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Particle Dynamics Using Direct Application of Newton's Law

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Abstract:

Accepting and exploiting the response of charged particles to electromagnetic forces is the basis of particle optics and accelerator concept. The goal is to find the time-dependent position and velocity of atoms, given stated electric and magnetic fields. Measures calculated from position and velocity, such as total energy, kinetic energy, and momentum, are also of interest. In this chapter, the response of particles to general forces will be reviewed. These are précised in laws of motion. The Newtonian laws, preserved in the first sections, relate at low particle energy. This chapter reviews particle mechanism. And then condenses the possessions of electrons and ions. Newtonian mechanism also designates ions in medium energy accelerators used for nuclear physics. The Newtonian equations are regularly simpler to solve than relativistic formulations. Occasionally it is possible to define transverse motions of relativistic elements using Newtonian equations with a relativistically modified mass. In the subsequent part, some of the principles of special relativity are derivative from two basic postulates, leading to a number of useful formulas abridged later.

Keywords — **Particle Dynamics, Newton's law, Relativity, Lorentz contraction, transverse motion.**

INTRODUCTION

2.1 CHARGED PARTICLE PROPERTIES:

In the concept of charged particle acceleration and transport, it is appropriate to treat particles as dimensionless points with no internal structure. Only the impact of the electromagnetic force, one of the four fundamental forces of nature, wants to be considered. Quantum theory is preventable except to define the emission of radiation at high energy. This rag will deal only with ions and electrons. They are modest, stable particles. Their response to the fields applied in accelerators is described entirely by two measures: mass and charge. However, it is conceivable to apply much of the material presented to other particles. For instance, the motion of macroparticles with an electrostatic charge can be treated by the approaches developed in Chapters 6-9. Applications comprise the suspension of small objects in wavering electric quadrupole fields and the acceleration and supervision of inertial fusion targets. At the other risky are unstable basic particles created by the interaction of high-energy ions or electrons with targets. Beamlines, acceleration gaps, and lenses are comparable to those used for stable particles with adjustments for dissimilar mass. The limited lifetime might influence hardware design by setting up a maximum length for a beamline or quarantine time in a storage ring.

An electron is a fundamental particle with relatively low mass and negative charge. An ion is an assemblage of protons, neutrons, and electrons. It is an atom with one or more electrons detached. Atoms of the isotopes of hydrogen have only one electron. Consequently, the associated ions (the proton, deuteron, and triton) have no electrons. These ions are simple nucleii containing of a proton with 0, 1, or 2 neutrons. Usually, the symbol Z signifies the atomic number of an ion or the number of electrons in the neutral atom. The symbol Z* is regularly used to represent the number of electrons detached from an atom to form an ion. Values of Z* greater than 30 might happen when heavy ions traverse exceptionally hot material. If Z* = Z, the atom is fully stripped. The atomic mass number A is the number of nucleons (protons or neutrons) in the nucleus. The mass of the atom is concentrated in the nucleus and is given nearly as Amp, where mp is the proton mass.

2.2 NEWTON'S LAWS OF MOTION

The charge of a particle decides the strength of its collaboration with the electromagnetic force.

2.2.1 Newtonian Dynamics

Newtonian dynamics is a mathematical model whose tenacity is to predict the motions of the numerous objects that we encounter in the world around us. The overall principles of this model were first enunciated by Sir Isaac Newton in a work entitled *Philosophiae Naturalis Principia Mathematica* (Mathematical Principles of Natural Philosophy). This effort, which was first published in 1687, is nowadays more frequently denoted to as the *Principa*.1 Up until the beginning of the 20th century; Newton's theory of motion was thought to establish a *complete* description of all categories of motion happening in the Universe.

