NPA/Int. 64-35
Meyrin, 5th November 1964

SOME CALCULATIONS ON NUCLEAR CASCADES INDUCED BY NEUTRINOS

I. Introduction

In the bubble chamber neutrino experiment many events are observed which contain more than one nucleon track. The occurrence of these extra nucleons may be attributed to secondary interactions in the nucleus of the products of the neutrino interaction. The purpose of the present work is to investigate the secondary interactions which are likely to occur when fast protons are liberated inside heavy nuclei.

II. Method

The method used is based on the mechanism proposed by Serber [(1)] for the interaction of high energy particles with complex nuclei. In the first stage the interactions are supposed to be with individual nucleons and the cross sections are those applicable in free space, apart from effects of the Pauli exclusion principle. The second stage consists of a de-excitation of the residual nucleus by the evaporation process. Since this process gives rise to only slow ($<$ 30 MeV) protons and neutrons, it has not been considered here. The first stage of the nuclear interaction is referred to as the cascade.

As a nuclear model we have used the degenerate Fermi gas of nucleons in a nuclear potential of radius $(1.3 \times 10^{-13})\ A^{1/3}$ cm, where A is the atomic number. The other parameters of the model were taken to be :

Nuclear potential	:	37 MeV
Fermi momentum	:	234 MeV/c

The nucleon-nucleon cross sections have been represented by the parameterizations given by Metropolis et al [(2)]. These parameterizations reproduce the experimental data in the range 25 - 350 MeV to within 6 o/o. On the basis of charge symmetry the neutron-neutron cross section was taken to be equal to the proton-proton cross section. The angular distributions were assumed to be isotropic in the centre of mass system. In reality there is forward and backward peaking, particularly in proton-neutron collisions. However, in the nucleus this peaking would be much reduced by the effect of the Pauli exclusion principle.

III. Details of the calculations

The calculations have been performed on the 7090 computer using the Monte-Carlo method. This method consists of choosing at random the next stage of a process from a number of equally likely possibilities. The calculation is repeated many times, and finally one obtains the mean values and fluctuations of all variables connected with the process. The results will represent nature to the extent that the model used is adequate.

A block diagram of the course of the calculation is shown in Fig. 1. The choice of starting point was made according to one of two ways :

1) For comparison with experimental measurements on incident protons the starting point was always chosen at the surface of the nucleus.

2) To simulate neutrino events the starting point was chosen randomly throughout the nuclear volume.

IV. Comparison of calculations with experimental data

Bernardini, Booth and Lindenbaum [3] have studied the interaction of 375 MeV protons with heavy emulsion nuclei, and Friedman [4] has obtained similar data at 310 MeV. To simulate the heavy emulsion nuclei the Monte Carlo programme was run for protons incident on Ru^{100} nuclei. The results chosen for comparison are those concerning the prong distribution in the energy range above 30 MeV. The experimental data and the Monte-Carlo calculations are shown in Table 1. It can be seen that the agreement is very satisfactory. This agreement serves as a justification of the model and gives confidence in using it to predict the behaviour of the protons liberated in neutrino events.

V. Results concerning neutrino-induced cascades

In Fig. 2 are shown the proportion of events which should appear as having no proton of energy greater than 30 MeV, and the proportion which will have less than 2 protons of energy greater than 30 MeV. The energy scale represents the kinetic energy of the proton inside the nucleus. The curve shown is the average of two runs using fluorine and bromine respectively as the target nucleus.

In order to cover the whole range of momentum transfer involved in the elastic neutrino interaction, a crude extension of the calculation has been made to cover the range 350 - 1000 MeV where pion production becomes important. Approximate parameterizations of the cross sections and inelasticity in this region have been used. Pion production predominantly through the (3/2, 3/2) isobar has been assumed and the effects of the Pauli principle have been included. If after a collision a pion was produced, the cascade was stopped at this point on the assumption that either the pion would emerge from the nucleus in which case the event would be classified as pionic or if the pion were absorbed, more than one fast proton would emerge in the majority of cases . This procedure should give a lower limit to the number of events with zero or one proton. The result of this calculation is shown as the dotted curve in Fig. 2. Although this method is obviously very crude it may well be adequate since less than 20 o/o of the 1 proton elastic candidates are in the region of momentum transfer where pion production is possible.

VI. An application of the results to the elastic neutrino events

The analysis of Stump [5] has shown that at low four momentum transfer (q^2) the one-proton non-pionic events are predominantly elastic. If the major contamination in non-pionic events is due to the absorption of pions, there is no reason to suppose that the one-proton events of high q^2 contain a larger proportion of inelastic events than those of low q^2. Thus a possible approach is to take only the one-proton non-pionic events as elastic and to correct the cross section and q^2 distribution for the bias introduced by this selection criterion.

In the energy region above 1 GeV there are 67 non-pionic events with not more than one proton of energy greater than 30 MeV. An additional selection has been made on the basis of the M^{*2} defined by :

$$M^{*2} = M_p^2 - q^2 + 2 M_p (E_\nu - E_\mu)$$

where M_p = proton mass
E_ν = neutrino energy
E_μ = muon energy

Only those events with M^{*2} in the range 0.48 to 1.28 $(GeV)^2$ have been retained. From the shape of the central peak near M_p^2 this criterion should eliminate only a few percent of good elastic events. In fact 17 events were rejected.

