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Addendum to the PROPOSAL TO STUDY HEAVY FRAGMENTS EMITTED IN THE INTERACTIONS OF 12 GeV PROTONS WITH COMPLEX NUCLEI

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Aim of the note

The present note is meant to give a more detailed presentation of the physics which is connected with the problem of fragmentation and with the use of the experimental set-up as described in document EmC 65/1.

1. Fragments produced in interactions with heavy nuclei

The usually adopted Serber picture[1] of interactions of high-energy particles with heavy nuclei assumes a two-stage process: an intranuclear cascade, developing in a time comparable with the nuclear time, followed by a much slower evaporation of the excited compound system. This picture seems to fail in the case of energy transfers to the target nucleus of the order of the total nucleus binding energy. As there is no alternative theoretical attempt to describe the effects of these high-energy interactions, the Serber picture is used as a working hypothesis. In this picture it is natural to assume that in a first stage the nucleonic cascade develops according to a sequence of processes involving one or two nucleons and that in a second stage the nucleus which has been left excited, decays and emits nuclear fragments. It is striking to find[2],[3] that the energy spectrum of the ^8Li fragments emitted in high-energy interactions has, with a good approximation, the <u>shape</u> given by the Weisskopf formula[4]:

$$P(E)dE = \frac{E - V}{T^2} \exp\left(- \frac{E - V}{T}\right) dE \qquad (1)$$

This observation and others as well suggest that the statistical model gives a satisfactory description of the fragment emission. On the other hand the fit of the formula (1) to the experimental distributions is obtained for the very high values of the nuclear temperature T = 12 – 13 MeV[(2),(3)]. Moreover, the large number of heavily ionizing particles in the nuclear interactions suggest large energy transfers to the target nucleus comparable with its total binding energy. The theoretical estimates (e.g. given recently by Ericson[(5)]) lead to believe that at so high excitation energies no long-lived compound system exists. The evaporation model is naturally limited to the class of interactions in which the excitation energy of the nucleus, left after the cascade process has taken place, is small in comparison with the total binding energy of the nucleus.

In this case could we use quantitatively the statistical model even after necessary modifications, if no long-lived compound system exists ? Even if the answer is positive for the main part of the energy spectrum of the fragments, it seems that the high-energy tail of the spectrum has anyway a specific situation. Apparently, the fast fragments ($E_{kin} > 10$ MeV per nucleon) do not fit the distribution (1), although the present statistics do not allow a definite conclusion, and the data available are in general only for the ^{8}Li fragments while they are easy to identify in emulsion.

It is clear that larger statistics on well defined samples of fast fragments are needed. In addition, there is some interest to produce highly excited nuclei in order to study their behaviour at large excitation energy. The proposed experiment meets such requirements. The high-energy incident proton will produce a large proportion of very excited nuclei; on the other hand the analysing magnetic field will select a very large number of fragments according to their energy, their angle and their nature. Moreover, it will be possible to study practically any type of target nucleus.

In the past years several processes have been proposed for explaining the mechanism of emission of the energetic fragments, but none of them has found enough well analysed data to test its validity region. The following processes were mentioned:

i) The quasi-elastic scattering of the incident particle and of the secondaries produced in the nucleonic cascade on nucleon clusters existing inside the nucleus(6),(7).

ii) The pick-up reactions produced by both primary and secondary particles.

iii) The breaking by the primary or by the cascade particle of the connections of a sub-structure with the rest of the nucleus, followed by the emission of the structure.

iv) The inelastic interactions with the structures existing inside the nucleus.

(For more details see references (6), (9), (10)).

The intranuclear cascade is of complex character and the detailed calculations of its behaviour in this energy region are not available. For this reason, we will try in a first step to deal with events where its influence is as small as possible. One can hope to reach partly this purpose in studying the fragments either in very light nuclei (lithium, beryllium, boron, carbon) or on the most energetic part of the spectrum of the fragments produced in heavy nuclei.

Each process mentioned above has typical characteristics which can be used for its identification. However, from the data already existing on fragment production, it seems possible that we have to involve simultaneously several processes for the explanation of the fragment production in heavy nuclei.

However, the idea is to study in a first step the behaviour of light nuclei in what concerns fragment emission. In a second step an attempt will be made to understand the fragment data for heavier nuclei in terms of what has been learned on lighter nuclei. Such a procedure has already been used recently on a small scale by Bogatin et al.(10) and has lead to some interesting comparison between carbon and aluminium.

