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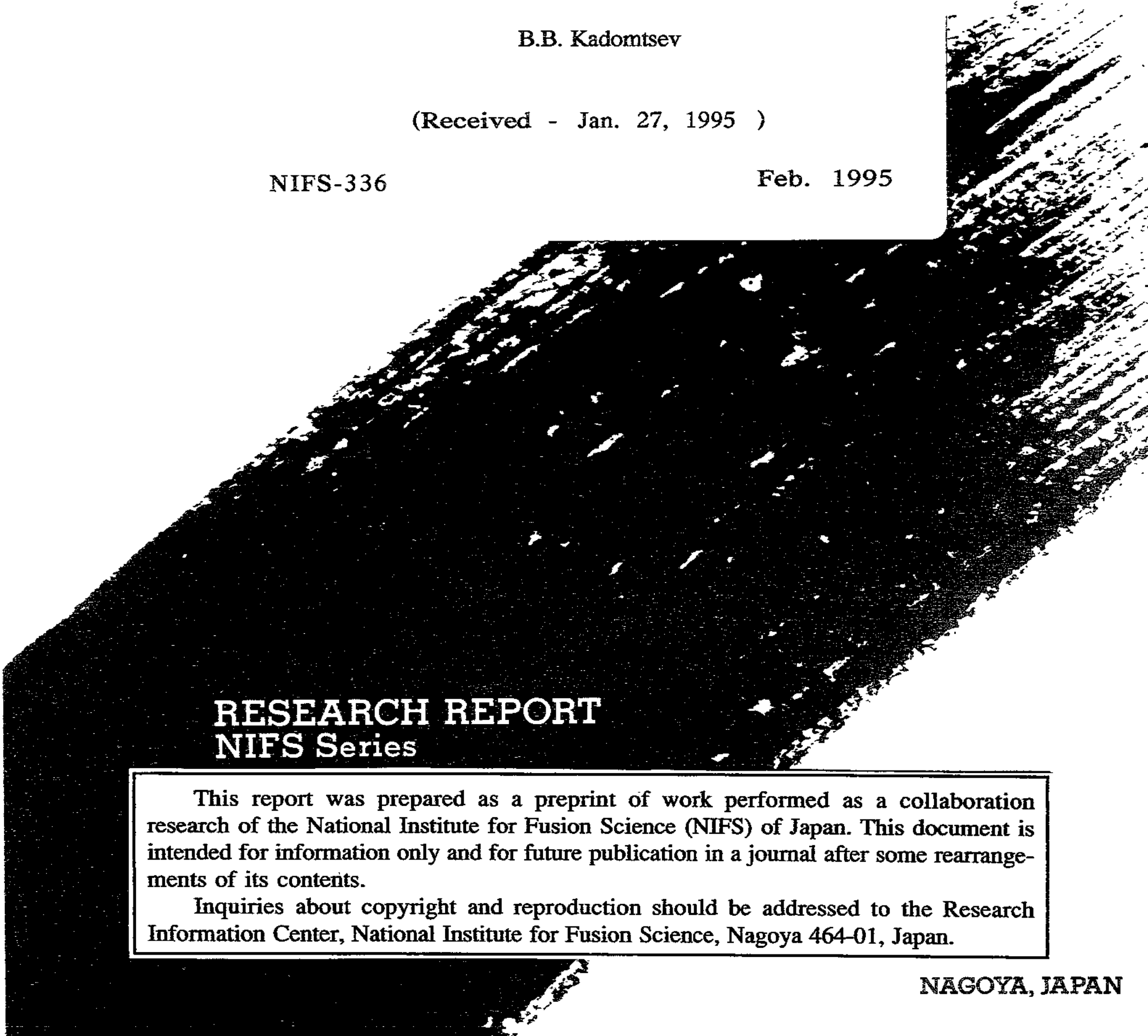

Quantum Telegragh : is it possible?

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Quantum Telegraph : is it possible?

