

Notes of Quantum Mechanics

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Preface

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1.1 Introduction

In classical mechanics, the motion of any physical system is determined through the position $\mathbf{r} = (x, y, z)$ and the velocity $\mathbf{v} = (\dot{x}, \dot{y}, \dot{z})$. One usually introduces generalized coordinates $q_i(t)$ whose derivatives with respect to time $\dot{q}_i(t)$ are the generalized velocities. With these coordinates, the position and velocity of any point can be calculated. Using the Lagrangian $\mathcal{L}(q_i, \dot{q}_i, t)$ one defines the conjugate momentum p_i of each of the generalized coordinates q_i :

$$p_i = \frac{\partial \mathcal{L}}{\partial \dot{q}_i}.$$

The $q_i(t)$ and $p_i(t)$ are called **fundamental dynamical variables**. All the physical quantities associated with the system (energy, angular momentum, etc) can be expressed in terms of the fundamental dynamical variables.

The motion (evolution) of a system can be studied by Lagrange's equations or the Hamilton-Jacobi canonical equation:

$$\text{Hamilton-Jacobi equations} \quad \frac{dq_i}{dt} = \frac{\partial \mathcal{H}}{\partial p_i}, \quad \text{and} \quad \frac{dp_i}{dt} = -\frac{\partial \mathcal{H}}{\partial q_i}.$$

The classical description of a physical system can be summarized as follows:

- The state of the system at time t_0 is defined by specifying N generalized coordinates $q_i(t_0)$ and their N conjugate momenta $p_i(t_0)$.
- Knowing the state of the system at t_0 , allows to predict with certainty the result of any measurement performed at time t_0 .
- The time evolution of the state of the system is given by the **Hamilton-Jacobi** equations. The state of the system is known for all time if its initial state is known.

1.2 Statements of the postulates

1.2.1 State and measurable physical quantities of a system

The quantum state of a particle at a fixed time is characterized by a ket of the space \mathcal{E}_r .

First postulate: State of a system

At time t_0 , the state of an isolated physical system is defined by specifying a ket $|\psi(t_0)\rangle \in \mathcal{E}_r$.

Recall that, since \mathcal{E} is a vector space, a linear combination of state vectors is a state vector.

Second postulate: Measurable physical quantities

Every measurable physical quantity \mathcal{A} is described by an operator A acting in \mathcal{E} : this operator is an **observable**.

In this sense, a state is represented by a vector, while a physical quantity by an operator.

Third postulate: Outcomes of measurements

The only possible result of the measurement of a physical quantity \mathcal{A} is one of the eigenvalues of the corresponding observable A .

- A measurement of \mathcal{A} gives **always** a real value, since A is Hermitian by definition.
- If the spectrum of A is discrete, the results that can be obtained by measuring \mathcal{A} are **quantized**.

1.2.2 Principle of spectral decomposition

Consider a system whose state is characterized, at a given time, by $|\psi\rangle$, which is assumed normalized. We want to predict the result of the measurement, at this time, of a physical quantity \mathcal{A} associated with the observable A .

Discrete spectrum

If all eigenvalues a_n of A are non-degenerate, there is associated with each of them a **unique** eigenvector $|u_n\rangle$. As A is an observable, the set of $|u_n\rangle$ which we assume normalized, constitutes a basis in \mathcal{E} and we can expand $|\psi\rangle$:

$$A|u_n\rangle = a_n|u_n\rangle \implies |\psi\rangle = \sum_n c_n|u_n\rangle$$

The probability $P(a_n)$ of finding a_n when \mathcal{A} is measured is therefore:

$$P(a_n) = |c_n|^2 = |\langle u_n|\psi\rangle|^2.$$

If, however, some of the eigenvalues a_n are degenerate, several orthonormalized eigenvectors $|u_n^i\rangle$ corresponds to them and we can still expand $|\psi\rangle$ on the orthonormal basis $\{|u_n^i\rangle\}$:

$$A|u_n^i\rangle = a_n|u_n^i\rangle, \quad i = 1, 2, \dots, g_n \implies |\psi\rangle = \sum_n \sum_{i=1}^{g_n} c_n^i |u_n^i\rangle. \quad (1.1)$$

The probability now becomes

$$P(a_n) = \sum_{i=1}^{g_n} |c_n^i|^2 = \sum_{i=1}^{g_n} |\langle u_n^i|\psi\rangle|^2. \quad (1.2)$$

Fourth postulate (discrete case): Result of a measurement

When \mathcal{A} is measured on a system in the normalized state $|\psi\rangle$, the probability $P(a_n)$ of obtaining the eigenvalue a_n of the observable A is the discrete projection of ψ onto the eigensubspace \mathcal{E}_n :

$$P(a_n) = \langle \psi | P_n | \psi \rangle = \sum_{i=1}^{g_n} |\langle u_n^i | \psi \rangle|^2, \quad P_n = \sum_{i=1}^{g_n} |u_n^i\rangle \langle u_n^i|.$$

$\{|u_n^i\rangle\}$ is a set of orthonormal vectors which forms a basis in the eigensubspace \mathcal{E}_n .

