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DIFFRACTIVE EXCITATION OF HIGH-MASS NUCLEAR STATES

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ABSTRACT

Diffractional excitation is a very fundamental process, suitable for studying properties of hadronic wave functions at low Q^2 . No experimental information exists on diffractive excitation of nuclei to high masses. Potential experiments at the Super Proton Synchrotron Collider at CERN and the proposed Relativistic Heavy Ion Collider at BNL are outlined.

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1. INTRODUCTION

Elastic diffraction is a well-known wave-mechanical phenomenon. Inelastic diffraction (diffractive excitation, dissociation) of hadrons (nuclei included) can be reduced to elastic diffraction of a special set of components of the hadronic wave function^{1,2}. Thus inelastic diffraction is viewed as a filtering process which puts virtual states or fluctuations of the hadron or nucleus on the mass shell.

Despite the fundamental nature of the process, theoretical approaches to diffractive excitation have shown only partial success and more experimental information is needed, in particular for inelastic high-mass diffraction of hadrons in pp and p $\bar{p}$ interactions at the highest available energies, see recent reviews³⁻⁷.

So little is known about high-mass diffractive excitation of *nuclei* that almost nothing is excluded, not even the speculation that these excitations show nuclei in a state of partial or total deconfinement. (By high mass it is understood that the excitation energy is of the order of 10 times the ground-state mass; the critical energy density needed for the deconfinement phase transition is estimated to be about 10 times the ground-state energy density⁸.)

In the following, firstly, the process under consideration and the present state of knowledge of this process are described. Secondly, basic features of experiments are outlined which would improve our knowledge of high-mass diffractive excitation of nuclei and protons.

2. HIGH-MASS DIFFRACTIVE EXCITATION — PRESENT STATE OF KNOWLEDGE

What do we know about diffractive excitation to high masses of the smallest nuclei, protons? Consider the missing-mass experiment

$$p + p \rightarrow p + X,$$

where one measures the momentum of one of the outgoing protons and determines the mass and momentum of the system X. Figure 1^{6,9} shows the differential, inclusive, invariant cross-section as a function of the fractional longitudinal momentum loss, i.e. of

$$1 - x_F = (M_X^2 - m^2)/s,$$

where $x_F = 2p_L/\sqrt{s}$; p_L is the outgoing longitudinal momentum; s is the c.m. energy squared and $\sqrt{s}/2$ the incoming momentum (rest masses are assumed to be small compared to the incoming

FIGURE 1

Compilation of invariant cross-sections for inclusive p excitation at $549 < s < 1464 \text{ GeV}^2$ as a function of $1 - x_F = (M_X^2 - m^2)/s$ at $t = 0.25 \text{ GeV}^2$ (taken from Ref. 9). The shaded area indicates the estimated non-diffractive cross-section (proportional to $1 - x_F$ and equal to the diffractive cross-section at $x_F = 0.1$).

FIGURE 2

Topology of single diffractive excitation $pA \rightarrow pX$. Distribution of tracks (vertical lines) in rapidity and dn/dy (schematic).

energy); M_X is the missing mass and m is the proton rest mass. One recognizes a sharply falling distribution starting high at $1 - x_F = 0$ and flattening out at $1 - x_F \approx 0.1$. The strong rise towards $1 - x_F = 0$ is attributed to diffractive excitation of the other proton.

The measured properties of high-mass diffractive excitation of protons in pp interactions are reviewed in Refs. 6 and 7. Here, we want to draw attention to the following particular properties:

- i) The inclusive cross-section $E(d^3\sigma/dp^3)$ for $pp \rightarrow pX$ decreases as $s/(M_X^2 - m^2)$; this implies that it scales approximately as a function of $x_F = 1 - (M_X^2 - m^2)/s$.
- ii) The total inelastic diffractive cross-section (integrated over all masses and summed over target and projectile excitation), σ_D , saturates approximately the Pomplin bound¹⁰ $\sigma_D + \sigma_{el} < 0.5\sigma_{tot}$.
- iii) The event topology looks rather special. The sketch shown in Fig. 2 illustrates the distribution of final-state particles as a function of the rapidity y . The unfragmented proton has a rapidity very close to the incoming rapidity y_{in} ; the decay products of X are separated by a large rapidity gap from the unfragmented proton.
- iv) The multiplicity of secondaries emitted from X depends on M_X similarly to the way in which multiplicity in normal non-diffractive interactions depends on $\sqrt{s}$, i.e.

$$\langle N \rangle_{\text{charged}} \approx 2 M_X^{1/2} \quad (M_X \text{ in GeV}).$$

- v) A detailed discussion of the data on rapidity distributions can be found in Ref. 7. The available data are *not inconsistent* with a distribution as one expects from isotropic fireball decay.
- vi) Nothing at all is known on high-mass diffractive excitation of nuclei, $pA \rightarrow pX$ (only the coherent diffractive excitation of hadrons on nuclei, $hA \rightarrow XA$, has been studied in various experiments).

Next, a few remarks on the theoretical understanding of diffractive excitation. There are basically two classes of theoretical approaches which should be complementary (dual) but are not

FIGURE 3

a) The t-channel representation of single diffractive dissociation $pA \rightarrow pX$: exchange of a Pomeron P. b) The s-channel representation of diffractive excitation: the incoming wave fluctuates into virtual states with mass M_X for a number of periods. The specific state of the incoming wave at the time of interaction is selected by measuring the recoil momentum vector of the unfragmented target proton.

obviously so, at present: the t-channel and the s-channel view. The former sees inelastic diffraction as a Pomeron exchange (see Fig. 3a) and relates high-mass diffraction to a triple Pomeron coupling. The system X, in this view, is the result of the interaction of a high-energy Pomeron with a proton. If one identifies the members of this hypothetical trajectory with colourless combinations of exchanged gluons¹¹ then X should look similar to the final state after any other hadron-proton interaction. An experiment has been approved for the SPS Collider (UA8) which follows this idea and proposes to measure jet production in high-mass diffractive $p\bar{p}$ interactions in order to investigate hard gluon-proton interactions¹².

The s-channel view is more difficult to display despite the fact that the name diffraction dissociation is derived from this view. Elastic diffraction or shadow scattering is a very typical and fundamental wave-mechanical phenomenon. The pattern of elastic diffraction is due to the absorption of parts of the incoming wave, i.e. due to the non-diffractive channels. Inelastic diffraction can be reduced to elastic diffraction of basic states into which the initial state of a complex object such as a hadron can be decomposed. A related well-known phenomenon is K⁰ regeneration. There is no need for any exchanged object in the diffractive channel. Thus in the s-channel view, inelastic diffraction reveals virtual states or fluctuations of the incoming hadron (or nucleus). The graph of Fig. 3b is meant to illustrate how the incoming wave can fluctuate for a certain number of periods into a high-mass state. It is essential to realize that this is a coherent process. The coherence length for a fluctuation of mass M_X is

$$L = 1/\Delta p_L = 2p_{in}/(M_X^2 - m^2) = s/m_p(M_X^2 - m^2)$$

and the coherence condition is that $L \gg r_p$, the dimension of the unfragmented proton. In other words, even if M_X is high enough to allow a phase transition from hadron to quark matter, this wave component does not get out of phase, if s is large enough.

On the basis of the s-channel description as explained by Good and Walker² we make the following simple ansatz for the differential cross-section

$$d^2\sigma/(dM_X^2 dt) = f(t)g(M_X^2)L,$$

where ϱ is the invariant density of states per constant interval in M_X^2 . Since the inclusive pp data show that $d\sigma/dM_X^2$ is proportional to $L = s/m_p(M_X^2 - m^2)$ it follows that $\varrho(M_X^2)$ is constant.