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Abstract

The use of Einstein-Podolsky-Rosen (EPR) correlated microparticles for telecommunication purposes is considered from a new point of view. In spite of the fact that the usual nonlocality of EPR pairs is not controllable, the use of irreversible quantum systems opens new possibilities. A concrete scheme for a controllable correlated quantum system is considered. It might be used for non-wave type communication at not very large distances.

In their famous paper, Einstein, Podolsky and Rosen$^{1)}$ considered a thought experiment with two interacting microparticles. It is there shown that after interaction, at a time when the particles have become widely separated, a measurement of the state of one of the particles is immediately reflected in an effect on the state of the other. In other words, an apparently instantaneous collapse of the EPR wave function happens when one of two particles is detected. This feature was very surprising and some workers tried to investigate possibilities for its use for faster-than-light communication (see, for example$^{2)}$).

Investigation of the EPR paradox was facilitated by the subsequent proposition by Bohm$^{3)}$ of a variant of the EPR experiment in which atomic spin states were used. Bohm's thought experiment served as a model for the conceptual experiments. A further advancement in this area was Bell's$^{4)}$ discovery that the quantum-mechanical description can be tested against "hidden-variable" theories by measurement of certain inequalities which are valid in the "hidden-variable" approach but violated in quantum mechanics.

Bell's paper stimulated several real experiments on EPR-correlations. For such an experiment, Clauser, Horn, Shimony and Holt $^{5)}$ suggested the use of pairs of optical photons coming from atomic cascades. The results of experiments$^{6-8)}$ were shown to be compatible with the quantum mechanical predictions, violating Bell's inequality and confirming the existance of long-range correlations. In particular, the experiments by Aspect et al.$^{8-10)}$ demonstrate an excellent agreement with quantum mechanics and reject the theories obeying Bell's inequalities.

Faster-than-light correlations were definitely proved by the experiments of Aspect,Dalibard, and Roger$^{9)}$. However, this does not necessary imply that EPR pairs can be directly used for communication.

For communication purposes it is neccessary to accumulate a signal over many correlated EPR pairs. The corresponding response is described by the density matrix ρ.

When the two quantum systems A and B are considered, their joint density matrix ρ_{AB} depends on both A and B variables. The correlation between two systems exists only when their states are entangled, i.e. when ρ_{AB} can not be represented as a direct product $\rho_A \otimes \rho_B$. But even in this case, two correlated simple systems can not be used for communication based on the collapse of wave functions.

For the Bohm-type system with A and B particles, the behavior of particle B can be described[11)] by the reduced density matrix $\bar{\rho}_A = Tr_B \rho_{AB}$ where trace Tr_B is taken over the variables of system B. The reduced matrix $\bar{\rho}_A$ does not depend upon the variables of system B after this averaging procedure so the averaged results of measurements in system A do not depend upon the results of measurements in system B.

A similar situation takes place in more complicated systems. It was shown by Bussey[12)] that the temporal behavior of system A ceases to depend upon the evolution of system B after switching off their interaction. It is easy to see why this is so.

Let the interaction be "turned off" at time $t = 0$. Later on, the density matrix evolves causally and reversibly :

$$\rho_{AB}(t) = e^{-iHt/\hbar} \rho_{AB}(0) e^{iHt/\hbar}. \tag{1}$$

Here $H = H_A + H_B$ is the Hamiltonian for both systems in the absence of their interaction. Results of measurement of any operator U_A in system A is given by the relation $< U_A >= Tr U_A \rho_{AB} = Tr_A U_A \bar{\rho}_{AB}$, where $\bar{\rho}_A$ is the reduced density matrix :

$$\bar{\rho}_A = Tr_B \rho_{AB} = e^{-iH_At/\hbar} \left\{ Tr_B e^{-iH_Bt/\hbar} \rho_{AB}(0) e^{iH_Bt/\hbar} \right\} e^{iH_At/\hbar}. \tag{2}$$

This matrix is prescribed by the initial matrix value $\rho_{AB}(0)$ and therefore no manipulations with physical values in system B can influence system A.

