An Experimental Test of the EPR Paradox (*).

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In recent years there has been a revival of interest in the foundations of quantum mechanics either on the theoretical side or on experiments aimed at testing some controversial predictions of quantum mechanics as, for instance, those related to the so-called EPR paradox (1). (See the recent review articles quoted under ref. (2,3) and references quoted therein.)

It seems that many of the well-known paradoxes (4) are connected with the assumed existence of mixtures of the second kind or improper mixtures (5).

Moreover it has been shown (6) that such mixtures are incompatible with the existence of local hidden variables as defined in ref. (7-9).

Some authors, induced by different motivations, have suggested experiments able to discriminate between mixtures of the two kinds.

An experiment (10,11) concerns the measurement of polarization correlation of the two photons coming from the annihilation of positron-electron pairs in the singlet state.

In this case if we could measure the correlation function by means of ideal polarizers we should obtain, in the general case,

$$W(\varphi) = k \sin^2 \varphi + (1-k) \cos^2 \varphi \,, \tag{1}$$

(*) Preliminary results of this experiment have been presented at the *III International Conference on Positron Annihilation, Helsinki, August 7-9, 1973.*

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(1) A. EINSTEIN, B. PODOLSKY and N. ROSEN: *Phys. Rev.*, **47**, 777 (1953).

(2) V. CAPASSO, D. FORTUNATO and F. SELLERI: *Riv. Nuovo Cimento*, **2**, 149 (1970).

(3) A. I. AKHIEZER and R. V. POLOVIN: *Sov. Phys. Uspekhi*, **15**, 500 (1973).

(4) J. M. JAUCH: *Foundations of Quantum Mechanics* (Reading, Mass., 1968), p. 185.

(5) B. D'ESPAGNAT: *Conception de la physique contemporaine* (Paris, 1965).

(6) V. CAPASSO, D. FORTUNATO and F. SELLERI: *Intern. Journ. Theor. Phys.*, **7**, 319 (1973) and private communication.

(7) J. S. BELL: *Physics*, **1**, 195 (1965).

(8) J. F. CLAUSER, R. A. HOLT, M. A. HORNE and A. SHIMONY: *Phys. Rev. Lett.*, **23**, 880 (1969).

(9) F. SELLERI: *Lett. Nuovo Cimento*, **3**, 581 (1972).

(10) D. BOHM and Y. AHARANOV: *Phys. Rev.*, **108**, 1070 (1957).

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where φ is the angle between the relative orientation of the polarizers and k is the correlation constant introduced in ref. (11) which expresses, in our case, the probability of observing the photon pair with orthogonal linear polarizations.

In case of mixtures of the second kind the quantity k will be unity, while in case of mixtures of the first kind we have (10-12) $k=\frac{3}{4}$.

More generally if we pretend that (1) be compatible with Bell's inequality (7) in the more general form given in ref. (9), we find out the relation

$$\frac{1}{7}\approx\frac{1}{2}-\frac{\sqrt{2}}{4}\leqslant k\leqslant\frac{1}{2}+\frac{\sqrt{2}}{4}\approx\frac{6}{7}.$$

Obviously for the 510 keV annihilation quanta we do not have ideal polarizers and we must resort to Compton scatterers in order to analyse the polarization correlation in an indirect way as will be described in the following (see also ref. (13)).

However if we assume as empirically valid the Klein-Nishina formula for the Compton-scattering cross-section for polarized radiation and use the method of the partial-polarization analysis (13), we find for the direction correlation function of the coincident scattered radiation

$$W(\theta_1,\theta_2,\varphi)\propto K_1^2K_2^2\{\gamma_1\gamma_2-\gamma_1\sin^2\theta_2-\gamma_2\sin^2\theta_1+ + 2\sin^2\theta_1\sin^2\theta_2[(2k-1)\sin^2\varphi+1-k]\}, \tag{2}$$

where $\gamma_i=K_i/K_0+K_0/K_i$, θ_1 and θ_2 are the scattering angles and φ the azimuthal angle (see Fig. 1), K_0 and K_i ingoing and outgoing wave numbers, respectively.