We now know that this is not the case. The modern view is that Newton's theory is only an *approximation* which is valid under definite conditions. The theory breaks down when the velocities of the objects under investigation method the speed of light in vacuum, and must be altered in agreement with Einstein's *special theory of relativity*. The theory also fails in regions of space which are adequately arched that the suggestions of Euclidean geometry do not hold to a good estimate, and need to be amplified by Einstein's *general theory of relativity*. Lastly, the theory breaks down on atomic and subatomic length-scales, and must be exchanged by *quantum mechanics*. In this book, we shall abandonment relativistic and quantum effects all together. It trails that we must limit our investigations to the motions of *large* (compared to an atom) *slow* (compared to the speed of light) objects moving in *Euclidean* space. Providentially, virtually all of the motions which we generally observe in the world around us fall into this group. Newton very purposely modelled his method in the Principia on that taken in *Euclid's Elements*. Certainly, Newton's theory of motion has much in common with a conventional *axiomatic system* such as Euclidean geometry. Like all such systems, Newtonian dynamics starts from a set of terms that are undecided within the system. In this case, the essential terms are *mass*, *position*, *time*, and *force*. It is taken for allowed that we recognize what these terms mean, and, additionally, that they resemble to *measurable* quantities which can be recognized to, or related with, objects in the world around us. In precise, it is presumed that the ideas of position in space, distance in space, and position as a function of time in space, are properly designated by the Euclidean vector algebra and vector calculus discoursed in Appendix A. The next constituent of an axiomatic system is a set of *axioms*. These are a set of unverified propositions, connecting the indeterminate terms, from which all other propositions in the system can be derivative via logic and mathematical analysis. In the current case, the axioms are called *Newton's laws of motion*, and can only be vindicated via experimental observation. Note, parenthetically, that Newton's laws, in their primeval form, are only related to *point objects*. Though, these laws can be applied to prolonged objects by considering them as groups of point objects. One alteration amongst an axiomatic system and a physical theory is that, in the latter case, even if a given estimate has been shown to follow unavoidably from the axioms of the theory, it is still inescapable upon us to test the guess against experimental observations. Lack of agreement may designate damaged experimental data, defective application of the theory (for example, in the case of Newtonian dynamics, there may be forces at work which we have not recognized), or, as a last resort, incorrectness of the theory. Luckily, Newtonian dynamics has been found to give estimates which are in excellent agreement with experimental remarks in all circumstances in which it is anticipated to be valid. In the subsequent, it is expected that we know how to set up a rigid Cartesian frame of reference or Cartesian co-ordinates, and how to measure the locations of point objects as functions of time within that frame.

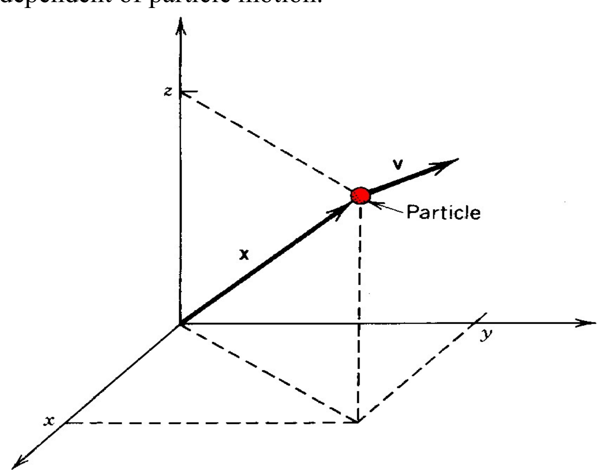
2.2.2 Newton's Laws of Motion:

Newton's laws of motion, in the reasonably obscure language of the Principia, take the following form:

1. Everybody continues in its state of rest, or uniform motion in a straight-line, unless compelled to change that state by forces captivated upon it.
2. The change of motion (*i.e.*, momentum) of an object is proportional to the force captivated upon it, and is made in the direction of the straight-line in which the force is fascinated.
3. To every action there is always opposed an equal reaction; or, the mutual actions of two bodies upon each other are always equal and directed to contrary parts.

Let us now examine how these laws can be applied to dynamical systems.

In Newtonian mechanics, mass is constant, independent of particle motion.



