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CUMULATIVE PARTICLE PRODUCTION IN FERMILAB EXPERIMENT E665*

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ABSTRACT

I estimate rates for cumulative particle production from C, Ca and Pb nuclei for conditions of Fermilab experiment E665 of $\mu - A$ deep inelastic scattering. Estimates have been obtained on the basis of hadron-nuclei interactions experimental data. The possibility of also detecting backward produced charged particles by liquid scintillator neutron counters is discussed. This experiment, to be run in 1990, will be a valuable precursor to physics with the PEGASYS facility.

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1. INTRODUCTION

Studies of inelastic interactions of high energy particles with nuclei accompanied with emission of fast particles (up to **1** GeV/c) in the backward hemisphere in the laboratory frame began more than twenty years ago.[1] The production of such particles could not be explained either by common evaporation (the energy . of evaporated particles usually does not exceed several tens of MeV) nor by simple cascade processes inside the nucleus. The detailed study of particle production in the kinematical region forbidden for projectile-nucleon interactions (later called cumulative particle production) prompted the formulation and then experimental confirmation of the nuclear scaling hypothesis.[2,3] According to this hypothesis the shape of cumulative particle inclusive spectra does not depend on the atomic weight of target nucleus for $A \geq 10$ and on the type of incident particle and its energy (if greater than several GeV). It should be noted that this conclusion is correct not only for incident hadrons but also for photons,[4] electrons[5] and neutrinos[6] (in these two latter cases the value of Q^2 was not measured, and therefore the data was strongly biased to low Q^2).

The processes leading to cumulative particle production were later attributed to the new class of nuclear reactions - Deep Inelastic Nuclear Reactions (DINR).[7] Of course, the fundamental mechanism of DINR (interactions with closely correlated nucleons, or from modern point of view multiquark bags in the nuclei) leads not only to cumulative particle production, where one has an almost pure sample of DINR, but mostly to forward particle production. It should be emphasized here that in nuclei with $A \geq 10$ DINR are not rare processes: for example the detailed study of high energy hadron-carbon interactions showed that approximately a half of the protons with kinetic energies from several tens to several hundreds of MeV emitted in the forward direction have their origin in DINR.[8] The relative contribution of DINR sharply increases with increasing atomic weight of the target nucleus!" A more detailed review of DINR features can be found in ref.[10]

As mentioned above, previous experiments of electron and photon interactions with nuclei have been dominated by low-Q^2 events. In this case one may consider that the photon dissociates into qq-pair for a considerably longer time than the nuclear traversal time[11] and therefore properties of such interactions are very similar to those of high energy hadron-nuclei interactions.[10] On the other hand in case of eA (or μA) interactions at high Q^2 ($Q^2 \geq 1$ $(\mathrm{GeV/c})^2$) the process of virtual photon emission and absorption becomes pointlike (on the nuclear scale). Moreover for sufficiently high values of $\nu = E\text{-}E'$ the hadronization of knocked-out quark may occur downstream of the nucleus,[12,13] and products of its hadronization would not interact with the rest of nucleus. Of course, this picture needs to be verified in detail experimentally. If this is indeed the case then one will have an exceptional opportunity to investigate the interaction of the initial particle with the single multiquark bag.

A good opportunity to make the preliminary measurement of cumulative particle production now appears in the Fermilab experiment E665.[14] In this paper we estimate the statistics of cumulative particle possible in this experiment and discuss the usefulness of the neutron counters being mounted there to the detection of charged particles as well.

2. STATISTICS EXPECTED FOR CUMULATIVE PARTICLE PRODUCTION

2.1. FNAL experiment E665

The Fermilab experiment E665 is intended for measurements of deep inelastic muon - nucleus scattering. The detailed description of the experiment may be found elsewhere!“’ Here we list only the advertized parameters of it and take into account future plans of its operation.[15] We have used the following parameters:

Beam energy	*500* GeV
Cycle time	*57* sec
Spill time	*20* sec

Muons/spill	$7 \cdot 10^7$
Targets	H;D,C,Ca,Pb
Target thickness	16 g/cm^2
Integrated luminosity per target	4 . 10^{36} nucleon/cm^2
Range of Q^2	$Q^2 \geq 1$ $(GeV/c)^2$ or $Q^2 \geq 2$ $(GeV/c)^2$
Distance from target to neutron counters	2.0 m
Angular position of neutron counters	$\theta = 90^o$ in lab.
Total solid angle of neutron counters	0.057 sr

For the sake of simplicity we suppose that the acceptance of muon spectrometer equals 100% at $Q^2 \geq 1$ $(GeV/c)^2$.