From this we can draw two conclusions. Firstly, if a change of density of states occurs at a given mass M_X , as expected for a phase transition, one should observe it as a step in the inclusive differential cross-section $d\sigma/dM_X^2$. Secondly, it is apparent that diffractive excitation selects very special states.

It may be that the high-mass states are mainly Regge recurrences of the incoming hadron. But this is only a speculation as it is a speculation that these fluctuations of the incoming hadron or nucleus are fireball-like excitations which, for masses around 10 times the ground state mass, may show the nucleus in a deconfined state.

Other speculations may be possible, but we shall neither discuss these nor enumerate the interesting experimental data on diffractive heavy-flavour production¹³ or on two-particle correlations in low-multiplicity events¹⁴. The point to which I want to draw attention is the following: diffractive excitation is a simple and very fundamental process, and little is known experimentally about the high-mass systems X excited in pp (or $p\bar{p}$) interactions; nothing is known about high-mass diffractive excitation of nuclei. So one ought to measure it!

3. COLLIDER EXPERIMENTS FOR HIGH-MASS DIFFRACTION OF NUCLEI

The first question is where one can study pp and pA collisions at an energy high enough to diffractively produce high masses. The required energy is indeed very large and can be estimated in the following way. The condition for diffraction is either read from the data (see Fig. 1) or derived from the mentioned coherence condition $L \gg r_p$,

$$0.1 > (M_X^2 - m^2)/s = 1 - x_F.$$

Since we are interested in masses 10 times the ground-state mass $m_p A$ of a nucleus A we need

$$0.1s > (10m_p A)^2 \quad \text{or} \quad \sqrt{s_{NN}} > 30 \sqrt{A} \text{ GeV}.$$

The following list shows the maximum c.m. energies at the highest energy hadron colliders, and the largest nuclei $A_{\max}$ which can be excited to the interesting mass range, according to the previous estimate:

CERN ISR (Intersecting Storage Rings)	: $\sqrt{s_{NN}} = 44$	GeV	$\rightarrow A_{\max} = 2$
BNL RHIC (Relativistic Heavy Ion Collider)	: $\sqrt{s_{NN}} = 200$ (300)	GeV	$\rightarrow A_{\max} = 44$ (100)
CERN SPS (Super Proton Synchrotron)	: $\sqrt{s_{NN}} = 450$	GeV	$\rightarrow A_{\max} = 225$

The CERN ISR do not exist any longer, and the BNL RHIC does not exist yet and will presumably not be built in the near future. However, from 1986 on, ^{16}O will be accelerated in the CERN SPS and experts believe that the SPS could operate as an $\bar{p}$ ^{16}O collider¹⁵. This mode of operating the SPS requires some interesting RF gymnastics; for instance, one realizes that the velocities of $\bar{p}$ and nuclei, if they have the same momentum per charge, differ by $1.5 \times 10^{-5} c$. Thus during one revolution of the $\bar{p}$ the ^{16}O lags 10 cm behind and the crossing point would quickly wander around the machine. In order to keep the bunch-crossing fixed in space, the $\bar{p}$ has to have a momentum about 1 % higher than the nominal momentum, so its orbit is longer by 10 cm¹⁵.

Next, the principal features of an experimental set-up to investigate diffractive excitation of nuclei at a collider like the RHIC or the SPS are outlined. Let us recall the expected event topology (see Fig. 2). There is i) an unfragmented p or $\bar{p}$ with a momentum up to 10% smaller than the beam, ii) a large rapidity gap, and iii) the decay products of the system X . At RHIC or SPS Collider energies the incoming rapidity in the c.m. system, y_{in} , is around 6. The average rapidity of the system X is shifted by an M_X -dependent amount. For masses 10 times the ground state mass the shift is $\ln(10) = 2.3$.