Relation (2) reduces to the standard result of ref. (13) for $k=1$ (mixtures of 2-nd kind) and to the resut of ref. (10) for $k=\frac{3}{4}$ (mixtures of the 1-st kind).

The schematic diagram of the experimental arrangement is shown in Fig. 1.

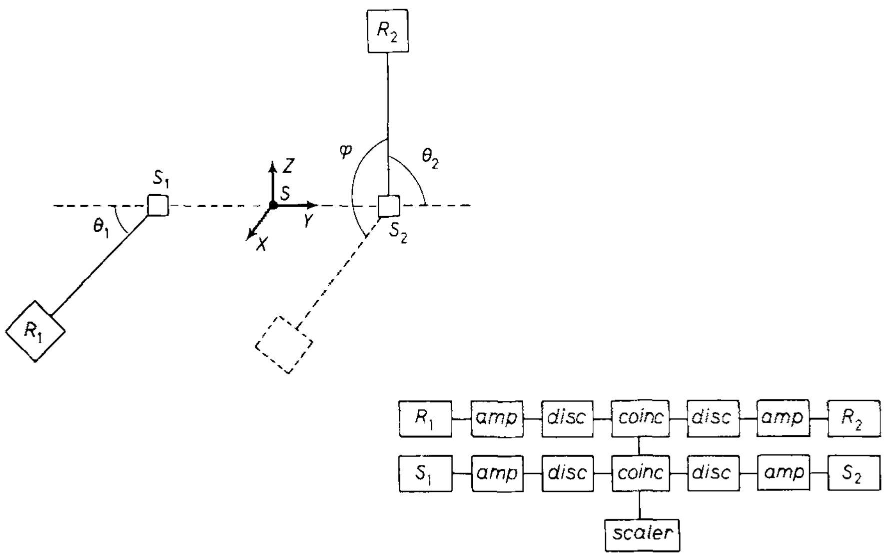

Fig. 1. – Schematic diagram of experimental arrangement.

(12) The value $k=\frac{3}{4}$ given in ref. (11) refers to the case of particles with spin $\frac{1}{2}$.

(13) H. S. SNYDER, S. PASTERNACK and J. HORNBOSTEL: *Phys. Rev.*, **73**, 440 (1948).

We measure the coincidence counting rates $N(\theta_1, \theta_2, \varphi)$ between the four scintillators S_1, S_2, R_1, R_2. S_1 and S_2 are plastic scintillators (NE 202) which act as Compton scatterers for the radiation coming from the source S, which consists of a ^{22}Na positron source enclosed in a plexiglass container acting as annihilator; R_1 and R_2 are NaI(Tl) scintillators. We take quadruple coincidences in order to improve the signal to noise ratio (≈ 30) and the coincidence resolving time (≈ 30 ns).

In order to relate the counting rate $N(\theta_1, \theta_2, \varphi)$ to the correlation function defined in (2) we must take into account the effects of finite geometry. This is done, in our case, by means of a Monte Carlo computation which also corrects for absorption in the scatterers and in the detectors and for instrumental thresholds. Contribution from the triplet state should be negligible.

Details of the experimental apparatus and of the Monte Carlo Fortran program will be given elsewhere.