2.2. Expected statistics

In order to estimate the number of deep inelastic scattering events (DIS events) we use the parton model with the F_2 structure function of the form [16]

$$F_2(x) = 3.9x^{0.55}(1-x)^{3.2} + 1.1(1-x)^8$$

Then the differential cross section of DIS on "an isoscalar average" nucleon is

$$\frac{d^2\sigma}{d\nu dQ^2} \approx \frac{2\pi\alpha^2}{\nu S(S-M^2)} \cdot \frac{1+(1-y)^2}{x^2y^2} \cdot \frac{5}{18} \cdot F_2(x)$$

where $\nu = E - E'$; $x = \frac{Q^2}{2M\nu}$; $y = \frac{\nu}{E}$ and $S = \frac{Q^2}{xy} + M^2$.
We have integrated this equation with the following kinematical restrictions:

$Q^2 \geq 1$ $(GeV/c)^2$ and $Q^2 \geq 2$ $(GeV/c)^2$

3 GeV$< \nu <$400 GeV

$W^2 > 4$ GeV^2 where $W^2 = M^2 + 2M\nu - Q^2$.

For the known integrated luminosity we may therefore expect 1.4 . 10^6 DIS events at $Q^2 \geq 1$ $(\mathrm{GeV/c})^2$ and 6 . 10^5 DIS events at $Q^2 \geq 2$ $(\mathrm{GeV/c})^2$ for each target.

In order to estimate the number of cumulative particles we used energy and angular distributions for particles produced in DINR in hadron-nucleus interactions. It is known for example,[8] that the inclusive spectra of protons produced in DINR at high energies are well described by simple dependence

$$\frac{Ed\sigma}{d^3p} \propto \exp\left(-\frac{(T-\mu)\cdot(1-\beta\cos\theta)}{T_0}\right)$$

where T_0, β and μ are parameters independent on target atomic weight; type and energy of the initial particle (at energies greater than several GeV); E, p and T - total energy, momentum and kinetic energy of proton respectively; θ - the emission angle in the lab frame. The modification of the properties of DINR with the transition to high Q^2 have been taken into account by reducing the mean multiplicity of secondary particles by a factor of two. Effects of nuclear transparency for the knocked-out quark have been neglected. Finally we take into account the solid angle covered by the neutron counters and a 10% efficiency for fast neutron detection.[17]

Table 1 shows the expected numbers of events for C, Ca and Pb targets in E665 experiment for followed particles and kinetic energy ranges:

p,n (60-120 MeV), d (So-160 MeV), π (20-60 MeV).

For the pions we have assumed that the yield of π^+ and π^- are equal, and have calculated the pion yield of both signs.

Strictly speaking, the pions in mentioned energy range are not cumulative, but previous hadron-nucleus investigations[18] show that the most of the pions in this angular and energy range originate by DINR and their yields obey similar regularities as for cumulative particles.

The lower limits of energy ranges have been chosen to avoid any contribution from evaporative processes, and the upper limits have been chosen on the basis of feasibility of charged particles detection by the available neutron counters, as will be discussed below.

Tab.1 The expected numbers of particles detected by the neutron detectors.

	$Q^2 \geq 1$ (GeV/c)^2			$Q^2 \geq 2$ (GeV/c)^2		
Particle E(MeV)	C	Ca	Pb	C	Ca	Pb
Protons (60-120)	440	1050	3400	195	460	1490
Neutrons (60-120)	45	110	350	20	45	150
Deuterons (80-160)	80	220	850	35	95	370
Pions* (20-60)	340	440	640	145	190	280

* (π^+ and π^- together)

3. DETECTION OF CHARGED PARTICLES BY NEUTRON COUNTERS

3.1. Charged particles detection

The liquid scintillator neutron counters[17] available in E665 are intended for detection of slow neutrons (up to 20 MeV). 7 counters are placed at a distance of 2 m from the target.[19] Each cylindrical counter is 8” (20.3 cm) in diameter and 4” (10.2 cm) in thickness. Pulse shape and time-of-flight are measured to discriminate between neutrons and gammas and to determine the neutron energy. Veto counters of 1 cm thickness plastic scintillator are placed in front of the neutron detectors.