Bussey's very elegant argument looks like a rigorous and complete proof of the impossibility of superluminal communication. In fact his argument is based on the simplifying assumption that the measurement device does not participate in the measurement process. This is not so in general. As Watanabe[13)] points out, the measuring apparatus must be involved in the measurement description to avoid contradictions.

A more clear analysis of this situation is provided by Shimony's[14)] paper. He has shown explicitly that the entangled quantum state of spatially separated particles is noncontrollable. This means there is no way to affect the statistics of measurement of system A by local operations performed upon system B. The final proof is based on more detailed analysis of the relation (2) taking into account the apparatus Hamiltonian H_M in addition to $H_A + H_B$. For this purpose it is sufficient to replace ρ_{AB} in (2) by ρ_{ABM} and H_B by $H_B + H_M$ and then to average ρ_{ABM} over B and M variables. The conclusion is again the same : superluminal communication based on quantum correlations is prohibited by quantum mechanics.

Shimony's analysis looks like a rigorous proof of the impossibility of superluminal communication between quantum systems A and B. But it turns out that even this proof has a "hole in the net". His analysis is based on the assumption that apparatus M is also described by quantum mechanics with the Hamiltonian H_M. This means that the apparatus behavior must be completely reversible. But real quantum-mechanical measurements are of a somewhat different nature. They are usually produced with the help of an irreversible device surrounded by the classical external world. That is why the measurement description demands a more delicate approach.

This problem is not new. Starting from the well known discussion between Bohr and Einstein, the theory of measurement in quantum mechanics continues to be a matter of different and controversial points of view. Without a detailed discussion of this problem, it is sufficient to point out that for an irreversible apparatus evolution the total density matrix ρ_{ABM} evolution deviates from that of type (1) with the total Hamiltonian H : dissipation destroys the unitarity of the evolution operator.

Therefore upon time reversal we obtain :

$$\rho_{AB}(t \to +0) = e^{\imath(H_A+H_B)t/\hbar}\rho_{AB}(t)e^{-\imath(H_A+H_B)t/\hbar} \neq \rho_{AB}(0). \qquad (3)$$

In other words the initial value $\rho_{AB}(0)$ can not be obtained by a simple backward transformation of the density matrix when irreversible processes are involved.

In the general case, the inequality (3) can lead to a similar relation for the reduced matrix $\bar{\rho}_A = Tr_{BM}\rho_{ABM}$. If so the irreversible evolution of apparatus M measuring the B system can lead both to a collapse of the A system wave function and to a change of its reduced matrix $\bar{\rho}_A$ as well. But the apparatus state or at least the rate of its irreversible evolution can be controlled externally. Thus the possibility for an arrangement of some equipment to communicate faster-that-light via quantum correlations is not excluded.

Let us now consider this possibility in more detail. We have to understand what kind of irreversible system might be used for communication via quantum correlations (for simplicity let us call such an arrangement a "quantum telegraph").

It is easy to see that controlled nonlocality can not be realized in the case when both systems A and B have discrete sets of eigenstates. The pure state in this case is $\psi = \sum\limits_i c_i u_i$, where u_i is the i th eigenstate function. The corresponding density matrix is $\rho = |\psi >< \psi| = \sum\limits_{ij} c_i c_j^* \; |u_i >< u_j|$. An irreversible dissipation in this case leads simply to erasing the phase correlations so that $\rho \rightarrow \sum\limits_i |c_i|^2 |u_i >< u_i|$. Mathematically this wave function reduction can be described with the help of many Hilbert-space formalism for apparatus as was suggested by Machida and Namiki$^{15)}$.

Furthermore, any change in apparatus arrangement corresponds to unitary transformation changing the eigenstate basis from the set u_i to another set v_i.