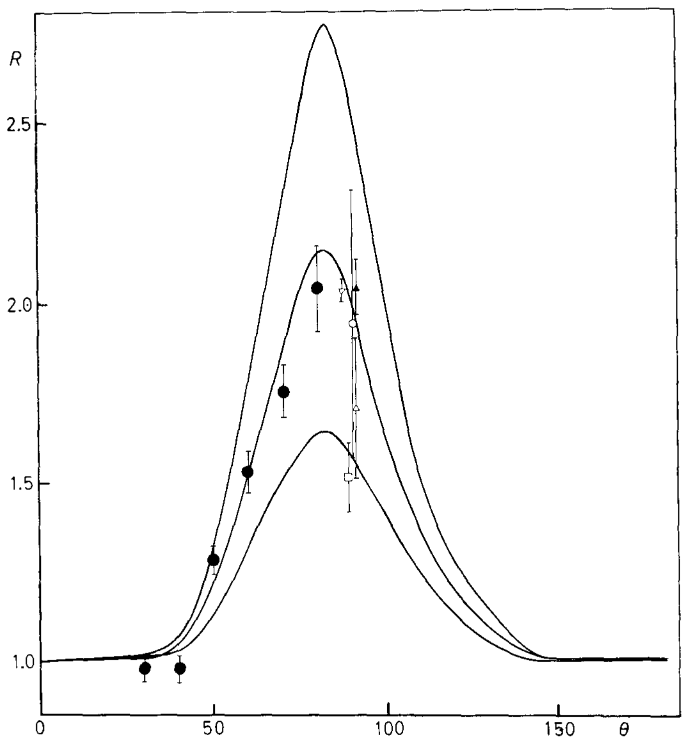

Fig. 2. – Anisotropy ratio as a function of the scattering angle. Upper curve: theoretical prevision correct for finite geometry (see text) for 2-nd–kind mixture. Lower curve: theoretical prevision corrected for finite geometry (see text) for 1-st–kind mixture. Intermediate curve: theoretical prevision corrected for finite geometry (see text) for Bell's limit. • Present results, ○ ref. ([14]), □ ref. ([15]), ▲ ref. ([16]), △ ref. ([17]), ▽ ref. ([18]).

([14]) E. BLEULER and H. L. BRANDT: *Phys. Rev.*, **73**, 1398 (1948).
([15]) R. C. HANNA: *Nature*, **142**, 332 (1948).
([16]) C. S. WU and I. SHAKNOV: *Phys. Rev.*, **77**, 136 (1950).
([17]) N. A. VLASOV: *Sov. Akad. Nauk. SSSR*, **14**, 337 (1950).
([18]) L. KASDAY: *Rendiconti S.I.F.*, Course IL, edited by B. D'ESPAGNAT (New York, 1971).

In Fig. 2 the experimental ratio $N(\theta, \theta, 90°)/N(\theta, \theta, 0°)$ is reported together with the theoretical predictions corrected for finite geometry. The upper curve corresponds to $k=1$ (mixture of 2-nd kind), the lower curve corresponds to $k=\frac{3}{4}$ (mixture of 1-st kind), the intermediate curve to $k=\frac{6}{7}$ (Bell's limit).

Our experimental results are consistent with previous measurements taken at $\theta_1=\theta_2=90°$ (see ref. ([14-18])).

We cannot, at present, effect measurements at this angle because of some absorption in the lead shielding, however all the experimental data are consistent with the curve corresponding to the Bell's limit for the existence of local hidden variables ([7,9]).

The same conclusion can be seen from Fig. 3 where we have reported the ratio $N(60°, 60°, \varphi)/N(60°, 60°, 0°)$.

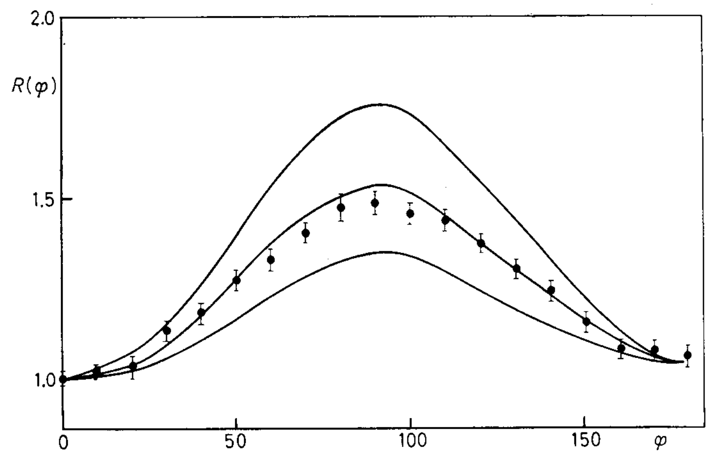

Fig. 3. – Normalized direction correlation as a function of the azimuthal angle. Legend as in Fig. 2.