A dedicated experiment would have three tasks: i) to detect the unfragmented p ($\bar{p}$) and measure its momentum, ii) to cover the expected rapidity gap in order to veto events where there are particles in this gap, and iii) to measure properties of the system X in detail, such as rapidity distributions, p_T distributions, flavour composition, E_T , signatures for the quark-gluon plasma, and so on. The expected multiplicity of tracks is only moderate compared to what one extrapolates for central nucleus-nucleus collisions at comparable energy. None of the listed experimental tasks are trivial, but they do not seem impossible.

i) In order to detect p 's or $\bar{p}$'s with small momentum loss, say from a few per cent up to 10%, and with as small a p_T as possible (the p_T should be $< r_p/A^{1/3}$ so that the whole nucleus is diffractively excited as opposed to single nucleons) one has to get very close to the beam. Moreover, since p_T and angles are to be close to zero, a dispersive beam element is needed in order to bend them away from the beam; then the question is at which point they have separated well enough from the machine acceptance in position-slope space to allow detecting them, with counters brought close to the beam by Roman pots or with counters within the beam tube (see Fig. 4). For the RHIC this problem was studied¹⁶ and it seemed resolvable with a small modification

FIGURE 4

Typical Roman pot arrangement at a collider (from the underground experiment UA4 at the CERN SPS Collider).

of the standard lattice around the intersect (see Fig. 5). Based on crude estimates it was concluded that protons in the range $-\Delta p/p$ from 4% to 10% can be detected. At the SPS Collider the problem will be harder because the energy is even higher, the lattice is already given, and the trick to compensate for the higher $\bar{p}$ velocity works against detecting $\bar{p}$'s with slightly decreased momentum.

ii) The second task implies a detector which has good efficiency for charged tracks, for gammas from π^0 decay and for neutrons, over a range in rapidity from about -1 to roughly $y_{in} + \ln(0.1)$ [since the trigger p ($\bar{p}$) has $p_L > 0.9p_{in}$, the maximum energy a particle accompanying the trigger particle can have is $0.1p_{in}$]. Some kind of calorimeter surrounding the beam tube can do the job. Fine graininess or good energy resolution are not required, just efficiency.

iii) For the detector which is able to measure the decay particles from system X , a solution was found during a recent workshop at BNL, which would cover most of the fragmentation region of the

FIGURE 5

Modified crossing region in the narrow angle hall of the proposed RHIC at BNL. Trajectories of asymmetric beams (p and p') and of a recoil p with a momentum of 90% of the beam momentum. BC1 and BC2 are standard beam-crossing dipole magnets.

FIGURE 6

The L4 (Long Island, large, low-field, long) magnet for experiments in the nuclear fragmentation region at the proposed RHIC¹⁷. It is proposed to make the magnet 10 m long, to have an aperture 1 by 1 m², and to operate at a field less than 2 T. The figure also shows trajectories, through the magnet, of positive, neutral, and negative particles with $p_T = 0$ and various high p_L .

nucleus, i.e. a rapidity range $2 < y < 5.0$ and the full azimuth: the solution there (see Fig. 6) was a long dipole suitably equipped with time-projection and drift chambers, calorimeters, and Cherenkov counters at an approximate cost of 5 M\$¹⁷. Since many physics questions can be answered without full solid angle coverage much less expensive solutions could be envisaged.

4. SUMMARY

Despite the fundamental nature of diffractive excitation, theory does not provide much more than a basic understanding of the inclusive momentum distribution of the unfragmented hadron; it fails to make specific predictions for the properties of the hadron excited to high mass and leaves ample room for speculations. Much has to be learned from future experiments investigating high-mass single diffractive excitation in $p\bar{p}$ interactions.

The energy available at the CERN SPS Collider and the proposed BNL RHIC opens up the completely unexplored field of high-mass excitation of nuclei. The deconfinement phase transition, predicted for an energy density around 10 times the ground state mass density, may already show up in the inclusive differential cross-section of the unfragmented $p(\bar{p})$. Measurements of the produced secondaries will provide unique information on the properties of highly excited states of nuclear matter.

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