IL NUOVO CIMENTO VOL. 33 B, N. 2 11 Giugno 1976

Measurement of the Circular-Polarization Correlation in Photons from an Atomic Cascade (*).

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(ricevuto il 30 Gennaio 1976)

Summary. — The results of an experiment are reported which measured the circular-polarization correlation of photons emitted in the $9\,^1P_1 \rightarrow 7\,^3S_1 \rightarrow 6\,^3P_0$ cascade of atomic mercury. The results appear to be in general agreement with the predictions of quantum theory. They are compared with the predictions by several inequalities derived for various alternatives to quantum theory.

1. – Introduction.

Polarization correlations (PC's) have been important to the study of the foundations of quantum mechanics ever since the introduction by BOHM (1) of a *gedankenexperiment* to illustrate the EPR paradox. Relevant experimental evidence, albeit scant, was first discussed by BOHM and AHARONOV (2), in an effort to refute an hypothesis originally considered by FURRY (3). More recently, the discussion of Bell's theorem (4) has brought PC measurements

(*) Work supported by the Energy Research and Development Administration.

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(1) D. BOHM: *Quantum Theory* (Englewood Cliffs, N. J., 1951), p. 614.

(2) D. BOHM and Y. AHARONOV: *Phys. Rev.*, **108**, 1070 (1957).

(3) W. H. FURRY: *Phys. Rev.*, **49**, 393, 476 (1936).

(4) J. S. BELL: *Physics*, **1**, 195 (1965); see also J. F. CLAUSER and M. A. HORNE: *Phys. Rev. D*, **10**, 526 (1974), and references therein.

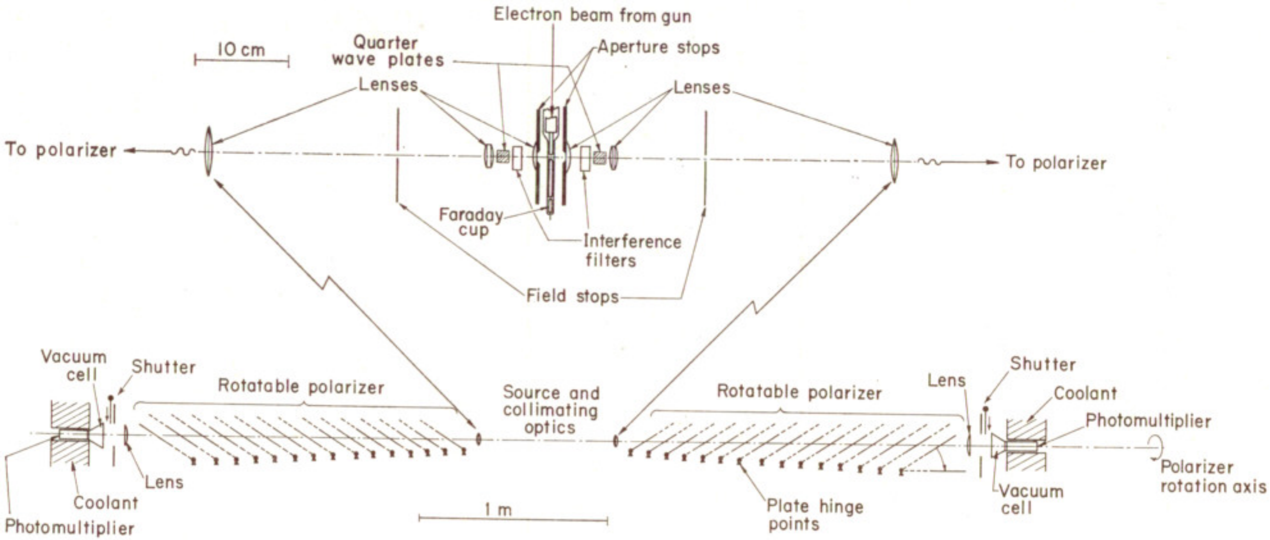

Fig. 1. – Diagram of the apparatus. Upper drawing depicts collimating optics, wavelength filters, quarter-wave plates, and source lamp containing electron gun and ^{202}Hg vapor. Lower drawing shows rotatable polarizer assemblies and photomultipliers. Polarizers are removed from optical path by folding them about hinge points.

into even stronger focus. None the less, the only PC measurements heretofore performed have used linear polarizations; circular PC measurements have been largely ignored. In this paper we report measurements of both linear and circular PC's, and compare these with the predictions made by various alternatives to the usual quantum theory.

