allows the one-shower-inside-a-cluster hypothesis to be reduced to a problem of minimization of the quantity

$$L(e,x,y)=\sum_{i=1}^{4}\frac{(e_i-\hat{e}_i)^2}{d_i} \qquad (6)$$

for four arbitrary figures e_1, e_2, e_3, e_4 interpreted as the energy releases in the block of 2x2 cells. This problem is solved in the maximum general form in section 3.

Checking the hypothesis of two showers, one can find two blocks of 2x2 cells (denoted by B_1 and B_2), where two showers released all their energy, for each pair of the hypothetical points $(x^{(1)}, y^{(1)})$, $(x^{(2)}, y^{(2)})$, where the primary particles hit the blocks. Then

$$\chi^2=\sum_{i\in B_1\cup B_2}\frac{(e_i-\hat{e}_i)^2}{d_i}+\sum_{i\in C\setminus(B_1\cup B_2)}\frac{e_i^2}{d_i} \qquad (7)$$

Quantity (7) can be minimized by the following scheme:

a) to look through all pairs of the blocks of 2x2 cells running across the given cluster;

b) to minimize only the first summand in (7) for each pair of blocks B_1 and B_2, since the second summand does not depend on the shower parameters;

c) to choose the smallest value among all minimal values of the function χ^2, obtained above; it will provide the best fit for the parameters of two showers in the given cluster.

The form of the first summand in (7) largely depends on the mutual position of blocks B_1 and B_2. Four variants are possible:

1) blocks B_1 and B_2 coincide;
2) blocks B_1 and B_2 have two common cell;
3) blocks B_1 and B_2 have one common cell;
4) blocks B_1 and B_2 do not intersect.

In the fourth case the first summand in (7) becomes a sum of two summands of form (6), each depending only on the parameters of one shower. So each summand is minimized separately, using twice the minimization algorithm of (6), described below in section 3.

Cases 1-3 require independent solutions, they are described in sections 4-6 of the present paper.

3. Fitting the parameters of one shower inside a block of 2x2 cells

According to (1), function (6) is re-written as

$$L(e,x,y)=\sum_{i=1}^{4}\frac{(e_i-e f_i(x,y))^2}{d_i}. \qquad (8)$$

In the point of the minimum of function (8) $\partial L/\partial e=0$, which allows the unknown e to be expressed through x, y:

$$e=\sum_{i=1}^{4}\frac{e_i f_i(x,y)}{d_i}\Big/\sum_{i=1}^{4}\frac{f_i^2(x,y)}{d_i}.$$

Substituting it to (8) we reduce our problem to minimization of the quantity

$$L(x,y)=\sum_{i=1}^{4}\frac{f_i^2(x,y)}{d_i}\Big/\left(\sum_{i=1}^{4}\frac{e_i f_i(x,y)}{d_i}\right)^2. \qquad (9)$$

The vital procedure is the introduction of new variables

$$u_k=f_k(x,y)\Big/\sum_{i=1}^{4}\frac{e_i f_i(x,y)}{d_i}, \qquad (10)$$

$k = 1,2,3,4$. Then (9) becomes of the form

$$L(u_1,u_2,u_3,u_4)=\sum_{i=1}^{4}\frac{u_i^2}{d_i}. \qquad (11)$$

It follows from (2) that

$$u_1u_4=u_2u_3 \qquad (12)$$

and from the definition of (10) it follows that

$$\sum_{i=1}^{4}\frac{u_i e_i}{d_i}=1. \qquad (13)$$

To stress the importance of introducing the variables u_i, we note that they can be considered as the independent variables with restrictions (12) and (13) imposed on them. Thus, minimization of the function of the general form (8) is reduced to minimization of a concrete simple function (11) on the variables u_i with restrictions (12) and (13). For the reconstruction of coordinates x, y by the known u_i one can use assumption 4d on the model distribution.