These results seem surprising because they do not give a clear answer for discriminating between mixtures of the two kinds, besides they do not give a decisive answer for the existence of local hidden variables because they stay, within the experimental uncertainties, just on the Bell's limit.

In order to clarify this point we have measured the anisotropy ratio at different distances of the scatterers S_1, S_2 from the source S (see Fig. 1).

In fact, the hypothesis has been advanced ([10,11]) that the state of the two correlated photons can pass continuously from a second kind to a first kind mixture because of interaction with the surrounding.

This effect might be displayed by arrangements with larger and/or unequal flight paths for the two photons; as, for instance, much larger than the coherence length of the photons ([18]).

In our case the photons should have a coherence length of ≈ 7 cm for the 70% of cases and of ≈ 47 cm for the remaining 30%.

In Fig. 4 the ratio $N(60°, 60°, 90°)/N(60°, 60°, 0°)$ is plotted as a function of the difference in the flight paths of the two photons.

Measurements have been taken at 5.5 cm, 10 cm and 20 cm, with symmetrical flight paths and at (6 cm, 13 cm) and (5.5 cm, 34 cm) with asymmetrical flight paths.

This last result seems to confirm the hypothesis of effects connected with the distance of the scatterers from the source. In fact this last experimental point (Fig. 4) agrees with the expectation for mixtures of the first kind.

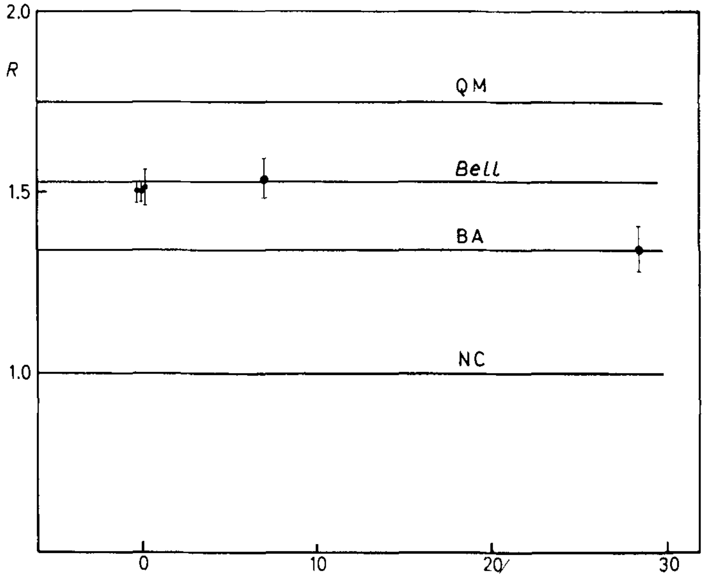

Fig. 4. – Anisotropy ratio at $\theta_1 = \theta_2 = 60°$ as a function of the difference in the flight paths of the two photons (see text).

Of course this result cannot tell if the effect depends on the difference of the flight paths or simply on the relative distance of the scattering events.

This effect might explain the agreement with what is expected for mixtures of the second kind of a recent similar experiment performed with a calcium atomic cascade (19). In fact, in that case, one has a coherence length of ≈ 150 cm and the postulated transition to a mixture of the first kind might be observed at distances much larger than used hereto.

We are planning a new experimental arrangement in order to study in detail this question and, in the mean time, improve in statistics and in geometry and, obviously, also further check the absence of any systematic errors owing to the relevance of the reported result.

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(19) S. J. FREEDMAN and J. F. CLAUSER: *Phys. Rev. Lett.*, **28**, 938 (1972).