Continuous case

If now the spectrum of A is continuous and non-degenerate, the eigenvectors of A forms a continuous basis in \mathcal{E} , in terms of which $|\psi\rangle$ can be expanded:

$$A|v_\alpha\rangle = \alpha|v_\alpha\rangle \implies |\psi\rangle = \int d\alpha c(\alpha)|v_\alpha\rangle.$$

In this case, we cannot define the probability on a single point; we must define a probability density function. The differential probability of obtaining a value included between α and $\alpha + d\alpha$ is

$$dP(\alpha) = \rho(\alpha)d\alpha, \quad \text{with} \quad \rho(\alpha) = |c(\alpha)|^2 = |\langle v_\alpha|\psi\rangle|^2.$$

Fourth postulate (continuous case, non-degenerate): Result of a measurement

If \mathcal{A} is measured in the normalized state $|\psi\rangle$, the probability of obtaining a result within between α_1 and α_2 is the continuous projection of ψ onto that interval:

$$P(\alpha_1 < \alpha < \alpha_2) = \langle \psi | P_{\alpha_1, \alpha_2} | \psi \rangle = \int_{\alpha_1}^{\alpha_2} |\langle v_\alpha | \psi \rangle|^2 d\alpha, \quad P_{\alpha_1, \alpha_2} = \int_{\alpha_1}^{\alpha_2} |v_\alpha\rangle \langle v_\alpha| d\alpha. \quad (1.3)$$

In cases where the state $|\psi\rangle$ is **not normalized**, we then use the following expressions:

$$\begin{array}{ll} \text{Discrete case} & \text{Continuous case} \\ P(a_n) = \frac{1}{\langle \psi | \psi \rangle} \sum_{i=1}^{g_n} |c_n^i|^2 & \rho(\alpha) = \frac{1}{\langle \psi | \psi \rangle} |c(\alpha)|^2. \end{array} \quad (1.4)$$

On the other hand, two proportional state vectors, $|\psi'\rangle = ae^{i\theta}|\psi\rangle$, represent **the same** physical state:

$$|\langle u_n^i | \psi' \rangle|^2 = |e^{i\theta} \langle u_n^i | \psi \rangle|^2 = |\langle u_n^i | \psi \rangle|^2.$$

a is simplified when dividing by $\langle \psi' | \psi' \rangle$.

Global versus relative phase factor

A global phase factor does not affect the physical predictions, but the relative phases of the coefficients of an expansion are significant.

1.2.3 Reduction of the wave packet

We want to measure at a given point the physical quantity \mathcal{A} . If the ket $|\psi\rangle$ before the measurement is known, the fourth postulate allows us to predict the probability of the various possible outcomes. Immediately after the measurement, we cannot speak of probability, as we have already got the result (collapse).

If the measurement of \mathcal{A} resulted in a_n (assuming discrete spectrum of A), the state of the system immediately after this measurement is the eigenvector $|u_n\rangle$ associated with a_n :

$$\text{State of collapse} \quad |\psi\rangle \xrightarrow{(a_n)} |u_n\rangle. \quad (1.5)$$

- If we perform a second measurement of \mathcal{A} immediately after the first one, we shall always find the same result a_n .
- We use just after the measurement to assume the system had not time to evolve, because otherwise the state evolves and we need the sixth postulate to keep track of this motion.

When the eigenvalue a_n is degenerate, then the state just before the measurement is written as (equation (1.1)):

$$|\psi\rangle = \sum_n \sum_{i=1}^{g_n} c_n^i |u_n^i\rangle.$$

And the state of collapse just after the measurement is

$$|\psi\rangle \xrightarrow{(a_n)} \frac{1}{\sqrt{\sum_{i=1}^{g_n} |c_n^i|^2}} \sum_{i=1}^{g_n} c_n^i |u_n^i\rangle. \quad (1.6)$$

The square root factor is the normalization so that we get a unitary norm of the state. We rewrite the above expression in the following fifth postulate.

Fifth postulate: State of collapse

If the measurement of the \mathcal{A} in the state $|\psi\rangle$ gives the result a_n , the state of the system immediately after the measurement is the normalized projection of $|\psi\rangle$ onto the eigensubspace \mathcal{E}_n associated with a_n :

$$|\psi\rangle \xrightarrow{(a_n)} \frac{P_n |\psi\rangle}{\sqrt{\langle \psi | P_n | \psi \rangle}} \quad (1.7)$$

It is not an arbitrary ket of \mathcal{E}_n , but the part of $|\psi\rangle$ that belongs to \mathcal{E}_n .

1.2.4 Time evolution of Systems

Sixth postulate: Time evolution of the system

The time evolution of the state vector $|\psi(t)\rangle$ is governed by the Schrodinger equation:

$$i\hbar \frac{d}{dt} |\psi(t)\rangle = H(t) |\psi(t)\rangle, \quad (1.8)$$

where $H(t)$ is the **Hamiltonian operator** (observable) associated with the total energy of the system.