It easy to see that after a phase randomization in the new basis we again obtain the matrix $\rho = \sum\limits_i^2 |c_i|^2 |v_i >< v_i|$ with the same $|c_i|^2$, (perhaps renumbered).

Thus for communication purposes at least one of the two systems, say B, must be continuous, i.e. not discrete. For instance, it might be a free particle.

To be more concrete we shall discuss the Sokolov et al.$^{16)}$ experimental arrangement in which a new irreversible quantum effect was discovered.

This effect was explained by B. Kadomtsev and M. Kadomtsev$^{17)}$ as produced by EPR-pair correlations. Since a further experimental check$^{18)}$ of this idea was in good agreement with theoretical calculations we are tempted to consider this arrangement as a candidate for the quantum telegraph$^{19)}$.

The Sokolov effect manifests itself as a small increment of the $2P$ amplitude in a metastable $2S$ hydrogen atom after its transit near a metal sample. This effect was quite surprising and required a nonorthodox explanation. All attempts to explain it by the dynamic interaction of the atom with fluctuating electric fields or with the image fields in the metal are unsuccessful while an explanation based on quantum microcorrelations$^{17)}$ gives reasonable agreement with experiment$^{18)}$.

The physics of the exited atom interaction with a conduction electron in the metal is shown in Fig. 1. The wave packet of a conduction free electron in its initial state I_e is moving towards the metal surface. After reflection from the surface this electron moves inside the metal and its wave packet looks as indicated by F_e in Fig. 1. The electron-atom interaction takes place when the electron is in a thin surface layer of thickness $l \sim n^{-1/3}$ where electrons do not screen each other (n is the conduction electron density). During the flight-time of the electron wave packet across this layer the excited hydrogen atom A moves along the x-axis from the initial I_A to the final state F_A. The nondiagonal dipole component of the $S \rightarrow P$ transition for the atom is directed along the same x-axis.

We see that the electron and the atom are in an entangled state because different positions of the moving atom correspond to different parts of the electron wave packet.

We can sum up the inputs from all the electrons in the metal taking into account the ion metal lattice input as well. The net result will be almost zero and can be expressed in terms of the macroscopic electric field, which is very low (thermal fluctuations of this electric field are practically zero).

But the story of the electron is not finished with the specification of the state F_e in Fig. 1. The electron penetrates inside the metal core where the coherence of state F_e is destroyed due to interactions with lattice imperfections, impurities and other electrons. We can say that an electron in the metal is "continously measured" by its environment[20]. As a result its wave function experiences a chain of subsequent collapses. The main question is whether or not these collapses follow exactly a $|\psi|^2$ probability distribution. We shall argue that they do not follow this law exactly. For this we have to consider the "free-electron" behavior in more detail.

Let us consider the electron interaction with impurities, lattice defects and phonons all of which can be considered heavy quasiparticles, in that they scatter electrons almost elastically. Phonons are able to transfer the information on collisions to very far distances where the information is "forgotten" completely (this process resembles the measurement).

A similar effect of particle-environment interaction was studied by Unruh and Zurek[21] on an exactly solvable model, a harmonic oscillator interacting with a one-dimensional massless scalar field. It was shown that the density matrix decays rapidly to a mixture of "approximate eigenstates" resembling the monitoring of the particle by the environment. The effect of "collapses" indicated by their numerical simulations is of most interest for us. In the case of their "upside down" oscillator the wave function was transformed into a mixture of coherent Gaussian states resembling a mixture of coherent pieces of the wave packet.

