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序

我和政道相识相知于60年前昆明西南联大。当时我们曾一起听吴大猷老师的量子力学课，对物理学的共同热爱，把我们紧紧联系在一起。那时，政道已显露出超人的物理才华，深受老师的赞誉和同学们的钦佩。1946年夏我们一同赴美留学，尽管不在同一所大学学习，但经常相聚探讨物理学问题。1950年我回国后，我们的联系中断了20多年，直到1972年才复在北京相聚。而今政道和我都已至耄耋之年，60年来的经历仍历历在目。

政道物理研究的面很广泛，诸如天体、流体、粒子、统计、核物理等方面都有所涉及，他的许多成就对物理学的发展起了很大的推进作用。在政道80华诞之际，中国高等科学技术中心的叶铭汉院士等同仁，把政道60年的科学论文精选了一百余篇，汇集成《李政道科学论文选》。为了使中国读者能更准确地了解其科学意义，每篇论文前增加了中文评注。这本科学论文选的出版，我相信必然在中国学术界产生重大影响。它不但忠实记载了政道60年来在物理学研究上多方面的成就，而且生动反映了他献身科学、不懈追求的执着精神，尤其使人们看到了耄耋之年的他仍然保持着旺盛的学术创造力，仍在孜孜不倦、夜以继日地进行物理研究。仅2006年头7个月内他已在几个物理领域研究发表了5篇论文。如此高龄仍能取得这样广泛的科学成果，这在科学史上是比较罕见的。他对物理研究情有独钟，把它融入了自己的生命之中。正是这种全身心的投入和深厚热爱，才能使他在纷扰世界和沧桑历史变迁中，心无旁骛，一直保持物理研究的强大动力和浓厚兴趣，才使他对世界物理学的发展做出如此重要的贡献，才使他持久拥有青年时代的研究活力。他十分喜欢杜甫诗句“细推物理须行乐，何用浮名绊此身”，我想这也是政道治学为人的写照。

我衷心祝愿我的老友耄耋之年身体健康，永葆学术青春，再创新的辉煌。

朱光亚

2006年9月6日

凡 例

1. 本书选收了李政道有代表性的论文共106篇，约为李政道已发表论文总数的三分之一。

2. 本书所收论文，按内容分为61个单元，每单元含一篇或多篇论文。

3. 本书分上、下两册出版。上册收有1－42单元，64篇论文；下册收有43－61单元，42篇论文。

4. 每个单元中，在论文之前，加有编者的评注，介绍该单元论文的主题、在学科上的重要性，以及相关背景，并插有人物照片或相关图片。

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6. “已发表论文总目”收有截至2007年5月李政道已发表论文的篇题和相关数据。并依论文发表的先后次序，编有总目序号。该“总目序号”也与李政道已出版的英文版论文集的总目序号基本一致。

7. 在本书中，“总目序号”一律用中黑字体印刷，以区别于书中提及的他人论文的序号。在“已发表论文总目”中，“总目序号”不加方括号直接置于论文篇目数据前；在61个单元的评注中，则加方括号引用。

8. 本书所收论文，均保留了论文发表时的原有形态，包括文献的著录方式。与此一致，本书在目录、篇题，以及“已发表论文总目”中的著录方式，均采用国际流行的著录方式。但编者在评注中另作的著录，则采用我国的有关国家标准。

9. 在编者的评注中，所有的外国人名均在其第一次出现时给出中译名，并括注英文名，再次出现时则直接用中译名。

10. 本书评注后注释均为编者注。

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[183] Discrete Quantum Mechanics (with R. Friedberg), *Nucl. Phys.* B225 [FS9], 1 (1983).

[188] Derivation of Regge's Action from Einstein's Theory of General Relativity (with R. Friedberg), *Nucl. Phys.* B242, 145 (1984).

[189] Lattice Gravity near the Continuum Limit (with G. Feinberg, R. Friedberg and H. C. Ren), *Nucl. Phys.* B245, 343 (1984).

[评 注]

在前面[179，180，181]三篇文章中作者发展了一整套用于场论的离散公式。这些公式可以作为所关注的理论的各种非微扰近似的一个出发点。场论的理论一般是定义在传统的连续时空中的。然而，论文[182]使用了一种根本不同的途径，该途径假定时间是一个离散的动力学变量。通过这个假定，就能够将随机格点阵恢复为一种可能的量子场历程的确切描述。相当令人惊奇的是，尽管时间和空间是离散的，仍然存在着确切的能量和动量守恒定律，而这些守恒的量是由连续变量来描述的。可以证明，这种关于时间的新的解释可以应用到形形色色的各种力学中，从单个粒子的非相对论性的运动到量子场论。论文[183]进一步检验和发展了这种关于时间的新观念。

作者发展的将时间作为离散的动力学变量的离散描述方法具有广泛的应用前景。无论从理论角度还是从实验观察的角度来看，其中最有意思、最具有前景的应用是引力理论。论文[188]和[189]研究了这种应用。论文[188]证明了雷吉(Regge)在23年前发明的离散作用量能够精确地与爱因斯坦广义相对论对应的作用量关联。论文[189]详细研究了这一关联，显示如何从离散公式出发，可以得到通常是连续的广义相对论系统的近似。

任海沧（H.C. Ren）

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CAN TIME BE A DISCRETE DYNAMICAL VARIABLE? ☆

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The possibility that time can be regarded as a discrete dynamical variable is examined through all phases of mechanics: from classical mechanics to nonrelativistic quantum mechanics, and to relativistic quantum field theories.