It is convenient to reduce the number of variables to three by introducing a new one: $t = u_3/u_1$. Then $u_3 = t\,u_1$ and, in virtue of (12), $u_4 = t\,u_2$, so (11) is of the form

$$L(u_1, u_2, t) = u_1^2\left(\frac{1}{d_1} + \frac{t^2}{d_3}\right) + u_2^2\left(\frac{1}{d_2} + \frac{t^2}{d_4}\right), \qquad (14)$$

and restriction (13) becomes of the form

$$u_1\left(\frac{e_1}{d_1} + t\,\frac{e_3}{d_3}\right) + u_2\left(\frac{e_2}{d_2} + t\,\frac{e_4}{d_4}\right) = 1. \qquad (15)$$

If t is fixed, the minimum of (14) on the variables u_1, u_2 with restriction (15) is achieved at

$$u_1 = \left(\frac{e_1}{d_1} + t\,\frac{e_3}{d_3}\right)\left(\frac{1}{d_2} + \frac{t^2}{d_4}\right)/D\,,$$

$$u_2 = \left(\frac{e_2}{d_2} + t\,\frac{e_4}{d_4}\right)\left(\frac{1}{d_1} + \frac{t^2}{d_3}\right)/D\,, \qquad (16)$$

where

$$D = \left(\frac{e_1}{d_1} + t\,\frac{e_3}{d_3}\right)^2\left(\frac{1}{d_2} + \frac{t^2}{d_4}\right) + \left(\frac{e_2}{d_2} + t\,\frac{e_4}{d_4}\right)^2\left(\frac{1}{d_1} + \frac{t^2}{d_3}\right). \qquad (17)$$

Substituting these values to (14) we obtain

$$L(t) = \left(\frac{1}{d_1} + \frac{t^2}{d_3}\right)\left(\frac{1}{d_2} + \frac{t^2}{d_4}\right)/D. \qquad (18)$$

Function (18) is a fractional-rational one with polynomials of the 4-th power in the numerator and the denominator. There is no much difficulty in minimizing it. Making the derivative $L'(t)$ equal to zero, we obtain an equation of the 6th degree. We only need the roots in the region $L''(t) \geqslant 0$ (there are no more than three roots). The presence of the good initial approximation

$$t_0 = \frac{e_3 + e_4}{e_1 + e_2}$$

facilitates essentially finding the roots. (In order "to see" this approximation, one should use assumptions 4b and 4c: $t = u_3/u_1 = u_4/u_2 \approx e_3/e_1 \approx e_4/e_2$).

We would like to add that the above procedure cannot be used only in two quite rare cases: $e_1 = e_4 = 0$ and $e_2 = e_3 = 0$. In these cases function (18) achieves its maximum either at $t = 0$ or at $t = \infty$, which turns its minimization into a simple task.

4. Checking the hypothesis of two showers for a block of 2x2

Here we consider case 1 from section 2 with blocks B_1 and B_2 coincided. In this case $B_1 \cup B_2$ is a block of 2x2, and the first

summand of (7) includes 4 experimentally measured energies, denoted by e_i, $1 \leqslant i \leqslant 4$, as in section 3. At the same time the model distribution of two showers depends on six parameters $e^{(1)}$, $x^{(1)}$, $y^{(1)}$, $e^{(2)}$, $x^{(2)}$, $y^{(2)}$. Such an redundancy of parameters leads to a possibility of reducing the first summand of (7) exactly to zero, i.e. the equations $\hat{e}_i = e_i$ have an exact solution at $i \in B_1 \cup B_2$. Moreover, this is not a single solution (a set of these solutions makes up a two-dimensional surface in the six-dimensional space of parameters of two showers).

Usually, the model does not allow one to choose "the best" of all solutions. So it is enough to show one of them. It can be easily obtained by employing a concrete form of the functions $f_i(x,y)$ from (1). In model (3), adopted for the SHD of HYPERON, it is enough to assume that the energies e_1 and e_2 are released by one shower, and e_3 and e_4 by the other. Then there is no difficulty in reconstructing the shower parameters.