In our case an electron interacts with phonons in a similar way in addition to being scattered by lattice imperfections. This scattering can be considered as a random walk in some potential $U(\vec{r})$. Let us assume that the potential $U(\vec{r})$ is a slowly varying function of $\vec{r}$. Let us choose $\vec{r}_0 = <\vec{r}>$ as the coordinate of the wave packet center. Then we can represent $U(\vec{r})$ in the proper frame of reference as follows : $U(\vec{r}) = U(\vec{r}_0) - \vec{F}(\vec{r} - \vec{r}_0) + \sum_i k_i (x_i - x_{0i})^2$, where higher order terms are ignored. The term with $\vec{F}$ in this expression describes the stochastic motion of a classical particle with coordinate $\vec{r}_0$ and the next term corresponds to "quasielastic" forces. If the three elasticity coefficients k_i have random values then there are eight possible sign combinations. In seven of the eight cases at least one of the three eight k_i values is negative. Along the corresponding direction we have an inverted pendulum potential, so that the electron wave function interacting with phonons has a tendency to be split in several pieces in this direction. In other words we have the so called ergodically amplified collapse. We intend to show that such a collapse in our case does not exactly follow a $|\psi|^2$ probability distribution law.

When the wave function is collapsing into a smaller size packet the electron kinetic energy increases by an amount $\hbar^2/m\Lambda^2$ where Λ - is the packet size after collapse. This increase arises due to the uncertainty principle. But collisions with phonons and lattice imperfections are almost elastic ones. To conserve the energy value the electron velocity u has to be slightly decreased by an amount Δu, so that $mu\ \Delta u \sim \hbar/m\Lambda^2$. In other words the vanishing of the nondiagonal ρ matrix terms must be accompanied by the restoration of the diagonal equilibrium distribution. We can say that the collapse must preferentially select the slower part of the electron wave packet.

But this part has a slightly different matrix element for the electron-atom interaction as compared with its value before a collapse. Thus the collapse is immediately accompanied by a corresponding response in the atom, the second partner of EPR-pair, resembling a small increment of the P-amplitude value. Summing up all increments from all interacting electrons we obtain a definite detectable increase of the P-amplitude. Experiments show that the nonsymmetry value is of order of 10^{-2}.

The Sokolov effect is a completely new type of irreversible interaction in the microworld. If we accept the above explanation of the Sokolov effect as correct we can readly imagine a "quantum telegraph" based on this effect shown schematically in Fig. 2. Once again the metastable $2S$ hydrogen atom flies above a sample M. If this sample is made of a very pure metal, semimetal, or semiconductor, then at liquid helium temperature it is possible to increase the mean free path λ of a conduction electron up to value ~ 1 cm. If the sample and its boundaries are perfect the electron can fly without wave function collapses down to a scattering region R. The collapses in this region would then produce instantaneous $2P$ amplitude increases in the atom situated at position A'.

The collapses in the R region can be controlled by inhomogeneities changed by external deformations or by an external magnetic field if the R region contains magnetic scattering centers.

At the present time, the new principle of information transfer is more interesting than the device itself. Since it is based on the collapse of the wave function without any direct motion of matter (during the message transmission) or wave propagation there is no propagating signal which could be intercepted by somebody else. Moreover the speed of information transfer is not limited by the velocity of light, so that faster-than-light communication could be realized. As discussed in the paper[19) such superluminal communication does not contradict relativity theory. More precisely, any quantum correlations for superluminal communication must be prepared well before the message transmission so that causality breaking is forbidden. "An instantaneous call" simply uses the information stored by the previous preparation. Nevertheless this could be really faster-than-light communication.

In conclusion, communication via quantum correlations, the "quantum telegraph" , seems to be not prohibited by quantum mechanics if irreversible processes are involved. Such a communication can be "faster-than-light" being not based on matter transfer or wave propagation. Superluminal communication via correlations prepared previously does not contradict causality or the relativity principle in its dynamical form. Since a very small, of the order one percent, deviation from the $p \sim |\psi|^2$ probability distribution law can lead to a sizable effect using the Sokolov experimental arrangement additional research activity on quantum correlation information transfer should be encouraged.

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Figure Captions

Fig. 1 Schematic picture of the atom-electron interaction. See text for more detailed expanation.

Fig. 2 Schematic representation of the quantam telegraph based on the Sokolov effect. The sample M is made of a pure metal, a semimetal or a semiconductor. Its conduction electrons fly, after the interaction with an excited atom A, away from the interaction surface to a scattering region R. Their wave functions collapse in this region and simultaneously an atom located at the A' point at a distance L from the sample acquires a $2P$ amplitude.