1. Introduction. Throughout the development of physics, "time" always appears as a continuous parameter. Take the example of a nonrelativistic particle in quantum mechanics. In Feynman's path integration formulation, the probability amplitude for the particle to be at the position r_0 at an initial time t_0 and at r_f at a final time t_f is given by the amplitude sum over all paths $r(t)$ connecting $r(t_0) = r_0$ and $r(t_f) = r_f$. Apart from a normalization constant, it is equal to

$$\int \prod_t \mathrm{d}^3 r(t) \exp(\mathrm{i}A_\mathrm{c}), \tag{1}$$

where the action A_c is a functional of $r(t)$, related to the lagrangian L by

$$A_\mathrm{c} = \int_{t_0}^{t_\mathrm{f}} L(r(t), \dot{r}(t))\, \mathrm{d}t, \tag{2}$$

with the subscript c denoting the familiar case that t is continuous. We note that the position of the particle r is not treated on the same basis as the time t. At a given time the integration $\mathrm{d}^3 r(t)$ in eq. (1) can be viewed as that over the whole range of eigenvalues of the operator $r_{\mathrm{op}}(t)$. This then underlies the familiar difference between r as an operator and t as a parameter.

Actually this asymmetry can be traced back to classical mechanics. The classical trajectory of a particle is determined by the extremity of the action A_c, which is a functional of $r(t)$. While r is the dynamical variable, t appears only as a continuous parameter. By setting the variational derivative $\delta A_\mathrm{c}/\delta r(t) = 0$, we obtain the usual Lagrange equation of motion, whose solution gives the classical path $r(t)$.

In the relativistic quantum field theory, space r and time t have to be treated symmetrically due to Lorentz invariance. Our usual approach is to regard r and t all as parameters; the operators are now the field variables, say the scalar field $\phi(r,t)$. Expression (1) is then replaced by

$$\int \prod_r \prod_t \mathrm{d}\phi(r,t) \exp(\mathrm{i}A_\mathrm{c}), \tag{3}$$

where the action A_c is related to the lagrangian density $\mathcal{L}$ by

$$A_\mathrm{c} = \int \mathcal{L}(\phi, \nabla\phi, \dot{\phi})\, \mathrm{d}^3 r\, \mathrm{d}t. \tag{4}$$

Again, the integration over $\mathrm{d}\phi(r,t)$ can be viewed as that over the eigenvalues of the operator $\phi_{\mathrm{op}}(r,t)$.

In the following we wish to explore some alternative possibilities. In place of treating time as a continuous parameter, we may ask:

(1) Can time be a discrete parameter (discrete time formulation)?

(2) Can time be discrete and treated as a bona fide dynamical variable (discrete mechanics)?

As we shall see, both possibilities can be realized in all stages of mechanics. In a relativistic field theory, the discrete time formulation becomes the discrete space–

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time formulation. In the corresponding discrete mechanics both space and time, in addition to being discrete, are treated as genuine dynamical variables. Because this approach involves a fundamental change in our concept of space–time, we will develop our ideas gradually: first in classical mechanics, then in nonrelativistic quantum mechanics and finally in relativistic quantum field theory. The result is that in this new formalism our usual idea of continuous time or continuous space–time structure will appear only as an approximation.

2. Classical mechanics. Consider the simple example of a nonrelativistic particle of unit mass moving in a potential $V(\boldsymbol{r})$. The usual lagrangian is (regarding time as continuous)

$$L = \tfrac{1}{2}\dot{\boldsymbol{r}}^2 - V(\boldsymbol{r}). \tag{5}$$

The action is then given by the integral (2) from the initial position $\boldsymbol{r}(t_0) = \boldsymbol{r}_0$ to the final $\boldsymbol{r}(t_f) = \boldsymbol{r}_f$.