2. Interactions with light nuclei

At the present state of our knowledge of fragment emission it seems that intranuclear reactions leading to a residual nucleus are the most likely way of production of heavy fragments, in interactions with light target nuclei(9),(10). The mechanism for this process may be simply described by considering the collision of the impinging nucleon with a nucleon in the target in the impulse approximation. The rest of the nucleus behaves as a spectator forming a residual nucleus. This can be illustrated in the case of the simple reaction ^{9}Be (p,2p) ^{8}Li studied recently at 660 MeV by Bogatin et al.[8]. Whereas the majority of the ^{8}Li fragments identified in emulsion in this experiment have indeed a small momentum - as expected for the spectator particle - in some small but finite fraction of events the momentum of the ^{8}Li fragments extends up to 1.1 GeV/c. It is not clear if such high momenta are possible in the mentioned picture. From this point of view it is necessary to make a more detailed study of various fragments of light nuclei at higher energies of incoming particles and to produce for each of these fragments cross-sections, energy and angular spectra.

i) In this respect, the reaction of the type (p,2p) (p,pn) with or without pions produced seems to play a significant rôle and to contain interesting information. In these types of reactions, if they take place in suitable nuclei (like, for example, (p,2p) in ^{9}Be), a defined residual nucleus (^{8}Li in the example mentioned) could be ejected. As illustration, such types of consideration have lead Lozhkin and collaborators[9] to assume a substantial asymmetry in the case of ^{12}C since the two mirror nuclei ^{8}Li and ^{8}B are produced with a very different abundance. Many other light nuclei should be tested for this process. One can on this assumption write several possible reactions of fragment production like:

^{7}Li (p,2p) ^{6}He	^{6}Li (p,2p) ^{5}He(inst)	
^{7}Li (p,pn) ^{6}Li	^{6}Li (p,pn) ^{5}Li(inst)	
^{9}Be (p,2p) ^{8}Li	^{10}B (p,2p) ^{9}Be	^{11}B (p,2p) ^{10}Be
^{9}Be (p,pn) ^{8}Be	^{10}B (p,pn) ^{9}B(inst)	^{11}B (p,pn) ^{10}B
^{12}C (p,2p) ^{11}B		
^{12}C (p,pn) ^{11}C		

The fragments expected, when stable enough ($\gtrsim 10^{-8}$ sec.), will be easily identified by the magnetic analysis method proposed in EmC 65/1. The fact that the target nucleus is known helps considerably in this respect. There are other hypotheses or facts which can be investigated in this experiment:

ii) In particular, the presence of quasi-elastic scattering by a bombarding proton on α structures has been shown to take place in a carbon nucleus at comparatively lower energies (a few hundred MeV). In fact, the process of quasi-elastic scattering is able to detect any other existing and well defined structure in any nucleus and its signature is made of a very simple kinematical relation between the energy and the angle of the fragment emitted by elastic collision.

iii) The light nuclei like lithium, beryllium, boron are not found to be present in the originally accelerated cosmic rays radiation, while nuclei like oxygen and nitrogen are much more abundant. If data were available on fragment emission probabilities at accelerator energies as high as possible, they could be fed into the transfer equations[11] for solving questions about the age of cosmic rays and its models of propagation and about the nature of cosmic ray sources.

iv) Finally one must notice that the data collected in the usual way from stars produced inside the nuclear emulsion meet big difficulties or even impossibilities for providing the major part of the essential information mentioned in this discussion. It is for example impossible to check properly typical reactions like (p,2p) or (p,pn) for which the knowledge of the target nucleus and a powerful method of identification are necessary. Even for heavy nuclei, the choice of stars with $N_h \geqslant 8$ to be sure that one deals with a nucleus of silver or bromine is not satisfactory; it introduces a limitation towards the interactions where the nucleus has received a large amount of energy of excitation and neglects those where a primary interesting act has taken place without any further nuclear interactions destroying eventually the initial pattern.

It is clear that such a work on fragment production could be undertaken in using other detectors like solid state detectors, for example. In fact, any other method will probably meet similar difficulties, if not more, and lead to comparable results with a somewhat bigger effort for setting up the detecting device and with more machine time consumption. The apparatus being set up and working properly, one can then imagine a faster production rate of the data. However, the emulsion technique is well adapted for recording and analysing short range particles. Its possibilities in this field have been extensively used and studied in the past, and its use should be recommended as a first step safe and promising enough to provide with a reasonable effort and speed data well analysed and statistically meaningful for a better knowledge of the fragment production.

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