We have calculated the response of these neutron counters to charged particles. These calculations include slowing down in air, passing through the veto counters and detailed energy loss processes in the BC-501 liquid scintillator counter. The non-linear response of scintillator for heavily-ionizing particles[20] and dependence of the light collection on position inside the scintillator[17] have also been taken into account. We have taken the effective speed of light in the counter to be 1.2 times slower than given by refractive index, that is typical for such geometries.[21]

Fig.1 shows the dependence of pulse height (in equivalent electron units) on time-of-flight measured by the same counter for pions, protons and- deuterons. The numbers inside the boxes are the kinetic energies of the particles. As the time resolution of the counter is 0.32 ns (FWHM)[17] particle identification will be possible even for particles passing through the detector if the pulse height resolution will be adequate.

3.2. Resolution

The kinetic energy resolution of time-of-flight counters is given by

$$\frac{\delta E}{E} = \gamma(\gamma + 1)\frac{\delta t}{t}$$

where γ is Lorentz factor, δt is time-of-flight uncertainty and t is the time-of-flight. The factor St includes both the uncertainty of track-position and the counter's time resolution. Overall we estimate it to be 0.35 ns (FWHM). This expression implies *(SE/E)* = 6% for 120 Mev protons and *(SE/E)* = 13% for 60 MeV pions. This resolution is entirely adequate for the proposed measurements.

3.3. Efficiency

Estimates of identification efficiency were based on results of measurements carried out with a thick plastic scintillator counter.[21] The identification efficiency depends on the rejection of events when particles interact in the scintillator. Only processes with energy transfers higher then several MeV need to be taken into account. These estimates give a proton identification efficiency which slowly decreases from 99% at 40 MeV to 95 $\pm$ 1% at 120 MeV, and remaining approximately constant up to 200 MeV.

3.4. Background

Here we cite only a few of the possible background sources. First, since the muon beam time structure consists of RF buckets spaced at 19 ns intervals ,[14] at the indicated beam intensity about 7% of the occupied RF buckets contain more than one muon. The cross section of muon-nucleus interactions at low Q^2 is significantly greater than at high Q^2, so the interactions of a second muon in the target at low Q^2 may imitate the process being studied. In order to obtain the upper limit of such accidental events we assume the cross section of muon-nucleus interactions at low Q^2 to be $\alpha \cdot \sigma_{in}^{hA}$ where σ_{in}^{hA} is the proton-nucleus inelastic cross section and $\alpha = 1/137$. Then we may expect at $Q^2 \geq 1$ $(\mathrm{GeV/c})^2$ 115, 85 and 55 events and at $Q^2 \geq 2$ $(\mathrm{GeV/c})^2$ 50, 35 and 25 events for C, Ca and Pb respectively, which imitate DIS events. In spite of the multiplicities being two times larger in this-case the resulting background for cumulative particles will be not more than $2 \cdot 10^{-4}$ and may be neglected. We also may neglect the interactions of muons in neighbouring buckets since they will be out of the time-of-flight range (see Fig.1).

Count rates caused by halo muons may be estimated from Fermilab NM beam data.[14] Halo muons beyond a radius of 20 cm from the beam axis are of the order of 10-15% of useful beam and spread over 20 m^2. Each counter covers 0.02 m^2 or 10^{-3} of this area. Therefore the count rate of each counter will be 10^4 per spill and the probability of a signal in a counter, caused by a halo muon from the next bucket, will be 10^{-5}. It is comparable with the number of fast neutrons and hence halo muons should be vetoed.

The other background source for protons is misidentification of pions interacting in the counter. This background depends on the target nucleus and decreases with increasing of atomic weight. Estimates, based on previous plastic scintillator data[21] indicate that for a C target the admixture of misidentified pions to protons up to 120 MeV is less than 1%.

4. CONCLUSION

We have shown that in the Fermilab experiment E665 it is possible to measure the yields of cumulative charged particles from C, Ca and Pb nuclei in deep inelastic scattering processes at Q^2 higher than 1-2 $(\mathrm{GeV/c})^2$. The measurements may be-carryed out by available liquid scintillator counters intended for slow neutron detection.

Estimates of the number of events have been obtained here neglecting effects of nuclear transparency for the knocked-out quark. The presence of these effects may cause the decrease of cumulative particle multiplicities for the heavy nuclei (for Pb nucleus by a factor of $\sim$ 3) in comparison with predicted values. The weak A-dependence $(\sim A^{1/3})$ of cumulative particle yields remaining in this case is connected with the influence of the surface nucleons, which do not take part in the formation of multiquark bags.