For each of the remaining 50 events the mean kinetic energy T_p of the recoil proton was obtained fromthe relation :

$$q^2 = 2 M_p T_p$$

The probability of producing a multiproton event at this q^2 was then obtained from Fig. 2. The expected number of multiproton events was found to be only 5. The observed number of multiproton non-pionic events with visible energy $>$ 1 GeV is 52. This suggests that most of the multiproton events are not elastic.

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References

1) R. Serber - Phys. Rev. 72, 1114 (1947)

2) N. Metropolis, R. Bivins, M. Storm, A. Turkevich and G. Friedlander - Phys. Rev. 110, 185 (1958)

3) G. Bernardini, E.T. Booth and S.J. Lindenbaum - Phys. Rev. 85, 826 (1952)

4) J. Friedman - private communication to Metropolis et al., quoted in ref. 2.

5) R. Stump - NPA/Int. 64-26

Fig. 1 Block diagram of the Monte-Carlo calculation

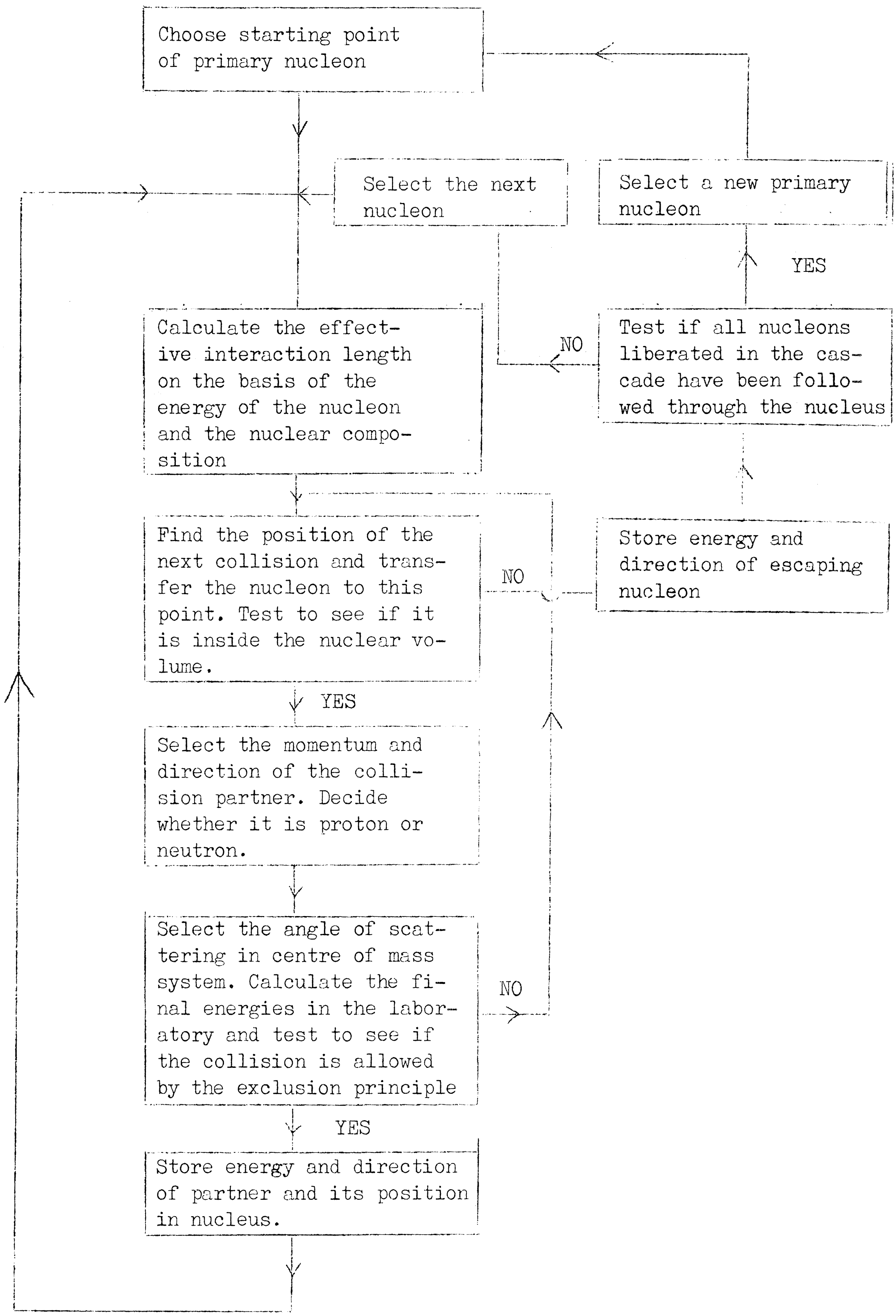
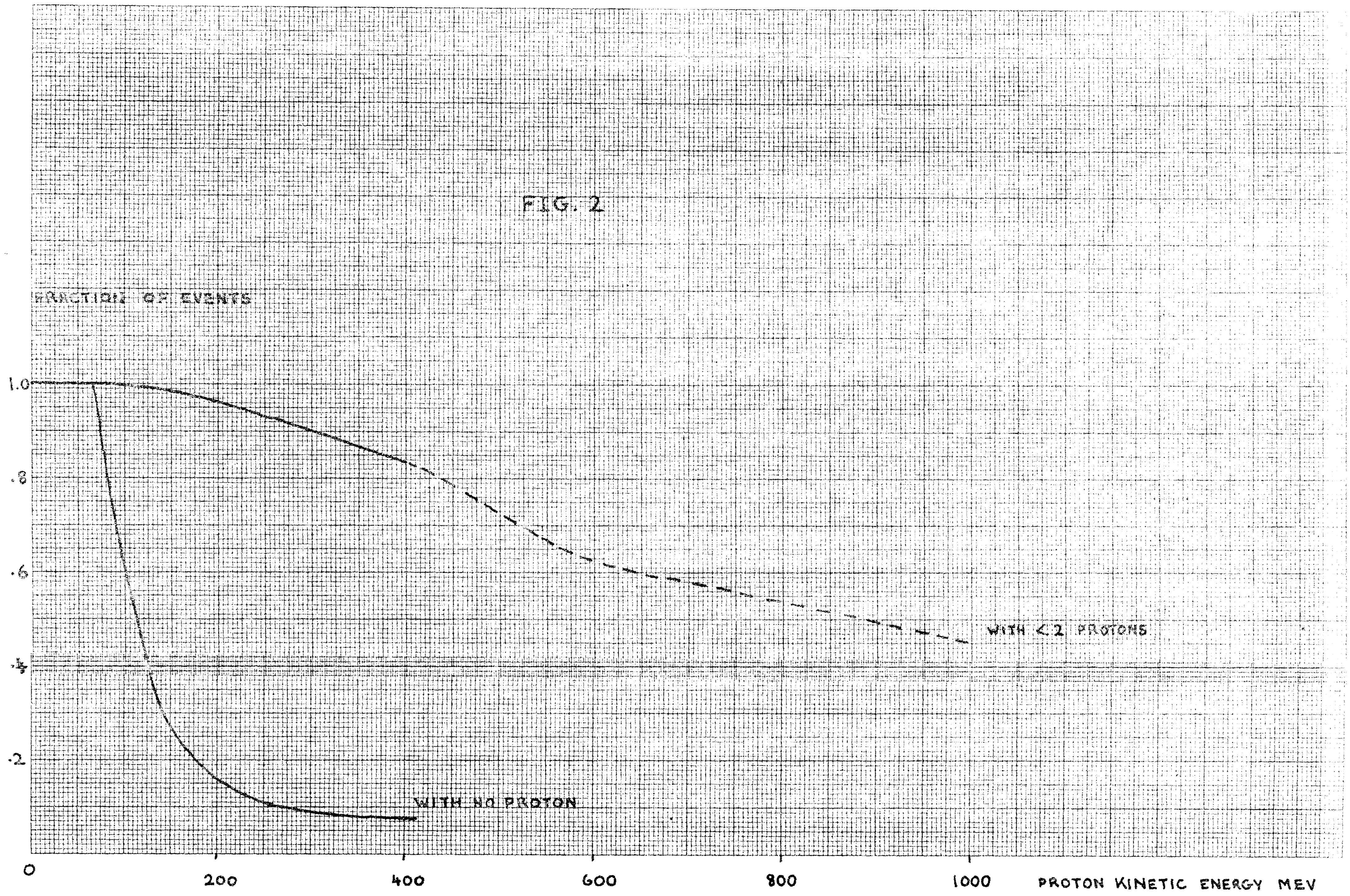