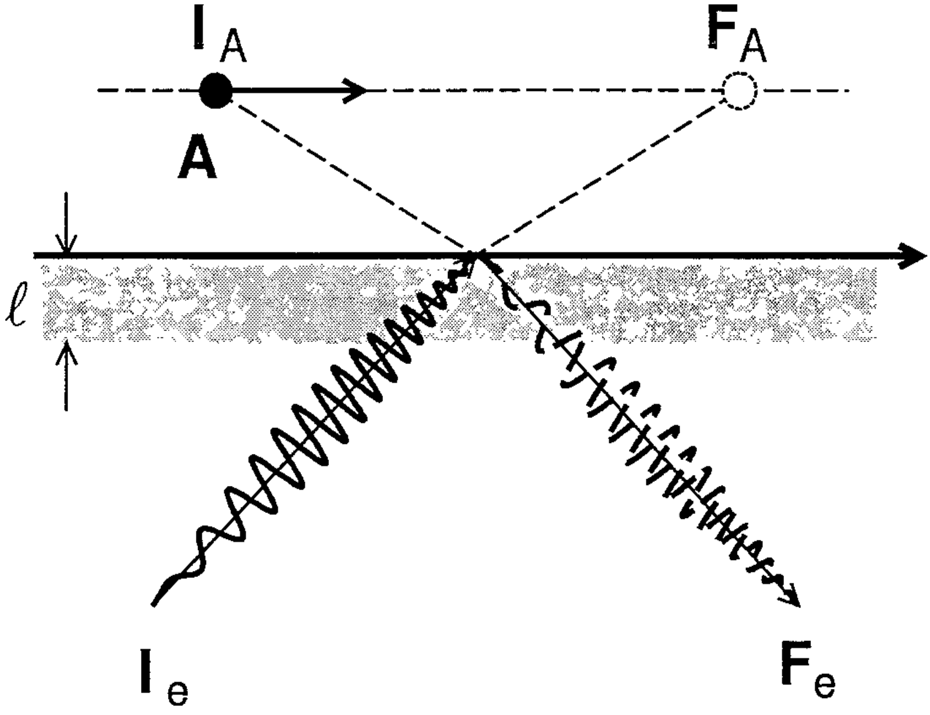

Fig. 1

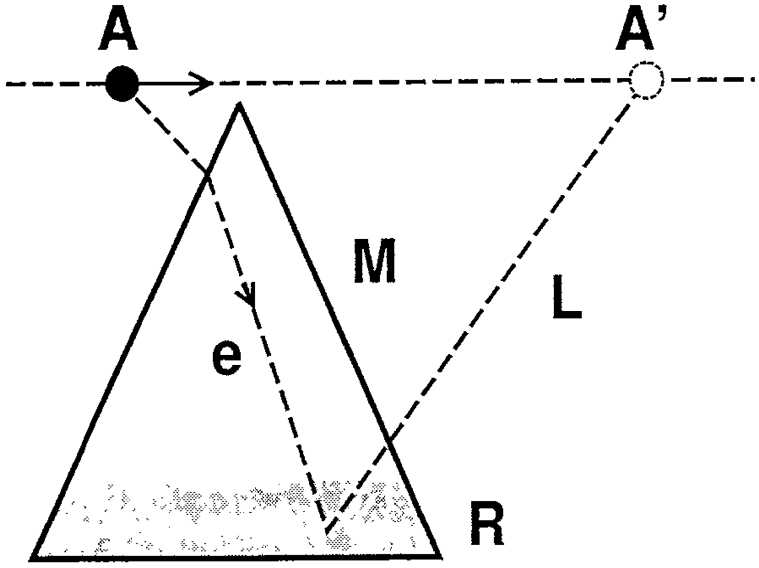

Fig. 2

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