1.2.5 Quantization rules

We will discuss how to construct, for a physical quantity \mathcal{A} already defined in classical mechanics, the operator A which describes it in quantum mechanics.

1.3 The physical interpretation of the postulates

1.3.1 Quantization rules are consistent with probabilistic interpretation

Lets consider a one-dimensional problem. If the particle is in the normalized state $|\psi\rangle$, the probability that a measurement of its position will yield a result included between x and $x + dx$ is equal to (equation (1.4)):

$$dP(x) = |\langle x|\psi\rangle|^2 dx.$$

Now, to the eigenvector $|p\rangle$ of the observable P corresponds the plane wave:

$$\langle x|p\rangle = (2\pi\hbar)^{-1/2} e^{\frac{ipx}{\hbar}}. \quad (1.9)$$

and we have seen that de Broglie relations associate with this wave a well-defined momentum which is precisely p . In addition, the probability of finding, for a particle in $|\psi\rangle$, a momentum between p and $p + dp$ is:

$$dP(p) = |\langle p|\psi\rangle|^2 dp = |\tilde{\psi}(p)|^2 dp. \quad (1.10)$$

1.3.2 The measurement process

There is the question of the "fundamental" perturbation involved in the observation of quantum system. The origin of these problems lies in the fact that the system under study is treated independently from the measurement device, although their interaction is essential to the observation process. One should actually consider the system and the measurement device together as a whole. This raises delicate questions concerning the details of the measurement process.

The nondeterministic formulation of the fourth and fifth postulates is related to the problems that we have mentioned. Of course, the abrupt change from one state vector to another due to the measurement corresponds to the fundamental perturbation of which we have spoken. We shall consider here only ideal measurements: the perturbation they provoke is due only to the quantum mechanical aspect of the measurement. Of course, real devices always present imperfections that affect the measurement and the system.

1.3.3 Mean value of an observable in a given state

The predictions deduced from the fourth postulate are expressed in terms of probabilities. To verify them, it would be necessary to perform a large number of measurements under identical conditions. This means measuring the same quantity in a large number of systems which are all in the same quantum state. If these predictions are correct, the proportion of N identical experiments resulting in a given event will approach, as $N \rightarrow \infty$, the theoretically predicted probability P of this event. In practice, of course, N is finite, and statistical techniques must be used to interpret the results.

The **mean value of an observable** A in the state $|\psi\rangle$, which we shall denote by $\langle A \rangle_\psi$, or $\langle A \rangle$, is defined as the average of the results obtained when a large number N of measurements of this observable are performed on systems which are all in the state $|\psi\rangle$. When $|\psi\rangle$ is given, we can compute the probabilities of finding all the possible results, and therefore, $\langle A \rangle_\psi$ is known.

If $|\psi\rangle$ is normalized, $\langle A \rangle$ is given by

$$\langle A \rangle_\psi = \langle \psi|A|\psi\rangle \quad (1.11)$$

Assuming discrete spectrum, out of N measurements of \mathcal{A} , the eigenvalue a_n will be obtained $N(a_n)$ times, with

$$\lim_{N \rightarrow \infty} \frac{N(a_n)}{N} = P(a_n), \quad \text{and} \quad \sum_n N(a_n) = N. \quad (1.12)$$

In the limit, we can approximate therefore the mean value of the results as

$$\langle A \rangle_\psi = \lim_{N \rightarrow \infty} \frac{1}{N} \sum_n a_n N(a_n) = \sum_n a_n P(a_n). \quad (1.13)$$

The last expression is then treated:

$$\begin{aligned} \langle A \rangle_\psi &= \sum_n a_n P(a_n) = \sum_n a_n \langle \psi | P_n | \psi \rangle = \sum_n a_n \sum_{i=1}^{g_n} \langle \psi | u_n^i \rangle \langle u_n^i | \psi \rangle = \sum_n \sum_{i=1}^{g_n} \langle \psi | a_n | u_n^i \rangle \langle u_n^i | \psi \rangle \\ &= \sum_n \sum_{i=1}^{g_n} \langle \psi | A | u_n^i \rangle \langle u_n^i | \psi \rangle = \langle \psi | A \left[\sum_n \sum_{i=1}^{g_n} | u_n^i \rangle \langle u_n^i | \right] | \psi \rangle = \langle \psi | A \mathbf{1} | \psi \rangle = \langle \psi | A | \psi \rangle. \end{aligned}$$

In the continuous case, we have something similar:

$$\lim_{N \rightarrow \infty} \frac{dN(\alpha)}{N} = dP(\alpha). \quad (1.14)$$

In the limit, we can approximate the mean value of the results as

$$\langle A \rangle_\psi = \lim_{N \rightarrow \infty} \frac{1}{N} \int \alpha dN(\alpha) = \int \alpha dP(\alpha). \quad (1.15)$$