The measurements were made on photon pairs generated in the $9\,^1P_1 \to 7\,^3S_1 \to 6\,^3P_0$ cascade of ^{202}Hg. The wavelengths of these transitions were $\lambda_1 = 5676$ Å and $\lambda_2 = 4046$ Å; the excitation was by electron impact. The excited atoms were viewed by two symmetrically placed optical systems each containing a rotatable linear polarizer, a wavelength filter and a single-photon detector (see fig. 1). In another publication [5] a more complete description of the apparatus was given, along with the comparison of the linear-polarization results with a generalization of Bell's inequality [6]. For the circular polarization runs, the basic apparatus was modified by installation of quarter-wave plates ahead of the linear polarizers. The rate of coincidence counts $R(\varphi_1, \varphi_2)$ for two single-photon detections was measured as a function of the angles φ_1 and φ_2 between the orientations of the inserted linear polarizers and the electron beam axis. It was compared with the coincidence rate R_0 measured with both polarizers removed but with the quarter-wave plates still in place. If we denote by ξ_1 and ξ_2 the retardations of the quarter-wave plates, then the quantum-mechanical prediction for the ratio of these rates is given by

$$(1)\qquad R(\varphi_1, \varphi_2)/R_0 = R(\varphi_1 - \varphi_2)/R_0 = \tfrac{1}{4}(\varepsilon_M^1 + \varepsilon_m^1)(\varepsilon_M^2 + \varepsilon_m^1) + \tfrac{1}{4}(\varepsilon_M^1 - \varepsilon_m^1)\cdot \\ \cdot(\varepsilon_M^2 - \varepsilon_m^2)F_2 \cos(\xi_1 - \xi_2)\cos 2(\varphi_1 - \varphi_2)\,.$$

Here ε_M^i (ε_m^i) is the transmission of the i-th polarizer for light linearly polarized parallel (perpendicular) to the polarizer axis, and $F_2 = 0.874$ is a function of the detector solid angles and the abundances of residual ^{199}Hg and ^{201}Hg in the source lamp, discussed previously.

The quarter-wave plates consisted of bars of compressed commercial grade quartz. The compression directions of both of these were perpendicular to the electron beam and optic axis. In an attempt to maintain constant stress, the compression was applied by hydraulic slave cylinders. The master cylinders were then loaded by weights until $\frac{1}{4}$-wave retardation was obtained at the wavelength of the associated wavelength filter. However, considerable improvement in the stability, uniformity and accuracy of these is undoubtedly possible; a drift $\pm 8.5°$ was typical for each plate over the necessarily long periods between calibrations.

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(5) J. F. CLAUSER: to be published (*Phys. Rev. Lett.*, 1976).

(6) J. F. CLAUSER, M. A. HORNE, A. SHIMONY and R. A. HOLT: *Phys. Rev. Lett.*, **23**, 880 (1969); S. J. FREEDMAN and J. F. CLAUSER: *Phys. Rev. Lett.*, **28**, 938 (1972).

2. – Results as a function of $\varphi_1 - \varphi_2$

Equation (1) implies that for $\xi_1 = \xi_2 = 90°$ the predictions for arbitrary orientations of the linear polarizers are identical to those for the linear PC measurements described earlier, in which the quarter-wave plates were absent, *i.e.* $\xi_1 = \xi_2 = 0$. Data were taken at various relative angles $\varphi = \varphi_1 - \varphi_2$ between the inserted polarizers, averaged over rotations of the pair. The results, shown in fig. 2, were integrated over a running time of more than 90 h. Unfortunately,

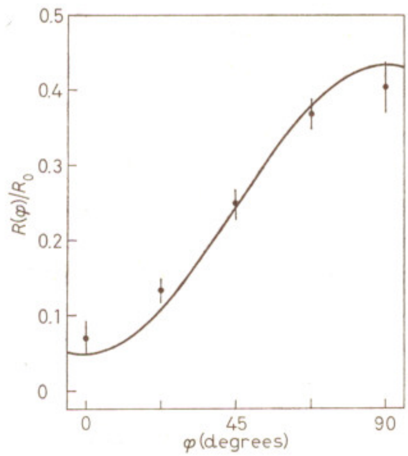

Fig. 2. – Coincidence rate as a function of relative polarizer orientation angle $\varphi = \varphi_1 - \varphi_2$, normalized to coincidence rate with polarizers removed.