Position and velocity vectors of a particle in Cartesian coordinates

The Newtonian mass (or *rest mass*) is signified by a subscript: me for electrons, mp for protons, and mo for a common particle. A particle's performance is designated entirely by its position in three-dimensional space and its velocity as a function of time. Three quantities are required to identify position; the position **x** is a vector. In the Cartesian coordinates above fig, **x** can be written

$$\boldsymbol{x} = (x, y, z).$$

The particle velocity is

$$\boldsymbol{v} = (vx, vy, vz) = (dx/dt, dy/dt, dz/dt) = d\boldsymbol{x}/dt,$$

Newton's first law statuses that a moving particle trails a straight-line path unless proceeded upon by a force. The propensity to resist changes in straight-line motion is named the momentum, **p**. Momentum is the product of a particle's mass and velocity,

$$\boldsymbol{p} = mo\boldsymbol{v} = (px, py, pz)$$

Newton's second law describes force F through the equation

$$d\boldsymbol{p}/dt = \boldsymbol{F}.$$

In Cartesian coordinates, above equation can be written

$$dpx/dt = Fx,\ dpy/dt = Fy,\ dpz/dt = Fz.$$

Motions in the three directions are decoupled in the above equation. With indicated force constituents, velocity components in the x, y, and z directions are resolute by distinct equations. It is significant to note that this decoupling happens only when the equations of motion are written in terms of Cartesian coordinates. The importance of straight-line motion is deceptive in Newton's first law, and the laws of motion have the humblest form in coordinate systems based on straight lines. Caution need to be exercised using coordinate systems based on curved lines. The analog of last equation for cylindrical coordinates (r, 0, z) will be derived in subsequent conversation. In curvilinear coordinates, momentum mechanisms might vary even with no force constituents along the coordinate axes.

2.3 GALILEAN TRANSFORMATIONS

In describing physical procedures, it is regularly useful to change the viewpoint to a frame of reference that moves with esteem to an original frame. Two common frames of reference in accelerator theory are the stationary frame and the rest frame. The stationary frame is recognized with the laboratory or accelerating structure. An observer in the rest frame moves at the average velocity of the beam particles; henceforth, the beam seems to be at rest. A coordinate transformation translates quantities measured in one frame to those that would be measured in another moving with velocity u. The transformation of the possessions of a particle can be written figuratively as

$$(x, v, m, p, T)\ \_\ (x', v', m', p', T')$$

where informed quantities are those measured in the moving frame. The operation that transforms quantities be contingent on **u**. If the alteration is from the stationary to the rest frame, **u** is the particle velocity **v**. The transformations of Newtonian mechanics (Galilean transformations) are effortlessly understood by inspection. Cartesian coordinate systems are well-defined so that the z axes are collinear with u and the coordinates are aligned at t = 0. This is steady with the usual convention of taking the average beam velocity along the z axis. The position of a particle transforms as

$$x' = x,\ y' = y,\ z' = z - ut.$$

Newtonian mechanics adopts innately that measurements of particle mass and time intervals in frames with constant relative motion are equal: m' = m and dt' = dt. This is not true in a relativistic description. Above equation joint with the assumption of invariant time intervals suggest that $dx' = dx$ and $dx'/dt' = dx/dt$. The velocity transformations are

$$v'x = vx,\ v'y = vy,\ v'z = vx, - u.$$

Since m' = m, momenta obey alike equations. The last expression displays that velocities are additive. The axial velocity in a third frame moving at velocity w with respect to the x' frame is connected to the original quantity by vz" = vz - u - w.

Above equation can be used to regulate the transformation for kinetic energy

$$T' = T + \tfrac{1}{2}mo(-2uvz + u^{\wedge}2)$$

2.4 POSTULATES OF RELATIVITY:

The principles of special relativity continue from two postulates:

1. The laws of mechanics and electromagnetism are alike in all inertial frames of orientation.
2. Measurements of the velocity of light give the same value in all inertial frames. Only the theory of special relativity wants to be used for the material of this book. Common relativity incorporates the gravitational force, which is insignificant in accelerator applications. The first postulate is forthright; it states that spectators in any *inertial frame* would derive the same laws of physics. An inertial frame is one that moves with continual velocity. A corollary is that it is difficult to determine an

absolute velocity. Relative velocities can be restrained, but there is no desired frame of reference. The second postulate trails from the first. If the velocity of light were referenced to a universal stationary frame, tests could be planned to measure absolute velocity. Additionally, since photons are the entities that carry the electromagnetic force, the laws of electromagnetism would be contingent on the absolute velocity of the frame in which they were derivative. This means that the practices of the Maxwell equations and the results of electrodynamics experiments would vary in frames in relative motion. Relativistic mechanics, through postulate 2, leaves Maxwell's equations invariant under a coordinate transformation.