5. Checking the hypothesis of two showers for a block of 2x3

Here we consider case 2 from section 2. In this case $B_1 \cup B_2$ makes up a block of 2x3 cells. We numerate the cells as shown in Fig. 3 and denote the respective energies by e_1, e_2, e_3, e_4, e_5, e_6.

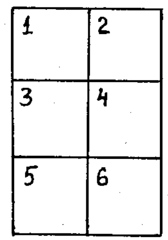

Fig. 3

The block of 2x3 can be positioned horizontally and the problem will have a similar solution.

The number of unknown parameters ($e^{(1)}$, $x^{(1)}$, $y^{(1)}$, $e^{(2)}$, $x^{(2)}$, $y^{(2)}$) coincides with the number of measured energies (e_1-e_6). It allows the assumption that in the general case the equation $\hat{e}_i = e_i$, $1 \leqslant i \leqslant 6$, has a solution, and this is the only solution. To obtain it, we assume that block B_1 consists of cells 1-4, and block B_2 consists of cells 3-6. Then, according to (1),

$$\begin{aligned} \hat{e}_1 &= e^{(1)} f_1^{(1)} \;; \qquad \hat{e}_2 = e^{(1)} f_2^{(1)} \\ \hat{e}_3 &= e^{(1)} f_3^{(1)} + e^{(2)} f_1^{(2)} \\ \hat{e}_4 &= e^{(1)} f_4^{(1)} + e^{(2)} f_2^{(2)} \\ \hat{e}_5 &= e^{(2)} f_3^{(2)} \;; \qquad \hat{e}_6 = e^{(2)} f_4^{(2)}, \end{aligned} \qquad (19)$$

where the functions $f_i^{(1)}$ and $f_i^{(2)}$ depend on ($x^{(1)}$, $y^{(1)}$) and

$(x^{(2)}, y^{(2)})$ respectively. Setting $\hat{e}_i$ equal to e_i and solving eq. (19), we obtain

$$\frac{f_3^{(1)}}{f_4^{(1)}} = \frac{f_1^{(1)}}{f_2^{(1)}} = \frac{e_1}{e_2} \quad ; \quad \frac{f_3^{(2)}}{f_4^{(2)}} = \frac{f_1^{(2)}}{f_2^{(2)}} = \frac{e_5}{e_6} \; ;$$

$$\frac{f_3^{(1)}}{f_1^{(1)}} = \frac{f_4^{(1)}}{f_2^{(1)}} = \frac{e_3 e_6 - e_4 e_5}{e_1 e_6 - e_2 e_5} \; ; \qquad (20)$$

$$\frac{f_1^{(2)}}{f_3^{(2)}} = \frac{f_2^{(2)}}{f_4^{(2)}} = \frac{e_1 e_4 - e_2 e_3}{e_1 e_6 - e_2 e_5} \, .$$

The ratios $f_i^{(1)}/f_j^{(1)}$, $f_i^{(2)}/f_j^{(2)}$ allow one to find respective coordinates $x^{(1)}, y^{(1)}$ and $x^{(2)}, y^{(2)}$ using assumption 4d. Using the coordinates, we can find the values of $f_i^{(1)}$, $f_i^{(2)}$ and the energies $e^{(1)}$, $e^{(2)}$ from eq. (19). Thus, the solution is found exactly.

However, the solution obtained will have a sense only if $e^{(1)} \geqslant 0$ and $e^{(2)} \geqslant 0$. It follows from (20) that in order to have this it is necessary and sufficient that three quantities

$$d' = e_1 e_6 - e_2 e_5, \quad d'' = e_3 e_6 - e_4 e_5, \quad d''' = e_1 e_4 - e_2 e_3$$

are all negative or all positive at the same time.

If the hypothesis of two showers is in good agreement with the e_1-e_6 data, the above condition is satisfied and one can find an exact solution by formulas (20).