Table 1

Proton Energy MeV	Prong Number	$T_p > 30$ MeV		$T_p > 100$ MeV	
		Experiment	Calculation	Experiment	Calculation
375	0	$.35 \pm .03$	$.227 \pm .035$	$.57 \pm .04$	$.50 \pm .05$
	1	$.54 \pm .04$	$.53 \pm .05$	$.40 \pm .04$	$.45 \pm .05$
	2	$.09 \pm .02$	$.227 \pm .035$	$.025 \pm .010$	$.044 \pm .016$
	3	$.017 \pm .007$	$.022 \pm .011$		
		$30 < T_p < 90$ MeV		$T_p > 90$ MeV	
310	0	$.59 \pm .13$	$.62 \pm .06$	$.54 \pm .03$	$.57 \pm .06$
	1	$.34 \pm .09$	$.29 \pm .04$	$.42 \pm .03$	$.390 \pm .046$
	2	$.07 \pm .04$	$.088 \pm .022$	$.034 \pm .010$	$.038 \pm .015$
	3	.003	.005	.005	0

FIG. 2


FRACTION OF EVENTS
1.0
·8
·6
·4
·2
0
200
400
600
800
1000
PROTON KINETIC ENERGY MEV
WITH <2 PROTONS
WITH NO PROTON