Note that invariance does not mean that measurements of electric and magnetic fields will be the same in all frames. Moderately, such measurements will always lead to the same prevailing equations.

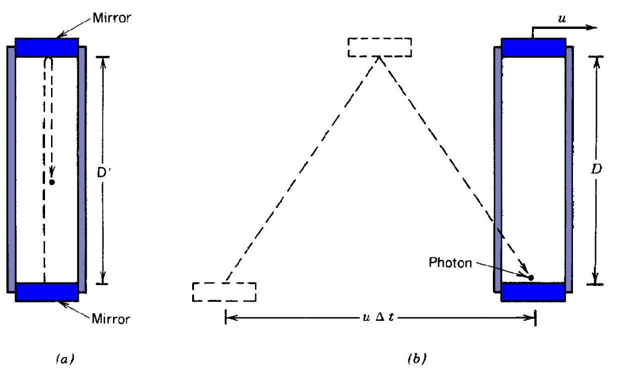


Fig 2.3 Effect of time dilation on the observed rates of a photon clock. (a) Clock rest frame. (b) Stationary frame.

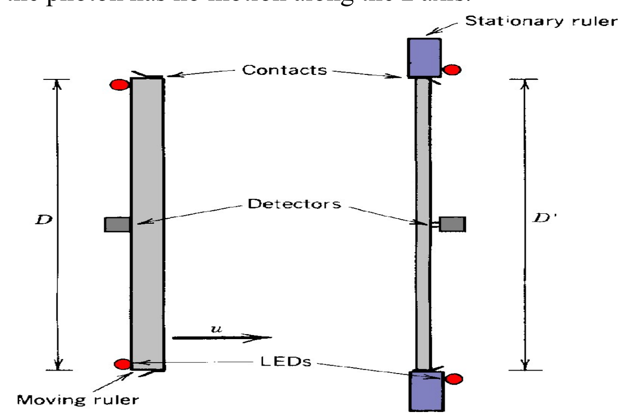
The validity of the relativistic postulates is determined by their covenant with experimental measurements. A major inference is that no object can be persuaded to gain a restrained velocity faster than that of light,

$$c = 2.998\times10^{8}\ m/s.$$

This result is confirmed by observations in electron accelerators. After electrons gain a kinetic energy beyond a few million electron volts, following acceleration causes no rise in electron velocity, even into the multi-GeV range. The constant velocity of relativistic particles is significant in synchronous accelerators, where an accelerating electromagnetic wave must be harmonized to the motion of the particle.

2.5 TIME DILATION

In Newtonian mechanics, spectators in relative motion measure the same time interval for an incident (such as the decay of an uneven particle or the period of an atomic oscillation). This is not steady with the relativistic postulates. The dissimilarity of observed time intervals (depending on the relative velocity) is called time dilation. The tenure *dilation* indicates extending or spreading out. The relationship among time intervals can be established by the clock shown in Figure 2.3, where double transits (back and forth) of a photon amongst mirrors with known spacing are dignified. This test could really be accomplished using a photon pulse in a mode-locked laser. In the rest frame (denoted by primed quantities), mirrors are detached by a distance D', and the photon has no motion along the z axis.