In the discrete time formalism we replace the continuous function $\boldsymbol{r}(t)$ by a sequence of discrete values: $(\boldsymbol{r}_0, t_0), (\boldsymbol{r}_1, t_1), \ldots, (\boldsymbol{r}_{N+1}, t_{N+1})$, where $(\boldsymbol{r}_{N+1}, t_{N+1}) = (\boldsymbol{r}_f, t_f)$. The action (2) is then replaced by

$$A = \sum_{n=1}^{N+1} \left(\frac{1}{2} \frac{(\boldsymbol{r}_n - \boldsymbol{r}_{n-1})^2}{t_n - t_{n-1}} - \tfrac{1}{2}(t_n - t_{n-1})[V(\boldsymbol{r}_n) + V(\boldsymbol{r}_{n-1})] \right), \tag{6}$$

with $t_n > t_{n-1}$. Newton's equation of motion is derived by setting the derivative

$$\partial A / \partial \boldsymbol{r}_n = 0. \tag{7}$$

Keeping the initial and final configurations fixed, we have altogether N such equations:

$$\boldsymbol{v}_{n+1} - \boldsymbol{v}_n = -\tfrac{1}{2}(t_{n+1} - t_{n-1}) \nabla V(\boldsymbol{r}_n) \tag{8}$$

where $\boldsymbol{v}_n = (\boldsymbol{r}_n - \boldsymbol{r}_{n-1})/(t_n - t_{n-1})$ is the velocity. For any given time distribution $t_1, \ldots, t_N$, the positions, $\boldsymbol{r}_1, \ldots, \boldsymbol{r}_N$ can then be determined.

An ad hoc discrete time distribution $t_1, t_2, \ldots, t_N$ is clearly not satisfactory for a closed mechanical system. Thus, in discrete mechanics we require that the time distribution should also be determined by the same action (6). This can be achieved by treating t_n as dynamical variables, on the same basis as $\boldsymbol{r}_n$. By setting

$$\partial A / \partial t_n = 0, \tag{9}$$

we derive N additional equations:

$$E_n \equiv \tfrac{1}{2}\boldsymbol{v}_n^2 + \tfrac{1}{2}[V(\boldsymbol{r}_n) + V(\boldsymbol{r}_{n-1})] = E_{n+1}. \tag{10}$$

Thus, the entire set $(\boldsymbol{r}_1, t_1), \ldots, (\boldsymbol{r}_N, t_N)$ can be determined from (8) and (10).

In the continuum case, the energy conservation law is a consequence of Newton's equation of motion. In the discrete case, these two are independent. By treating t_n and $\boldsymbol{r}_n$ both as dynamical variables, we manage to employ the same action principle for their determination. In our formulation of discrete mechanics, there is a *fundamental length* or time l (in natural units). Given any time interval $T = t_f - t_0$, the total number N of discrete points that define the trajectory is given by the integer nearest T/l.

As illustrations, we may consider some special examples:

(i) $V = 0$. In this case (8) gives $\boldsymbol{v}_n$ = constant, which also satisfies (10). The trajectory of the particle is always a straight line, independent of the time distribution.

(ii) ∇V = constant. It can be readily verified that (8) and (10) yield equal spacings for the time intervals. The trajectory consists of N discrete points $(\boldsymbol{r}_1, t_1), \ldots, (\boldsymbol{r}_N, t_N)$ all lying on a parabola, similar to the continuum case. (For more complicated potentials, the time intervals are in general of varying lengths.)

3. Nonrelativistic quantum mechanics. As above, let the initial and final configurations be $(\boldsymbol{r}_0, t_0)$ and $(\boldsymbol{r}_f, t_f)$. In the discrete quantum mechanics, we assume that within the given time interval $T = t_f - t_0$, there can be maximally N measurements of the particle's configurations possible, where the ratio $N/T = l$ is the fundamental constant mentioned before. Each measurement yields a set of values $(\boldsymbol{r}_n, t_n)$ where $n = 1, 2, \ldots, N$. [The initial $(\boldsymbol{r}_0, t_0)$ can be regarded as the result of a previous experiment, and the final $(\boldsymbol{r}_f, t_f) = (\boldsymbol{r}_{N+1}, t_{N+1})$ as that of the $(N+1)$th measurement.] Without any loss of generality, we may arrange $t_1, \ldots, t_N$ into an ordered sequence: $t_0 < t_1 < \ldots < t_N < t_f$. The probability amplitude of observing such a set $(\boldsymbol{r}_1, t_1), \ldots, (\boldsymbol{r}_N, t_N)$ is proportional to $\exp(\mathrm{i}A)$ with A given by eq. (6).

Summing over all possible $(\boldsymbol{r}_1, t_1), \ldots, (\boldsymbol{r}_N, t_N)$ we obtain the overall quantum mechanical amplitude $\langle f|G|0\rangle$ leading from $(\boldsymbol{r}_0, t_0)$ to $(\boldsymbol{r}_f, t_f)$:

$$\langle f|G|0\rangle = \int J \exp(\mathrm{i}A) \prod_{n=1}^{N} \mathrm{d}t_n \, \mathrm{d}^3 \boldsymbol{r}_n, \tag{11}$$