If the hypothesis of two showers does not agree with the e_1-e_6 data well enough, but the discrepancy is not very large, the following "trick" is possible. As shown, the first summand in (7) reaches the absolute minimum (zero) in the point beyond the region of allowable values $f_i^{(1)} \geqslant 0$, $f_i^{(2)} \geqslant 0$. If the minimum of (7) lies in the close vicinity of the boundary of the region of allowable values, the minimum of (7) is achieved at the boundary of the region. This boundary consists of points, for which $f_i^{(1)} = 0$ for some $1 \leq i \leq 4$, or $f_i^{(2)} = 0$ for some $1 \leq i \leq 4$.

The latter conditions mean that one of the showers hits only two of the six cells. It is easy to show that checking two variants, $f_3^{(1)} = f_4^{(1)} = 0$ and $f_1^{(2)} = f_2^{(2)} = 0$, is enough. In both variants the first summand of (7) becomes a sum of two summands, each depending on the parameters of only one shower. Each of the summands is minimized by the method described in section 3.

Finally, let the hypothesis of two showers be in very poor agreement with the measured energies e_1-e_6, so that the above considerations cannot be applied. Then minimization of (7) would require some iteration schemes of the general form, and the above solution could only be used as the initial approximation. Usually, however, this work has no sense for a simple reason: if the hypothesis of two showers poorly agrees with the data, it should be rejected without specifying the shower parameters, because it is senseless to fit the hypothesis known to be inadequate to the real data.

6. Checking the hypothesis of two showers for a block of seven cells

Here we consider case 3 of section 4. In this case $B_1 \cup B_2$ makes up a block of seven cells (Fig. 4a, 4b). We numerate the cells as shown in Fig. 4a and denote the respective energies of e_1-e_7. If the block is placed as shown in Fig. 4b, the problem is solved in a similar way.

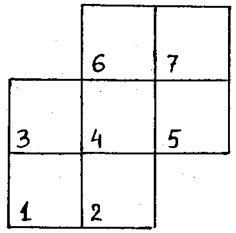

Fig. 4a

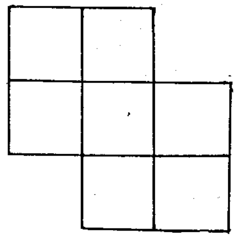

Fig. 4b

Let B_1 consist of cells 1-4 and B_2 consist of cells 4-7. Then $e_4 = e_4' + e_4''$, where e_4' and e_4'' are the energies released in cell 4 by the first and second showers respectively. If the two-shower hypothesis describes the e_1-e_7 data well, then in virtue of (2)

$$e_4' \approx e_2 \cdot e_3/e_1 \quad \text{and} \quad e_4'' \approx e_5 \cdot e_6/e_7 .$$

These relations allow an approximate estimation of e_4' and e_4''. Taking into account the requirement that $e_4' + e_4'' = e_4$, one can propose the following estimation:

$$e_4' = \frac{\frac{e_2 e_3}{e_1} e_4}{\frac{e_2 e_3}{e_1} + \frac{e_5 e_6}{e_7}} \quad ; \quad e_4'' = \frac{\frac{e_5 e_6}{e_7} e_4}{\frac{e_2 e_3}{e_1} + \frac{e_5 e_6}{e_7}} \, .$$

Then one can estimate the parameters of both showers by their energy release e_1, e_2, e_3, e_4' and e_4'', e_5, e_6, e_7, respectively. To do this, one should twice apply the method described in section 3. If there is good agreement between the two-shower hypothesis and the experimental data, we shall obtain the minimum of the first summand of (7) with a high accuracy.

In the general case, however, the obtained estimations can be only considered as the initial approximation to the sought-for solution. In this case in our programme further minimization of the first summand in (7) went on by the iteration scheme of quite a general form. We only note the general principles of this scheme.

1. Elimination of the unknown $e^{(1)}$, $e^{(2)}$ (shower energies) by the method described in section 3 for one shower. After that only four unknown quantities remain ($x^{(1)}$, $y^{(1)}$, $x^{(2)}$, $y^{(2)}$).