Experiment to demonstrate invariance of transverse lengths between frames in relative motion

In order to associate time intervals, the relationship amongst mirror spacing in the stationary and rest frames (D and D') need to be known. A test to establish that these are equal is demonstrated in Figure 2.4. Two scales have matching length when at rest. Electrical contacts at the ends allow associations of length when the scales have relative motion. Observers are positioned at the centres of the scales. Since the transfer times of electrical signals from the ends to the middle are equal in all frames, the observers agree that the ends are aligned concurrently. Measured length might depend on the magnitude of the relative velocity, but it cannot depend on the direction since there is no preferred frame or positioning in space. Let one of the scales move; the observer in the scale rest frame sees no change of length. Accept, for the sake of argument, that the stationary observer measures that the moving scale has reduced in the transverse direction, D < D'. The condition is symmetric, so that the roles of stationary and rest frames can be switched. This clues to conflicting finishes. Both observers feel that their clock is the same length but the other is shorter. The only way to decide the conflict is to take D = D'. The key to the disagreement is that the observers agree on simultaneity of the evaluation events (alignment of the ends).

2.6 LORENTZ CONTRACTION:

Additional acquainted result from relativistic mechanics is that a measurement of the length of a moving object along the direction of its motion rest on on its velocity. This phenomenon is well-known as Lorentz contraction.

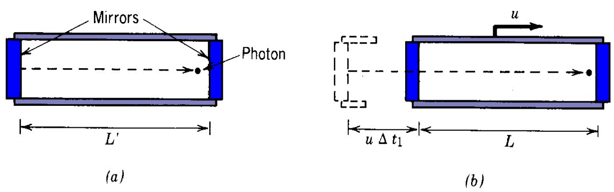


Figure 2.5 Lorentz contraction of a photon clock. (a) Clock rest frame. (b) Stationary frame

The effect can be established by allowing for the clock of Section 2.6 oriented as shown in Figure 2.5. The detector on the clock procedures the double transit time of light among the mirrors. Pulses are created when a photon leaves and returns to the left-hand mirror. Measurement of the single transit time would need interconnecting the arrival time of the photon at the right-hand mirror to the timer at the left-hand mirror. As the maximum speed with which this info can be transported is the speed of light, this is correspondent to a measurement of the double transit time.

2.7 LORENTZ TRANSFORMATIONS:

Charged particle orbits are categorized by position and velocity at a definite time, (**x**, **v**, t). In Newtonian mechanics, these measures vary if measured in a frame moving with a relative velocity with reverence to the frame of the first measurement. The relationship among quantities was précised in the Galilean transformations.

2.8 RELATIVISTIC FORMULAS:

The motion of high-energy particles needs to be designated by relativistic laws of motion. Force is correlated to momentum by the similar equation used in Newtonian mechanics

$$d\mathbf{p}/dt = \mathbf{F}.$$

This equation is constant with the Lorentz transformations if the momentum is well-defined as

$$\boldsymbol{P} = \boldsymbol{Zp} mo\boldsymbol{v}$$

The alteration from the Newtonian expression is the **Zp** factor. It is resolute by the total particle velocity v perceived in the stationary frame, **Zp** = (1-v2/c2)^-½. One interpretation of above equation is that a particle's effective mass upsurges as it approach the speed of light. The relativistic mass is associated to the rest mass by

$$m = \mathbf{Zp}\, mo.$$

2.9 NONRELATIVISTIC APPROXIMATION FOR TRANSVERSE MOTION:

A relativistically correct explanation of particle motion is regularly tougher to articulate and solve than one connecting Newtonian equations. In the study of the transverse motions of charged particle beams, it is regularly probable to precise the problem in the form of Newtonian equations with the rest mass substituted by the relativistic mass. This estimate is valid when the beam is well directed so that transverse velocity apparatuses are small related to the axial velocity of beam particles. Deliberate the effect of focusing forces applied in the x direction to restrain particles along the z axis. Particles make small angles with this axis, so that v_x is always small associated to v_z.

CONCLUSION

A thorough understanding of physics at the lower-division level, comprising a basic Working knowledge of the laws of mechanics, was offered. Charged particle acceleration and transport were elucidated using Charged Particle possessions then by applying Newton's laws of motion to the Dynamical systems. Additional dissimilar (Galilean, Lorentz) transformations were termed. Principles of special relativity time were designated by using hypothesizes. The relationship amongst time intervals was also established by the clock for time dilation.

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