The last expression is then treated:

$$\begin{aligned} \langle A \rangle_\psi &= \int \alpha dP(\alpha) = \int \alpha \langle \psi | v_\alpha \rangle \langle v_\alpha | \psi \rangle d\alpha = \int \langle \psi | A | v_\alpha \rangle \langle v_\alpha | \psi \rangle d\alpha \\ &= \langle \psi | A \left[\int d\alpha | v_\alpha \rangle \langle v_\alpha | \right] | \psi \rangle = \langle \psi | A \mathbf{1} | \psi \rangle = \langle \psi | A | \psi \rangle. \end{aligned}$$

- If the ket $|\psi\rangle$ is not normalized, then we use

$$\text{Mean value of } A \quad \langle A \rangle_\psi = \frac{\langle \psi | A | \psi \rangle}{\langle \psi | \psi \rangle}. \quad (1.16)$$

- In practice, one often places oneself in a particular representation to compute $\langle A \rangle_\psi$.

$$\begin{aligned} \langle X \rangle_\psi &= \langle \psi | X | \psi \rangle = \int d^3r \langle \psi | \mathbf{r} \rangle \langle \mathbf{r} | X | \psi \rangle = \int d^3r \psi^*(\mathbf{r}) x \psi(\mathbf{r}). \\ \langle P_x \rangle_\psi &= \langle \psi | P_x | \psi \rangle = \int d^3r \tilde{\psi}^*(\mathbf{p}) p_x \tilde{\psi}(\mathbf{p}), \quad \text{or} \\ \langle P_x \rangle_\psi &= \langle \psi | P_x | \psi \rangle = \int d^3r \langle \psi | \mathbf{r} \rangle \langle \mathbf{r} | P_x | \psi \rangle = \int d^3r \psi^*(\mathbf{r}) \left[\frac{\hbar}{i} \frac{\partial}{\partial x} \psi(\mathbf{r}) \right]. \end{aligned}$$

1.3.4 The root mean square deviation

$\langle A \rangle$ indicates the order of magnitude of the values of the observables A when the system is in the state $|\psi\rangle$. However, this mean values does not give any idea of the dispersion of the results we expect when measuring A .

We therefore define the **root mean square deviation** ΔA as

$$\text{RMS deviation} \quad \Delta A = \sqrt{\langle (A - \langle A \rangle)^2 \rangle} = \sqrt{\langle A^2 \rangle - \langle A \rangle^2}. \quad (1.17)$$

If this definition is applied to the observable R and P , we can shown, using commutation realtions, that for any state $|\psi\rangle$, we have

$$\begin{aligned} \Delta X \cdot \Delta P_x &\geq \frac{\hbar}{2} \\ \Delta Y \cdot \Delta P_y &\geq \frac{\hbar}{2} \\ \Delta Z \cdot \Delta P_z &\geq \frac{\hbar}{2} \end{aligned} \quad \text{Heisenberg relations} \quad (1.18)$$

1.3.5 Compatibility of observables

Compatibility and commutation rules

Let be two commute observable A and B $[A, B] = 0$, and assume discrete spectrum. There exists a basis of the state space composed of eigenkets commont to A and B , which we denote $|a_n, b_p, i\rangle$:

$$\begin{aligned} A|a_n, b_p, i\rangle &= a_n|a_n, b_p, i\rangle \\ B|a_n, b_p, i\rangle &= b_p|a_n, b_p, i\rangle. \end{aligned}$$

For any a_n and b_p , there exists at least one state $|a_n, b_p, i\rangle$ for which a measurement of A will always give a_n and a measurement of B will always give b_p . These observables which can be simultaneously determined are said to be **compatible**.

The initial state of a system $|\psi\rangle$ can always be written as

$$|\psi\rangle = \sum_{n,p,i} c_{n,p,i} |a_n, b_p, i\rangle.$$

Assume we measure A and then immediately we measure B . First, the probability of having a_n is

$$P(a_n) = \sum_{p,i} |c_{n,p,i}|^2. \quad (1.19)$$

When we then measure B , the system is no long in the state $|\psi\rangle$ but, if we found a_n in the state $|\psi'_n\rangle$ we have

$$|\psi'_n\rangle = \frac{1}{\sqrt{\sum_{p,i} |c_{n,p,i}|^2}} \sum_{p,i} c_{n,p,i} |a_n, b_p, i\rangle.$$

The probability of obtaining b_p when it is known that the first measurement was a_n is then

$$P_{a_n}(b_p) = \frac{1}{\sum_{p,i} |c_{n,p,i}|^2} \sum_i |c_{n,p,i}|^2. \quad (1.20)$$

The probability $P(a_n, b_p)$ of obtaining a_n in the first measurement and b_p in the second is then a composite event, we must first find a_n and then find b_p . Therefore,

$$P(a_n, b_p) = P(a_n)P_{a_n}(b_p) = \sum_i |c_{n,p,i}|^2. \quad (1.21)$$

The state of the system becomes immediately after the second measurement

$$|\psi''_{n,p}\rangle = \frac{1}{\sqrt{\sum_i |c_{n,p,i}|^2}} \sum_i c_{n,p,i} |a_n, b_p, i\rangle. \quad (1.22)$$

$|\psi''_{n,p}\rangle$ is an eigenvector common to A and B with the eigenvalues a_n and b_p , respectively.

