PARTICLE DIFFRACTION AT HIGH ENERGIES

Vladimir A.Petrov

Institute for High Energy Physics,
142284, Protvino, Russia

Diffraction of light was described by Italian physicist Grimaldi in his book published in 1665. One of the first (and wrong) explanations was given by Newton, who also contributed a lot into the experimental discovery and the study of new diffractive phenomena. Newton's explanation of light diffraction was based on a corpuscular theory of light. However, in the beginning of the XIX century the famous "Poisson's puzzle" (the prediction of a light spot in the center of the geometric shadow, a consequence of the Fresnel's wave theory of light) and its experimental confirmation affirmed wave nature of light for hundred years, until Einstein and Stark disovered that light demonstrated particle properties as well.

From the observation of the diffractive pattern one can judge about the size and the shape of the scatterer. At present this field is a highly developed branch of applied optics, with innumerous uses and applications in technology.

Since a fundamental guess made in 1923 by Louis de Broglie on wave properties of matter, confirmed experimentally by Stern in Germany and by Davisson and Germer in the USA, this peculiar quantum behaviour has found a lot of applications. The main lesson was that undulatory or corpuscular properties are inherent to all natural phenomena, though one or another aspect may dominate dependent on conditions.

High energy physics is usually synonymous to "particle physics". New phenomena in this field are related either to the discovery of new particles or to some typical particle — like effects as, say, Bjorken scaling in deeply inelastic scattering, or high $p_\perp$ jets, or else. In space-time language these regimes mean the probe of small distances.

However there is a field in high energy physics which even at very high energies is not related to short distances but rather to large (at nuclear scales) distances. Such are phenomena like small angle hadron scattering (elastic or inclusive). It is well known feature of these processes that the angular probability distribution of the scattered particle shows a typical diffractive pattern with a maximum at zero angle followed by the dip and, in some cases, second maximum.[1] Here we deal with wave properties of hadrons.

---

[1] Interesting discussion of "high energy diffraction" is contained in Ref.[1].

From such a distribution one can conclude about the size of the scatterer, or, more properly, the "interaction region".

An interesting feature of these "size measurements" is that the size appears to be energy dependent. This would correspond to dependence of the visible size of a lit object on the frequency (or the wavelength) of falling light.

Modern theory limits this energy dependence of the transverse (w.r.t. the incident beam (s)) size by a "maximal radius", $R_0 \approx (1/m_\pi)\log E$, where m_π is the pion mass ($1/m_\pi$ is the famous Yukawa radius), and E is the center-of-mass energy. Logarithmic dependence of the strong interaction transverse range was derived by W. Heisenberg in the framework of some model of high-energy collisions as early as in 1952. Later M. Froissart obtained the same limit on more general grounds in 1961, and, finally, A. Martin gave in 1966 a rigorous proof based on the first principles of quantum field theory. Lower bounds on the strong interaction radius were given by A. Logunov and Nguen Van Hieu [2].

Experiments confirm the energy dependence of the transverse interaction range which weakly grows with energy (but is far below the Heisenberg-Froissart-Martin radius R_0).

Whereas one can extract the transverse interaction radius from the differential cross section, what can one say about the longitudinal size of the interaction region or the interaction time?

Theoretically, the problem was addressed in an early paper by Wigner in the framework of non-relativistic quantum mechanics [3]. One can also mention papers [4]. In these papers the longitudinal range was related to some derivatives of the phase of the scattering amplitude. Unfortunately this procedure needed the knowledge of the off-mass-shell amplitude.

A different approach was used in Ref. [5], where the effective longitudinal size was estimated to grow with energy as fast as E/m^2. This is very interesting because at energies of the future Large Hadron Collider the longitudinal interaction range can achieve atomic scales.

Unfortunately at present no way to extract this size from the measured characteristics is known. Some hopes refer to nuclear targets where more than one nucleons could be involved into interaction with a "long"projectile.

If one imagines that the size and the shape of the interaction region are extracted from a complete enough set of experimental data, then the problem is to understand the information obtained on the basis of present theoretical frameworks. Let us consider a high energy collision in the laboratory frame when one hadron (nucleon, or nucleus in practice) is at rest ("observer") while another one flies on. Energy dependence then may be mainly related to the projectile, which seems to be longer in the longitudinal direction and larger in the transverse ones.

Is not it in an apparent contradiction with the special relativity which predicts that the longitudinal size should decrease with the growing velocity while the transverse ones remain intact? In fact there is no contradiction. The matter is that a particle is a quantum object which is hardly a rigid sphere as one could imagine in a classical manner. This is a quantum system which fluctuates into various virtual states which have their own lifetimes and sizes. The latters are by no means Lorentz invariant. Moreover, the maximal radius, R_0, refers, in the transverse plane, to distances between the points taken at different times, and this is not the same as the "instantaneous size" of special relativity.

Quantum fluctiations have specific features which should be related to modern views of microstructure of particles. For strongly interacting particles this is quantum chromodynamics, or shortly, QCD.

QCD gave many insights into understanding of phenomena, related to short distances ("hard processes").

Unfortunately, QCD is still not very effective when applied to large distance ("soft" or diffractive) processes. In the framework of Regge approach these are some attempts to obtain the leading Regge trajectory perturbatively. In spite of some progress serious problems remain to be resolved. One of these problems is that the method of quantum perturbations, which works nicely at short distances, fails at large distances. This is related to the confinement problem, i.e. absence of quarks and gluons in asymptotic states detected by the measuring apparatus.

It may well happen that "particle" approach, where quarks and gluons take part in the process of scattering as constituents of colliding hadrons, is not relevant to diffractive phenomena, which are more adequate to wave aspects. In this case it could be more appropriate to study some (gluon) field configurations which are beyond reach of usual perturbative treatment. That is why projects like TOTEM at LHC should be considered not just as an inevitable price for a precise measurement of luminosity but rather as a unique source of information about sizes and shape of the hadron interaction region. Explanation and description of these is a formidable task for QCD.

As a conclusion I should like to stress again that the experimental study of diffractive hadron scattering is important and interesting because:

1. Energy-dependent shape of the interaction region is interesting both from general quantum and relativistic points of view;

2. The interpretation of data can promote the new development of QCD at large space-time scales. This is definitely related to the long-standing confinement problem, which, as we see, is important not only at low energies.

References

[1] A.P. Samokhin. In Proc. XVIII Workshop on High Energy Physics and Field Theory (Protvino, June 26-30, 1995). Ed. V.A.Petrov et al. Protvino 1996.
[2] A.A. Logunov and Nguen Van Hieu. Teor.Mat.Fiz., v.1 (1969) 375.
[3] E. Wigner. Phys.Rev., v.98 (1955) 98.
[4] M. Froissart, M. Goldberger and K. Watson. Phys.Rev., v.131 (1963) 2820.
[5] V.N. Gribov, B.L. Ioffe and I.Ya. Pomeranchuk. Sov.Journ.Nucl.Phys., v.2 (1967) 768.