the marginal quarter-wave plate stability prevents highly accurate comparisons with the quantum-mechanical prediction. If one assumes the worse case systematic retardation error to have prevailed for the experiment, *i.e.* $\xi_1 - \xi_2 \approx 19°$, one calculates from eq. (1) the prediction plotted as the solid line on fig. 2. Here we have used the measured average polarizer efficiencies for these runs ($\varepsilon^1_{M,m} \approx 0.975, 0.011$) and ($\varepsilon^2_{m,m} \approx 0.972, 0.0084$). The appropriate generalization of Bell's inequality can be written [6]

$$\delta = |R(22.5°)/R_0 - R(67.5°)/R_0| - \tfrac{1}{4} \leqslant 0 \,. \tag{2}$$

For comparison with the present data we have $\delta_{\text{expt}} = -0.015 \pm 0.025$ and $\delta_{\text{QM}} = 0.002$. The retardation errors were evidently sufficiently large for this system that the quantum-mechanical predictions differ little from the generalized Bell-inequality prediction. No actual violation of this inequality can be sought here. None the less, the predictions by eq. (1) for this case appear at least to be approximately verified.

3. – Furry's hypothesis and state vectors of the second kind.

The quantum-mechanical predictions for the system are difficult to understand because they require a nonlocal interference between the separated photons. A natural alternative is to suggest that the interference terms weaken and eventually vanish as the systems become remote from each other. Such a hypothesis was first considered by FURRY (3), and it has been reconsidered frequently since then. BOHM and AHARONOV (2) exploited the results of WU and SHAKNOV, and subsequently CLAUSER (7) exploited the results of KOCHER and COMMINS to refute this hypothesis. For the above system, CLAUSER (7) showed that the following inequality is valid if Furry's hypothesis holds:

$$\frac{R(0^\circ)}{R(90^\circ)} \geqslant \frac{(\varepsilon_M^1+\varepsilon_m^1)(\varepsilon_M^2+\varepsilon_m^2)-\frac{1}{2}(\varepsilon_M^1-\varepsilon_m^1)(\varepsilon_M^2-\varepsilon_m^2)}{(\varepsilon_M^1+\varepsilon_m^1)(\varepsilon_M^2+\varepsilon_m^2)+\frac{1}{2}(\varepsilon_M^1-\varepsilon_m^1)(\varepsilon_M^2-\varepsilon_m^2)} \equiv r_F\,. \tag{3}$$

On the other hand, eq. (1) predicts

$$\frac{R(0^\circ)}{R(90^\circ)} = \frac{(\varepsilon_M^1+\varepsilon_m^1)(\varepsilon_M^2+\varepsilon_m^2)-(\varepsilon_M^1-\varepsilon_m^1)(\varepsilon_M^2-\varepsilon_m^2)F_2\cos(\xi_1-\xi_2)}{(\varepsilon_M^1+\varepsilon_m^1)(\varepsilon_M^2+\varepsilon_m^2)+(\varepsilon_M^1-\varepsilon_m^1)(\varepsilon_M^2-\varepsilon_m^2)F_2\cos(\xi_1-\xi_2)} \equiv r_{QM}\,. \tag{4}$$

For $\xi_1=\xi_2$, eq. (4) is incompatible with (3). Moreover, this is true whether or not we have $\xi_1=\xi_2=0$ or $\xi_1=\xi_2=90^\circ$.

The values of the linear-polarization correlation presented earlier (5) can be used to evaluate $R(0^\circ)/R(90^\circ)$ for the $\xi_{1,2}=0$ case, and the values from fig. 2 can be used for the $\xi_{1,2}=90^\circ$ case. Such a comparison is made in table I. As usual, all data are averaged over common rotations of the polarizer pair. In both cases, the hypothesis is clearly refuted.

TABLE I. *Values for inequality* (3).

ξ_1, ξ_2	$R(0^\circ)/R_0$	$R(90^\circ)/R_0$	r_F	r_{QM}	r_{expt}
0°	0.010 ± 0.015	0.468 ± 0.020	$\geqslant 0.351$	0.082	0.021 ± 0.033
$\approx 90^\circ$	0.070 ± 0.022	0.404 ± 0.034	$\geqslant 0.347$	0.011	0.017 ± 0.057

Under another guise, Furry's hypothesis was recently reconsidered by JAUCH and SELLERI (8). They defined « state vectors of the second type » to be those requiring such nonlocal quantum-mechanical interference. They

(7) J. F. CLAUSER: *Phys. Rev. A*, **6**, 49 (1972).