If we do the same in opposite order, that is, measuring B and then A we have

$$P(b_p, a_n) = \sum_i |c_{n,p,i}|^2, \quad \text{and} \quad |\psi''_{p,n}\rangle = \frac{1}{\sqrt{\sum_i |c_{n,p,i}|^2}} \sum_i c_{n,p,i} |a_n, b_p, i\rangle. \quad (1.23)$$

Consequence of compatible observables

When two observables are compatible, the physical predictions are the **same**, whatever the order of performing the two measurements. The probability and the state after the last measurements are for both cases:

$$P(a_n, b_p) = P(b_p, a_n) = \sum_i |c_{n,p,i}|^2 = \sum_i |\langle a_n, b_p, i | \psi \rangle|^2, \quad \text{and} \quad (1.24)$$

$$|\psi''_{n,p}\rangle = |\psi''_{p,n}\rangle = \frac{1}{\sqrt{\sum_i |c_{n,p,i}|^2}} \sum_i c_{n,p,i} |a_n, b_p, i\rangle. \quad (1.25)$$

When two observables A and B are compatible, the measurement of B does not cause any loss of information previously obtained from the measurement of A , and viceversa.

New measurement of A or B will yield the same values again without fail.

Preparation of a state

1.4 Physical implications of the Schrodinger equation

Recall the Schrodinger equation

$$i\hbar \frac{d}{dt} |\psi(t)\rangle = H(t) |\psi\rangle. \quad (1.26)$$

1.4.1 General properties of the Schrodinger equation

There is no indeterminacy in the time evolution of a quantum system. Indeterminacy appears only when a physical quantity is measured.

Between two measurements, the state vectors evolves (following Shrodinger equation) in a perfectly deterministic way.

Supeorposition

The equation (1.26) is linear and homogeneous, then their slutions are linearly superposable:

$$|\psi(t_0)\rangle = \lambda_1|\psi_1(t_0)\rangle + \lambda_2|\psi_2(t_0)\rangle \implies |\psi(t)\rangle = \lambda_1|\psi_1(t)\rangle + \lambda_2|\psi_2(t)\rangle. \quad (1.27)$$

Conservation of probability

Since the Hamiltonian operator $H(t)$ is Hermitian, the square of the norm of the state vector $\langle\psi(t)|\psi(t)\rangle$ does not depend on time:

$$\begin{aligned} \frac{d}{dt}\langle\psi(t)|\psi(t)\rangle &= \left[\frac{d}{dt}\langle\psi(t)| \right] |\psi(t)\rangle + \langle\psi(t)| \left[\frac{d}{dt}|\psi(t)\rangle \right] \\ &= \left[-\frac{1}{i\hbar}\langle\psi(t)|H(t) \right] |\psi(t)\rangle + \langle\psi(t)| \left[\frac{1}{i\hbar}H(t)|\psi(t)\rangle \right] \\ &= -\frac{1}{i\hbar}\langle\psi(t)|H(t)|\psi(t)\rangle + \frac{1}{i\hbar}\langle\psi(t)|H(t)|\psi(t)\rangle \\ \frac{d}{dt}\langle\psi(t)|\psi(t)\rangle &= 0. \end{aligned}$$

The property of conservation of the norm which we have derived is expressed by the equation

$$\langle\psi(t)|\psi(t)\rangle = \int d^3r |\psi(\mathbf{r}, t)|^2 = \langle\psi(t_0)|\psi(t_0)\rangle = 1. \quad (1.28)$$

This implies that time evolution does not modify the global probability of finding the particle in all space, which always remains equal to 1.

Evolution of the mean value of an observable

The mean value of the observable A at the instant t is

$$\langle A \rangle(t) = \langle\psi(t)|A|\psi(t)\rangle. \quad (1.29)$$

The mean value may depends on time by the state $\psi(t)$, but also by the observator itself $A(t)$. If we differentiate the above equation with time we have

$$\begin{aligned} \frac{d}{dt}\langle\psi(t)|A(t)|\psi(t)\rangle &= \left[\frac{d}{dt}\langle\psi(t)| \right] A(t)|\psi(t)\rangle + \langle\psi(t)|A \left[\frac{d}{dt}|\psi(t)\rangle \right] + \langle\psi(t)| \frac{\partial A}{\partial t} |\psi(t)\rangle \\ &= \frac{1}{i\hbar}\langle\psi(t)|[A(t)H(t) - H(t)A(t)]|\psi(t)\rangle + \langle\psi(t)| \frac{\partial A}{\partial t} |\psi(t)\rangle. \end{aligned}$$

Therefore,

$$\text{Evolution of the mean value of } A \quad \frac{d}{dt}\langle A \rangle = \frac{1}{i\hbar}\langle[A, H(t)]\rangle + \left\langle \frac{\partial A}{\partial t} \right\rangle. \quad (1.30)$$

The mean value $\langle A \rangle$ is a number which depends only on time t . It is this value that must be compared to the value taken on by the classical quantity $\mathcal{A}(\mathbf{r}, \mathbf{p}, t)$.