2. Going to new independent arguments $u_i^{(k)}$, $k = 1,2$, as in section 3 for one shower (the index k of the variables $u_i^{(k)}$ is the number of the shower, they are determined as in section 3).

3. Going further to new independent arguments

$$t^{(k)} = u_3^{(k)}/u_1^{(k)} \; ; \qquad s^{(k)} = u_2^{(k)}/u_1^{(k)}$$

(k is again the number of the shower), which actually generalizes the variable t of section 3 of the case under consideration.

4. Application of the known method of the gradient descent with the variable step for minimization of the first summand of (7) by $t^{(1)}$, $s^{(1)}$, $t^{(2)}$, $s^{(2)}$.

Implementation of the above principles in the data processing programme allowed a relatively fast and accurate procedure of reconstruction of the shower parameters. Nevertheless, this procedure is quite slow as compared with the methods described in sections 3-5. It was not further optimized, because the clusters of this type (i.e. with the blocks like 4a or 4b) are quite rarely encountered in practice.

7. Results of the test processing of the experimental data

The above algorithm was used to reconstruct the events in the experimental investigations of the K^+- meson decays at the HYPERON facility. To calibrate and check the algorithm, the decays $K^+ \rightarrow \pi^+\pi^o$ ($\pi^o \rightarrow 2\gamma$) were reconstructed. At first the energies and coordinates of gamma-quanta, reconstructed by two methods, were compared. The first method uses the programme with the above algorithm, the second one involves the standard package MINUIT /6/ for minimization of functional (4). Figs 5a and 5b show distributions of the differences of the electromagnetic shower core coordinates reconstructed by the two methods. As seen, in 98% of the cases the difference of the coordinates is within 2σ (σ = 10 mm) /4/. Fig. 6 shows distributions of the differences of the reconstructed energy values. They are also in good agreement within the measurement errors /4/.