(8) J. M. JAUCH: *Rendiconti S.I.F.*, Course XLIX, edited by B. D'ESPAGNAT (New York, N. Y., 1971), p. 20; F. SELLERI: *Rendiconti S.I.F.*, Course XLIX, edited by B. D'ESPAGNAT (New York, N. Y., 1971), p. 398.

hypothesized that systems described by such state vectors do not exist. To test this, GARRUCIO and SELLERI [9] recently proposed another inequality. If one expands the operators appearing in their expression as a sum of projection operators, it can be written as

$$(5)\qquad [R(45°, -45°) + R(-45°, 45°) - R(45°, 45°) - R(-45°, -45°) + \\ + R(\text{RHC}, \text{LHC}) + R(\text{LHC}, \text{RHC}) - R(\text{RHC}, \text{RHC}) - R(\text{LHC}, \text{LHC}) + \\ + R(0°, 90°) + R(90°, 0°) - R(0°, 0°) - R(90°, 90°)]/R_0 \equiv \Delta\,.$$

RHC and LHC refer to circular polarizations measured with the quarter-wave plates installed ($\xi_1 = \xi_2 = 90°$). Their inequality then may be written

$$\Delta_F < 1$$

if Furry's hypothesis holds, whereas the usual quantum-mechanical prediction requires $\Delta_{QM} \approx 3$. Data [10] at these orientations are presented in table 2. Inequality (6) makes predictions clearly at variance with these data.

TABLE II. – *Values for Garuccio-Selleri inequality.*

Polarization	Orientation		$R(\varphi_1, \varphi_2)/R_0$	Integration time (s)
	φ_1	φ_2		
linear	0°	0°	0.011 ± 0.043	10 000
$\xi_1 = \xi_2 = 0$	90°	90°	0.085 ± 0.048	9 600
	90°	0°	0.454 ± 0.075	9 600
	0°	90°	0.399 ± 0.066	9 600
	45°	45°	-0.005 ± 0.041	9 600
	−45°	−45°	-0.022 ± 0.045	9 800
	45°	−45°	0.532 ± 0.79	9 400
	−45°	45°	0.409 ± 0.072	9 800
circular	R	R	0.460 ± 0.100	10 000
$\xi_1 = (90 \pm 8.5)°$	L	L	0.347 ± 0.072	10 400
$\xi_2 = (90 \pm 8.5)°$	L	R	0.035 ± 0.049	10 200
	R	L	0.070 ± 0.061	9 800

$\Delta_{QM} = 2.37$, $\Delta_F < 1$, $\Delta_{expt} = 2.50 \pm 0.23$

(9) A. GARUCCIO and F. SELLERI: preprint.

(10) Negative entries in this table are due to the large background of accidental coincidences.

4. – Conclusion.

The circular-polarization correlation of the $9\,{}^1P_1 \to 7\,{}^3S_1 \to 6\,{}^3P_0$ cascade was found to be in reasonable agreement with theory, when one considers the quality of the retardation plates employed. However, it was of insufficient magnitude to violate (2). None the less, the measurement is interesting since it further constrains possible counter-examples to Bell's theorem of the type discussed by CLAUSER and HORNE [4]. Moreover, data from the linear and/or circular correlations can easily rule out the various predictions by Furry's hypothesis. In a sense, this latter conclusion is not surprising since CLAUSER and HORNE [4] showed that (2) follows from a generalization of Furry's hypothesis to include arbitrary (not necessarily quantum mechanical) mixtures. Inequality (2) has been violated by at least two different experiments [5,6].

● RIASSUNTO (*)

Si riportano i risultati di un esperimento che ha misurato la correlazione della polarizzazione circolare dei fotoni emessi nella cascata $9\,{}^1P_1 \to 7\,{}^3S_1 \to 6\,{}^3P_0$ del mercurio atomico. I risultati sembrano essere in generale accordo con le predizioni della teoria quantistica. Essi sono confrontati con le predizioni mediante numerose disuguaglianze dedotte per varie alternative alla teoria quantistica.

(*) *Traduzione a cura della Redazione.*

Измерения корреляции круговой поляризации протонов, образованных в атомном каскаде.

Резюме (*). — Приводятся результаты эксперимента по измерению корреляции круговой поляризации протонов, образованных в каскаде $9\,{}^1P_1 \to 7\,{}^3S_1 \to 6\,{}^3P_0$ для атомов ртути. Полученные результаты согласуются с предсказаниями квантовой теории. Результаты сравниваются с предсказаниями, выведенными для различных альтернативных подходов к квантовой теории.

(*) *Переведено редакцией.*

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11 Giugno 1976
Il Nuovo Cimento
Serie 11, Vol. **33** B, pag. 740-746