We can apply the equation (1.30) to the observables \mathbf{R} and \mathbf{P} , assuming a scalar stationary potential $V(\mathbf{r})$:

$$H = \frac{\mathbf{P}^2}{2m} + V(\mathbf{R}).$$

We also have

$$\frac{d}{dt}\langle \mathbf{R} \rangle = \frac{1}{i\hbar}\langle [\mathbf{R}, H] \rangle = \frac{1}{\hbar}\langle [\mathbf{R}, \frac{\mathbf{P}^2}{2m}] \rangle = \frac{i\hbar}{m}\mathbf{P}, \quad \text{and} \quad \frac{d}{dt}\langle \mathbf{P} \rangle = \frac{1}{i\hbar}\langle [\mathbf{P}, H] \rangle = \frac{1}{i\hbar}\langle [\mathbf{P}, V(\mathbf{R})] \rangle = -i\hbar\nabla V(\mathbf{R}).$$

Therefore, we have the **Ehrenfest's theorem**:

$$\text{Ehrenfest's theorem} \quad \begin{aligned} \frac{d}{dt}\langle \mathbf{R} \rangle &= \frac{1}{m}\langle \mathbf{P} \rangle \\ \frac{d}{dt}\langle \mathbf{P} \rangle &= -\langle \nabla V(\mathbf{R}) \rangle \end{aligned} \quad (1.31)$$

classical limits of the Ehrenfest's theorem

1.4.2 Conservative systems

When the Hamiltonian of a physical system **does not** depend explicitly on time, the system is said to be **conservative**. It can also be said that the total energy of the system is constant of the motion.

Solution of the Schrodinger equation

Lets consider the eigenequation of H (assuming discrete spectrum):

$$H|\varphi_{n,\tau}\rangle = E_n|\varphi_{n,\tau}\rangle. \quad (1.32)$$

τ is used to denote the set of indices other than n necessary to uniquely characterizes a unique vector $|\varphi_{n,\tau}\rangle$. Since H does not depend on time, neither E_n nor $|\varphi_{n,\tau}\rangle$. Because $|\varphi_{n,\tau}\rangle$ form a basis, it is always possible to expand the state $|\psi(t)\rangle$:

$$|\psi(t)\rangle = \sum_{n,\tau} c_{n,\tau}(t)|\varphi_{n,\tau}\rangle, \quad \text{with} \quad c_{n,\tau}(t) = \langle \varphi_{n,\tau} | \psi(t) \rangle.$$

All the time dependence of $|\psi(t)\rangle$ is contained within $c_{n,\tau}(t)$. Let us project the Schrodinger equation onto each of the states $|\varphi_{n,\tau}\rangle$:

$$\begin{aligned} i\hbar \frac{d}{dt} \langle \varphi_{n,\tau} | \psi(t) \rangle &= \langle \varphi_{n,\tau} | H | \psi(t) \rangle \\ i\hbar \frac{d}{dt} c_{n,\tau}(t) &= E_n c_{n,\tau}(t). \end{aligned}$$

This equation can be integrated to give

$$c_{n,\tau}(t) = c_{n,\tau}(t_0) e^{-E_n(t-t_0)/\hbar}. \quad (1.33)$$

When H does not depend on time, to find $|\psi(t)\rangle$ given $|\psi(t_0)\rangle$, proceed as follows:

- Expand $|\psi(t_0)\rangle$ in terms of the eigenstates of H :

$$|\psi(t_0)\rangle = \sum_n \sum_\tau c_{n,\tau}(t_0) |\varphi_{n,\tau}\rangle, \quad \text{with} \quad c_{n,\tau}(t_0) = \langle \varphi_{n,\tau} | \psi(t_0) \rangle.$$

- To obtain $|\psi(t)\rangle$, multiply each coefficient $c_{n,\tau}(t_0)$ of the expansion by the term $e^{-iE_n(t-t_0)/\hbar}$:

$$|\psi(t)\rangle = \sum_n \sum_\tau c_{n,\tau}(t_0) e^{-iE_n(t-t_0)/\hbar} |\varphi_{n,\tau}\rangle. \quad (1.34)$$

or, in the continuous case,

$$|\psi(t)\rangle = \sum_\tau \int dE c_\tau(E, t_0) e^{-iE_n(t-t_0)/\hbar} |\varphi_{n,\tau}\rangle. \quad (1.35)$$