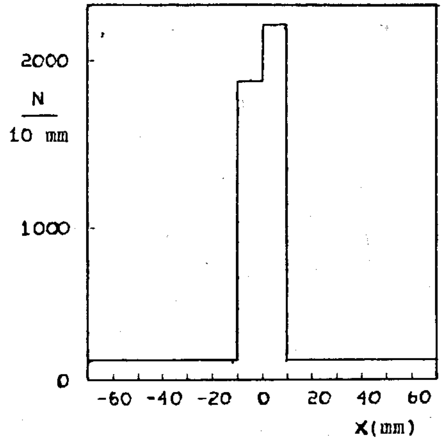

Fig. 5a

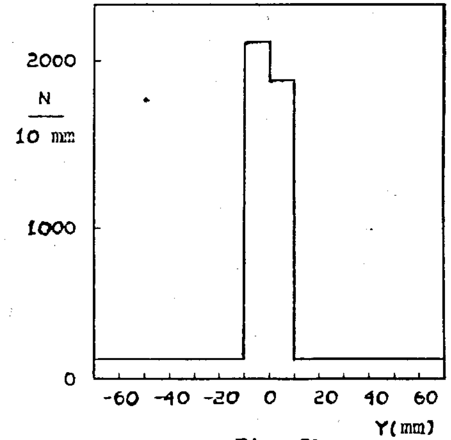

Fig. 5b

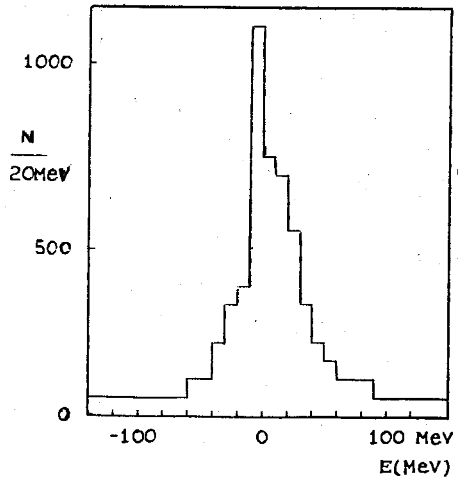

Fig. 6

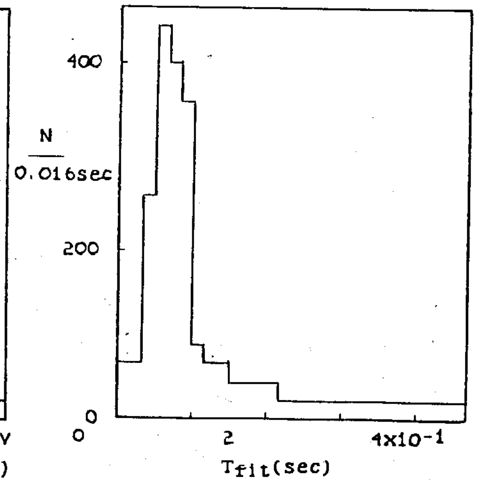

Fig. 7

The main advantage of the proposed algorithm is its fast action. Fig. 7 shows the time distribution of the reconstructed two-cluster events ($K^+ \rightarrow \pi^+\pi^o$, $\pi^o \rightarrow 2\gamma$). For these events the programme with the above algorithm reconstructs the energies and coordinates of the showers 8.1 times faster than MINUIT. It reduced the processing time almost by an order of magnitude (the comparison was carried out at an IBM/AT-type computer).

The proposed method also allowed a 10-12% increase in the number of the reconstructed decays of K^+-mesons owing to a higher efficiency of the algorithm in determination of the parameters of the overlapping showers (when more than 5 cells of the electromagnetic calorimeter are in operation).

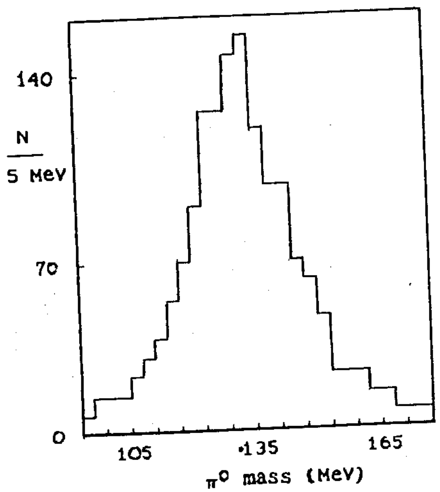

Fig. 8

Fig. 8 shows the effective mass of π^0 from the decays $K^+ \to \pi^+\pi^0$ for 2028 reconstructed events. The mean value of the π^0 mass is in good agreement with the table value (134.9 MeV), and the peak width (30 MeV at half-maximum) corresponds to the one obtained in simulation and agrees with the experimental data /7/ and /8/.

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Метод восстановления параметров электромагнитных ливней в калориметре с прямоугольной ячеистой структурой

Составной частью установки ГИПЕРОН /ЛЯП, ОИЯИ/ и многих других современных экспериментов является ливневый годоскопический детектор /ЛГД/ - калориметр с ячейками прямоугольной формы. В работе рассмотрена модель распределения энерговыделений в ячейках ЛГД и предложено аналитическое решение задачи подгонки модельного распределения к реальным данным. Соответствующая программа была включена в систему математического обеспечения установки ГИПЕРОН и позволила ускорить обработку данных в 8 раз с повышением надежности на 10%.

Работа выполнена в Лаборатории вычислительной техники и автоматизации ОИЯИ.

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A Method for Reconstruction of Electromagnetic Shower Parameters in a Calorimeter with a Rectangular Cellular Structure

The Shower Hodoscopic Detector (SHD) is an important part of the detector HYPERON (INP, JINR) as well as many other up-to-date detectors. It is a calorimeter with rectangular cells. In the present paper we consider a model of the distribution of energy release in the SHD cells and propose as analytical solution of the problem of fitting the model distribution to experimental data. The corresponding programme was included in the HYPERON software and allowed one to raise the rate of the data processing 8-9 times with about 10% reliability increase.

The investigation has been performed at the Laboratory of Computing Techniques and Automation, JINR.

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