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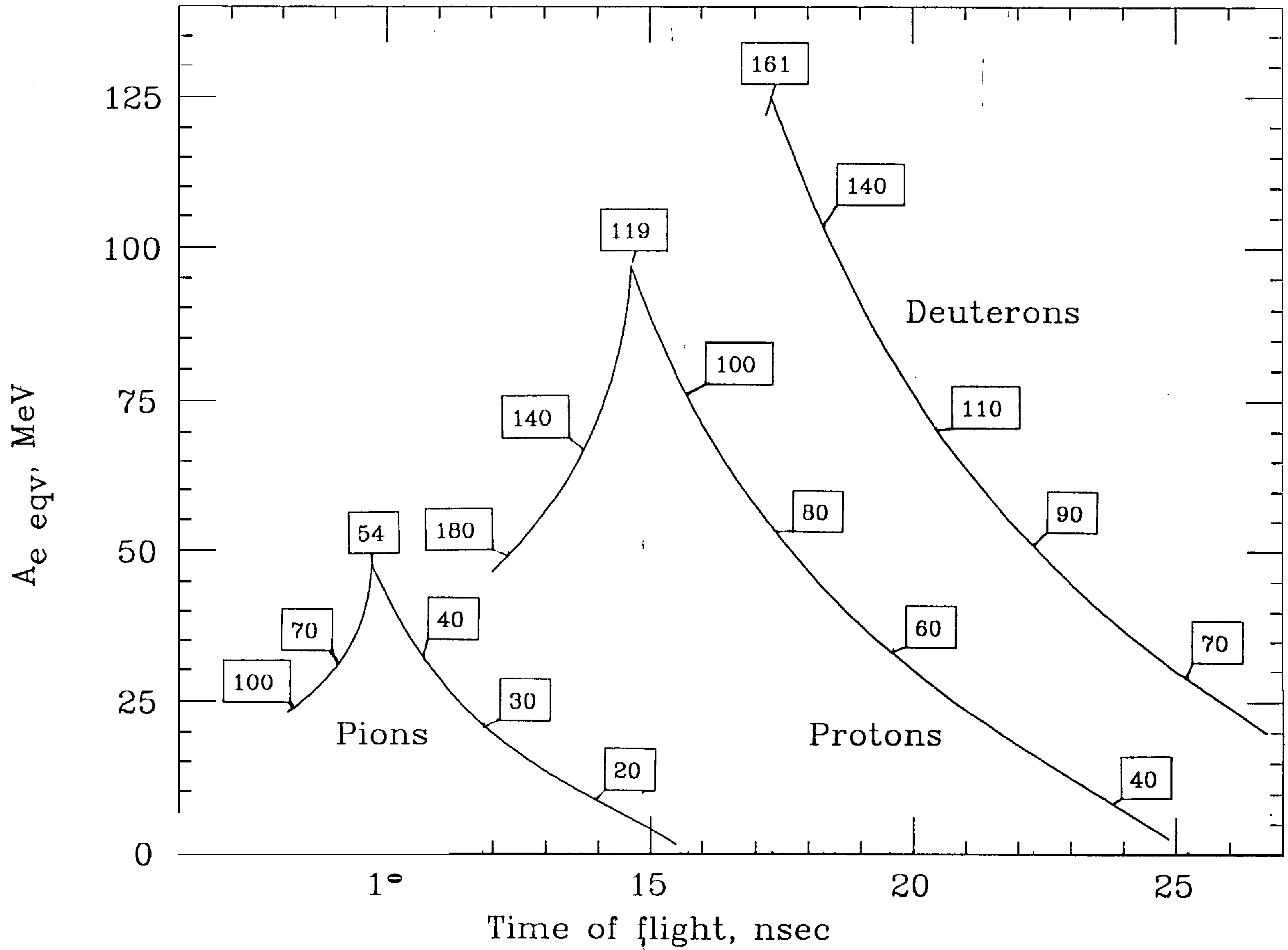
161
140
119
Deuterons
100
110
140
75
90
80
54
180
50
70
60
40
70
100
25
Pions
30
Protons
20
40
125
100
0
A_e eqv, MeV
1°
15
20
25
Time of flight, nsec

Fig.1