Stationary states

An important special case is that in which $|\psi(t_0)\rangle$ is itself an eigenstate of H . Then, the expansion of $|\psi(t_0)\rangle$ involves only eigenvalue of H with the same eigenvalue:

$$|\psi(t_0)\rangle = \sum_\tau c_{n,\tau}(t_0) |\varphi_{n,\tau}\rangle.$$

We notice there is no summation over n , and the passage from $|\psi(t_0)\rangle$ to $|\psi(t)\rangle$ involves only one factor of $e^{-iE_n(t-t_0)/\hbar}$, which can be taken outside the summation over τ :

$$|\psi(t)\rangle = \sum_\tau c_{n,\tau}(t_0) e^{-iE_n(t-t_0)/\hbar} |\varphi_{n,\tau}\rangle = e^{-iE_n(t-t_0)/\hbar} \sum_\tau c_{n,\tau}(t_0) |\varphi_{n,\tau}\rangle = e^{-iE_n(t-t_0)/\hbar} |\psi(t_0)\rangle.$$

$|\psi(t)\rangle$ and $|\psi(t_0)\rangle$ therefore differ only by a global phase factor. These two states are physically indistinguishable.

All the physical properties of a system which is an eigenstate of H do not vary over time: the eigenstates of H are called **stationary states**.

The state of the system will no longer evolve after the first measurement and will always remain an eigenstate of H with eigenvalue of E_k . A second measurement of the energy at any subsequent time will always yield the same result E_k as the first one.

Constants of the motion

A constant of the motion is an observable A which does not depend explicitly on time and which commutes with H :

$$\text{Constant of the motion } A \quad \frac{\partial A}{\partial t} = 0 \wedge [A, H] = 0. \quad (1.36)$$

For a conservative system, H is therefore itself a constant of the motion.

- The mean value of A does not evolve over time:

$$\frac{d}{dt}\langle A \rangle = \frac{1}{i\hbar}\langle [A, H(t)] \rangle + \left\langle \frac{\partial A}{\partial t} \right\rangle = 0.$$

- Since A and H are observables which commute, we can always find for them a system of common eigenvectors:

$$\begin{aligned} H|\varphi_{n,p,\tau}\rangle &= E_n|\varphi_{n,p,\tau}\rangle \\ A|\varphi_{n,p,\tau}\rangle &= a_p|\varphi_{n,p,\tau}\rangle \end{aligned}$$

Since the states $|\varphi_{n,p,\tau}\rangle$ are eigenstates of H , they are stationary states. But it is also an eigenstate of A .

When A is a constant of motion, there exist stationary states of the physical system ($|\varphi_{n,p,\tau}\rangle$) that always remain, for all t , eigenstates of A with the same eigenvalue a_p . The eigenvalues of A are called **good quantum numbers**.

- The probability of finding the eigenvalue a_p , when the constant of motion A is measured, is not time-dependent.

$$|\psi(t_0)\rangle = \sum_{n,p,\tau} c_{n,p,\tau}(t_0)|\varphi_{n,p,\tau}\rangle, \quad |\psi(t)\rangle = \sum_{n,p,\tau} c_{n,p,\tau}(t)|\varphi_{n,p,\tau}\rangle, \quad \text{with} \quad c_{n,p,\tau}(t) = c_{n,p,\tau}(t_0)e^{-iE_n(t-t_0)/\hbar}.$$

The probability $P(a_p, t_0)$ of finding a_p when A is measured at t_0 on the system of state $|\psi(t_0)\rangle$ is

$$P(a_p, t_0) = \sum_{n,\tau} |c_{n,p,\tau}(t_0)|^2. \quad \text{Similarly,} \quad P(a_p, t) = \sum_{n,\tau} |c_{n,p,\tau}(t)|^2.$$

We see from the coefficient relation equation that $c_{n,p,\tau}(t)$ and $c_{n,p,\tau}(t_0)$ have the same modulus. Therefore,

$$P(a_p, t) = P(a_p, t_0). \quad (1.37)$$

If all but one of the probabilities $P(a_p, t_0)$ are zero, the physical system at t_0 is in an eigenstate of A with an eigenvalue of a_k . Since the $P(a_p, t)$ do not depend on t , the state of the system at time t remains an eigenstate of A with an eigenvalue of a_k .

Bohr frequencies of a system

Let B be an arbitrary observable of the system. Its time derivative is

$$\frac{d}{dt}\langle B \rangle = \frac{1}{i\hbar}\langle [B, H] \rangle + \left\langle \frac{\partial B}{\partial t} \right\rangle.$$

For a conservative system, we know how to construct $|\psi(t)\rangle$ (1.34). Therefore, we can compute explicitly $\langle \psi(t)|B|\psi(t)\rangle$ and not only $d\langle B \rangle/dt$:

$$\begin{aligned} \langle B \rangle(t) &= \langle \psi(t)|B|\psi(t)\rangle \\ &= \left[\sum_{n',\tau'} c_{n',\tau'}^*(t_0)e^{iE_{n'}(t-t_0)/\hbar} \langle \varphi_{n',\tau'}| \right] B \left[\sum_{n,\tau} c_{n,\tau}(t_0)e^{-iE_n(t-t_0)/\hbar} |\varphi_{n,\tau}\rangle \right] \\ &= \sum_{n,\tau} \sum_{n',\tau'} c_{n',\tau'}^*(t_0)c_{n,\tau}(t_0) \langle \varphi_{n',\tau'}|B|\varphi_{n,\tau}\rangle e^{i(E_{n'}-E_n)(t-t_0)/\hbar}. \end{aligned}$$

