PHENOMENOLOGY OF NUCLEAR INCLUSIVE REACTIONS

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15 AUG 1978

ABSTRACT

The possible role of clustering phenomena in inclusive nuclear reactions is reviewed. Models for cluster emission accompanying fast backward going protons in the reaction $A(p,p')X$ are described. Scaling behaviour of $A(p,d)X$ and $A(p,t)X$ reactions indicating a direct knockout mechanism is discussed.

INTRODUCTION

In this talk I will discuss some of the recent work that has been going on in the study of inclusive nuclear reactions. The particular type of reaction to be dealt with here is that in which the secondary particles (protons, deuterons, tritons) are observed in the backward hemisphere in the laboratory frame. Since this is a kinematic region forbidden for scattering from free stationary nucleons the internal dynamics of the target nucleus must play a crucial role in these reactions. In keeping with the theme of this conference the two main topics to be discussed are (i) the possible role of clustering or correlation effects in the reaction $A(p,p')X$ (ii) the phenomenology of the reactions $A(p,d)X$ and $A(p,t)X$ where one might think that there is direct d or t knockout.

The idea that highly correlated nuclear subsystems play a role in inclusive reactions is actually an old one. About twenty years ago Blokhintsev¹ introduced the notion of nuclear density fluctuations to try to explain the energy spectrum in (p,d) reactions. The idea was revived a couple of years ago by Burro *et al.*² as the basis for a model of inclusive pion production. Fujita³ has used a very similar concept to describe $A(p,p')X$. I will discuss Fujita's model in some detail and describe a variation of it which has recently been worked out.

$$A(p,p')X$$

The basic assumption of the density fluctuation² or correlated cluster³ model is that the inclusive cross section is the incoherent sum of cross sections for the incoming protons to interact with clusters of different nucleon number. Fujita³ gives the inclusive cross section in the form

$$\frac{d\sigma}{d^3q} = \sum_{n=1}^A \frac{G_n}{(3\pi)^2 \text{ nm}} \int \frac{d^3k}{(2\pi)^3 E_p E_c} |M_{p-cc}|^2 W_n(k) \delta(\text{energy}), \quad (1)$$

*Work supported by the National Research Council of Canada.

where G_n is the effective number of correlated clusters in the nucleus, W_n the cluster momentum distribution and M_{p-cc} is the proton-cluster scattering amplitude. This is a single scattering model and using the cluster mass and Fermi motion the incoming proton can be scattered into a kinematic region forbidden for scattering on stationary free nucleons. It is presumed that the cluster is emitted essentially coherently into the forward hemisphere. For $Ta(p,p')X$ at 180° with 600 MeV protons (Fig. 1) Fujita obtained reasonable agreement with the data of Frankel *et al.*⁴

Fig. 1. Comparison of Fujita's model with 180° data of Frankel *et al.*⁴

coil momentum. The scattered projectile also goes off into the forward hemisphere so the final state can be thought of as made up of three bodies rather than two as in Fujita's model. The $A-1-n$ remaining nucleons will be treated as spectators. The inclusive cross section is again an incoherent sum over clusters of different nucleon number and extends from a minimum number determined by energy and momentum conservation up to $A-1$. The inclusive cross section takes the form

$$\frac{d\sigma}{d^3q} \sim \sum_{n=1}^{A-1} \int \frac{d^3p'}{E_q E_p} \frac{d^3k}{E_n} P_{A,n} f(\vec{p}, \vec{q}, \vec{p}', \vec{k}; n) \delta^3(\vec{p} - \vec{q} - \vec{p}' - \vec{k}) \times \delta[E_p + W_A - E_q - E_p' - W_{A-1-n} - E_n(k)], \quad (2)$$

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Fig. 2. (a) Prediction of Fujita's model for $\text{Cu}(p,p')X$ at 740 MeV. (b) Data of Cochran *et al.*⁵

where $(E_p, \vec{p})$, $(E_q, \vec{q})$ and $(E_{p'}, \vec{p}')$ are the four-momenta of the incident, observed and scattered projectile nucleons respectively. k is the momentum of the n -nucleon recoil cluster. It is implicit in this model that the fast falloff of the inclusive cross section is due primarily to the decreasing probability of finding high momentum nucleons in the nucleus. The two models for which results will be shown differ mainly in the assumption about which momentum variable describes this rapidly decreasing probability. One model assumes that the nuclear dynamics is introduced through the dependence of the amplitude on the cluster recoil momentum (k) while the other model assumes it is the observed proton momentum that is important.

Model I:

$$\frac{d\sigma}{d^3q} \sim \frac{1}{E_q |\vec{p}-\vec{q}|} \sum_{n=n_{\min}}^{A-1} P_{A,n} \left\{ F_n[k_{\min}(n)] / \mathcal{E}_n[k_{\min}(n)] \right. \\ \left. - F_n[k_{\max}(n)] / \mathcal{E}_n[k_{\max}(n)] \right\} e^{bTn}, \quad (3)$$

where $t_n = (p-p')^2$ when $k = k_{\min}(n)$.