If we assume B does not depend explicitly on time, the matrix elements $\langle \varphi_{n',\tau'} | B | \varphi_{n,\tau} \rangle$ are constant. The evolution of $\langle B \rangle(t)$ is described by a series of oscillating terms, whose frequencies

$$\text{Bohr frequencies of the system} \quad \nu_{n',n} = \frac{1}{2\pi} \frac{|E_{n'} - E_n|}{\hbar} = \left| \frac{E_{n'} - E_n}{h} \right|$$

are characteristic of the system under consideration, but independent of B and the initial state of the system. The importance of each frequency $\nu_{n',n}$ depends on the matrix elements $\langle \varphi_{n',\tau'} | B | \varphi_{n,\tau} \rangle$. This is the origin of the selection rules which indicate what frequencies can be emitted or absorbed under given conditions. One would have to study the non-diagonal matrix elements $n \neq n'$ of the various atomic operator such as the electric and magnetic dipoles, etc.

Using the $\langle B \rangle(t)$ expression, we can say that the mean value of a constant of the motion is always time-independent. The only terms of $\langle B \rangle$ that are non-zero are thus constant.

Time-energy uncertainty relation

1.5 The superposition principle and physical predictions

One of the important consequences of the first postulate, when it is combined with the others, is the appearance of **interference effects**.

1.6 Evolution operator

The transformation of $|\psi(t_0)\rangle$ into $|\psi(t)\rangle$ is linear. Therefore, there exists a linear operator $U(t, t_0)$ such that

$$\text{Evolution operator} \quad |\psi(t)\rangle = U(t, t_0) |\psi(t_0)\rangle, \quad (1.38)$$

where $U(t, t_0)$ is the **evolution operator** of the system.

1.6.1 General properties

From (1.38) we know that

$$U(t_0, t_0) = \mathbb{1}. \quad (1.39)$$

If we substitute the linear operator into the Schrödinger equation, we obtain:

$$i\hbar \frac{\partial}{\partial t} U(t, t_0) |\psi(t_0)\rangle = H(t) U(t, t_0) |\psi(t_0)\rangle \implies i\hbar \frac{\partial}{\partial t} U(t, t_0) = H(t) U(t, t_0). \quad (1.40)$$

This is a first-order differential equation completely defined $U(t, t_0)$. Equations (1.39) and (1.40) can be condensed into a single integral form:

$$U(t, t_0) = \mathbb{1} = \int_{t_0}^t H(t') U(t', t_0) dt. \quad (1.41)$$

Let's now take three instants t'', t', t so that $t'' < t' < t$, then

$$\left. \begin{aligned} |\psi(t)\rangle &= U(t, t') |\psi(t')\rangle \\ |\psi(t')\rangle &= U(t', t'') |\psi(t'')\rangle \end{aligned} \right\} \implies |\psi(t)\rangle = U(t, t') U(t', t'') |\psi(t'')\rangle = U(t, t'') |\psi(t'')\rangle.$$

From last expression, we have:

$$U(t, t')U(t', t'') = U(t, t'') \quad (1.42)$$

If we set $t = t''$ and interchange the roles of t and t' we have

$$\mathbb{1} = U(t', t)U(t, t') \implies U(t', t) = U^{-1}(t, t'). \quad (1.43)$$

On the other hand, the evolution operator between two instants separated by dt is :

$$d|\psi(t)\rangle = |\psi(t + dt)\rangle - |\psi(t)\rangle = -\frac{i}{\hbar}H(t)|\psi(t)\rangle dt.$$

From this we have

$$|\psi(t + dt)\rangle = \left[\mathbb{1} - \frac{i}{\hbar}H(t) dt \right] |\psi(t)\rangle = U(t + dt, t)|\psi(t)\rangle.$$

That is, we have the **infinitesimal evolution operator**:

$$\text{Infinitesimal evolution operator} \quad U(t + dt, t) = \mathbb{1} - \frac{i}{\hbar}H(t) dt. \quad (1.44)$$

Since $H(t)$ is Hermitian, $U(t + dt, t)$ is unitary. It is not surprising that the evolution operator conserves the norm of vectors on which it acts. We saw previously that the norm of the state vector does not change over time.

1.6.2 Case of conservative systems

When the operator H does not depend on time, equation (1.40) can be integrated easily:

$$U(t, t_0) = e^{-iH(t-t_0)/\hbar}. \quad (1.45)$$

Applying this operator on a state vector $|\varphi_{n,\tau}\rangle$ yields:

$$U(t, t_0)|\varphi_{n,\tau}\rangle = e^{-iH(t-t_0)/\hbar}|\varphi_{n,\tau}\rangle = e^{-iE_n(t-t_0)/\hbar}|\varphi_{n,\tau}\rangle. \quad (1.46)$$

1.7 Infinite potential well

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