Model II:

$$\frac{d\sigma}{d^3q} \sim \frac{1}{E_q |\vec{p}-\vec{q}|} \sum_{n=n_{\min}}^{A-1} P_{A,n} F_n(q) \int_{p'_{\min}(n)}^{p'_{\max}(n)} \frac{p' d p' d p'}{E_{p'}} e^{c n t}. \quad (4)$$

F_n is assumed to have an exponential falloff⁷ and to decrease more rapidly as n increases. With some adjustment of parameters the results shown in Fig. 3 are obtained. Also shown are the 800 MeV data of Frankel *et al.*⁸ Note that the calculated curves have a single overall normalization.

My interest in pursuing this calculation is that the recoil cluster model makes a definite assumption about the final state and one can therefore calculate semi-inclusive quantities which characterize the final state in some detail. For example Fig. 4 shows the average recoil multiplicity $\bar{n}$ and average scattered projectile energy $\bar{T}_1$ for 500 MeV $\text{Be}(p,p')X$. The measurement of such quantities would go a long way toward determining the reaction mechanism.

Fig. 3. Comparison of cluster recoil model with data of Frankel *et al.* 8 (a) Model I. (b) Model II.

Fig. 4. Calculated average scattered projectile energy $\bar{T}_L$ and average multiplicity $\bar{n}$ for $\text{Be}(p,p')X$ at 500 MeV. Solid line is for Model I, dashed for Model II.

COMPOSITE PARTICLE PRODUCTION

Fujita has described the 180° production of deuterons as a backward pickup reaction.

$$\left(\frac{d\sigma}{d^3q} \right)_{pA \rightarrow dX} = \int d^3p_1 \frac{[(d\sigma)/(d^3p_1)]_{pA \rightarrow p_1A'}}{\sigma_0} \left(\frac{d\sigma}{d^3q} \right)_{p_1A' \rightarrow dX}, \quad (5)$$

where $[(d\sigma)/(d^3p_1)]_{pA \rightarrow p_1A'}$ denotes the backward proton inclusive reaction cross section and $[(d\sigma)/(d^3q)]_{p_1A' \rightarrow dX}$ is the pick-up cross section. Figure 5 shows Fujita's results compared with the 180° data of Frankel *et al.* 4. Unfortunately angular distribution data are not

Fig. 5. Comparison of Fujita's calculation of $A(p,d)X$ at 180° with data of Ref. 4.

yet available so Fujita's model for (p,d) can not be put to as rigorous a test as was his model for (p,p') .

Frankel has tried a more phenomenological analysis namely the use of quasi-two-body scaling.¹⁰ Simply stated the scaling hypothesis is that the momentum and angle dependence of the inclusive cross section is dominated by a function of a single variable $k_{\min}$ which is the minimum allowed recoil momentum of the unobserved residual nuclear state. Using quasi-two-body scaling the cross section can be written as

$$\frac{d\sigma}{d^3q} = \frac{c(s,t)}{|\vec{p} - \vec{q}|} G(k_{\min}), \quad (6)$$

where $c(s,t)$ is a slowly varying function of the two-body variables s and t . Figure 6 shows the scaling function vs $k_{\min}$ for the data of

Fig. 6. Scaling function vs $k_{\min}$ for $\text{Cu}(p,p')X$ at 740 MeV.

Fig. 2b. In this analysis c in Eq. (6) was taken to be ebt , i.e., proportional to the N-N scattering cross section. Clearly scaling is very well satisfied for the (p,p') reaction. Frankel¹⁰ has compared scaling functions (calculated with c held constant) for proton, deuteron and triton cross sections at fixed angle for different energies. These are shown in Fig. 7-9. Since the scaling functions for p,d and t production are quite similar one is tempted to suggest that d and t

Fig. 7. Comparison of scaling functions for $p + A \rightarrow p, d, t + X$ at 600 MeV.

production proceed via the same kind of direct reaction mechanism as gives rise to scaling in (p,p') . Probably such a suggestion is premature until angular distribution data are available to verify the scaling behaviour of (p,d) and (p,t) cross sections in detail. Such data should be available in the near future from experiments at TRIUMF and LAMPF.

Fig. 8. Comparison of scaling functions for $p + \text{Pt} \rightarrow p, d, t + X$ at 2.9 GeV. Data from Piroue and Smith.¹¹

Fig. 9. Inclusive cross sections and scaling function for $p + C \rightarrow p, d + X$ at 5.7 GeV. Data from Bayukov *et al.*¹¹

SUMMARY

I have tried to address two questions in this talk. First, what role do clustering effects play in reactions in which high energy protons are emitted. The recoil cluster model, in which only a subset of the nucleons in the target nucleus participate in the reaction, provides a good description of the single nucleon inclusive distribution. Clearly the real test of this or any other model will come only when experimental information on the dominant types of final states contributing to the inclusive distribution becomes available. The second question is the extent to which $A(p, d)X$, $A(p, t)X$ etc. can be thought of direct knockout reactions. As a minimum requirement $A(p, d)X$ should then satisfy the same scaling behaviour as $A(p, p')X$. Data to test this should be available soon.

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