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SUCCESSIVE POLARIZATION MEASUREMENTS ON AN IMPROPER MIXTURE*

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ABSTRACT

We have performed two successive linear polarization measurements on the improper mixture of photons resulting from the $7^1S_0 \rightarrow 6^3P_1$ transition of Hg^{202}. Improper mixtures are important in measurement theory, and we speculate that a basic difference in the time evolution of proper and improper mixtures might resolve some of the difficulties in this field. Our experimental data are in agreement with the quantum mechanical prediction that no such difference exists.

In measurement theory improper mixtures, also called mixtures of the 2nd kind, play a central role. The possibility of experimentally distinguishing improper mixtures from proper mixtures by measurements performed only on the mixture in question would then be significant, especially in that the usual interpretations and rules of quantum mechanics deny this possibility. A particular experimentally accessible question concerns the outcome of two successive measurements of a given observable[1]. It appears that only single measurements have so far been performed on pure improper mixtures. We speculate that in a more complicated measurement process discrepancies with theoretical predictions may perhaps occur. In this paper we present the results of such measurements.

In a proper mixture, each element of the ensemble is assumed to have a definite, though possibly unknown, state vector. However, not all mixtures satisfy this assumption, and d'Espagnat[2] introduced the term "improper mixture' to emphasize this distinction.
A simple example of such a mixture may be derived from the system considered by Bohm[3] in his formulation of the paradox of Einstein, Podolsky and Rosen. This system consists of two spin-one-half particles produced by the decay of a single spin-zero particle. Conservation of total spin gives for the state vector following the decay

$$|\Psi\rangle = 1/\sqrt{2}(|a+\rangle|b-\rangle - |a-\rangle\ |b+\rangle), \qquad (1)$$

with $|a\pm\rangle$ and $|b\pm\rangle$ denoting the eigenvectors of σ_z for particles A and B respectively. The composite system of A and B is in a pure state. Since this state cannot be factored into the form:

$$|\Psi\rangle = |a\pm\rangle\ |b\mp\rangle \qquad (2)$$

particles A and B cannot be described by separate state vectors. Suppose we take an ensemble Σ of such systems and examine only the sub-ensenble Σ_A of particles A. Then Σ_A is an improper mixture.

The importance of improper mixtures in measurement theory can be seen from the following considerations. Let B be a system we desire to measure, and let A be our measuring apparatus. Here, b and a will specify respectively the final state of the measured system and the pointer position on our apparatus. In the measurement process systems A and B interact and then separate. A is now an improper mixture due to the correlation (1), which prohibits the description of A by a vector $\psi_A(a)$. It has been emphasixed by Wigner[4] that at some point in this process a transition must be made to a proper mixture so that the observer himself will not be left in a superposition of states. The point at which this transition takes place is still under debate, and not fully understood.[5]

Proper and improper mixtures are conceptually distinct, but the accepted evolutionary rules of quantum mechanics predict that no experimental distinction between them exists. Here, the possible states of the correlated, unobserved particles B are simply summed over. This results in a random distribution of these states. All correlation effects with the particles B are lost and the analysis thus becomes identical to that of a proper mixture. Two successive measurements performed on particles A should yield identical results, regardless of whether the mixture is proper or improper, since after the first measurement and associated collapse, the ensemble will be described by a pure state.

It seems reasonable to speculate that some of the difficulties encountered in the attempt to understand the measurement process might be explained by postulating that improper mixtures in general follow a time evolution different from that for proper mixtures. This has been done by various authors. Unfortunately it is not clear how such a difference might be conclusively sought. Jauch[6] has proposed correlation experiments as a suitable method, but the experiment of Freedman and Clauser[7] and one by Kasaday, Ulman and Wu[8] do not show the violation of quantum mechanics predicted by his scheme.

Wigner[9] has proved that violation of the unitarity of the evolution operator must occur during the transition between improper and proper mixtures, and thus at some point in the measurement chain. With this in mind Eberhard[10] searched for a violation of the unitarity of the evolution operator involved in π-p scattering. He found no evidence for such a violation.

A non-local hidden-variable theory with non-linear evolutionary equations was introduced by Bohm and Bub[11] to effect this transition. Papaliolios[12] searched for the violation of quantum mechanics suggested by their theory. The experiment was a measurement of the transmission of light by two, closely spaced, successive linear polarizers. No violation of theory was found for achievable spacings, but this measurement only put an upper limit on the "collapse time", a free parameter involved in their theory.

The improper mixtures in Papaliolios's experiment were of the usual object - apparatus variety, since he used light whose polarization was already described as a proper mixture. Although he found no violation of the quantum mechanical evolution rules, it seems plausible that much simpler improper mixtures might yield a violation where this one did not. Many of the schemes proposed for solutions to the measurement problem use the fact that the apparatus is a highly complex system. They suggest basically that the transition is somehow obscured or caused as the effects of this complexity become felt. We conjecture that experiments on very simple, or moderately simply inproper mixtures might uncover a discrepancy in the predictions of quantum mechanics if one is lucky enough to measure the system during this transition. Thus we start with a very simple improper mixture and try successive measurements upon it instead.

To this end we performed a modified version of Papaliolios's experiment using light which was formed in a pure improper mixture, free from proper mixture contamination. This then constitutes a more complicated experiment than any previously performed on two state improper mixtures, and it was hoped that a violation of accepted theory might be unearthed. Two-state mixtures were chosen since they are the simplest systems and most of the analyses of the measurement problem have concentrated upon them.

It is difficult, however, to produce an improper mixture of spin one-half particles. On the other hand a pure improper mixture of photons, also two-state systems may be generated with relative ease. These were the systems used in a recent experiment of Freedman and Clauser who sought and found the quantum mechanically predicted correlation between the A and B systems. The states of linear polarization are then the two required states.

A further motivation for doing the modified experiment also arrises in the analysis of the experiment of Freedman and Clauser. This experiment failed to reveal a violation of quantum mechanical predictions required by very general hidden-variable explainations of the measurement problem. Unfortunately in a consideration of possible physical models for their experiment a supplementary assumption has been found to be necessary.[13]

If these models are required to also agree with the quantum mechanical prediction for successive measurements, further rather severe constraints are imposed on them. Since it is not clear whether experiment requires such constraints, additional experimental evidence is thus welcome.

In a $J = 0 \rightarrow J=1$ atomic transition, conservation of total angular momentum requires that the resultant state vector takes the form

$$|\Psi\rangle = {}^1/\sqrt{2}\,\left(|R\gamma\rangle\,|m_A = +1\rangle + |L\gamma\rangle|m_A = -1\rangle\right), \quad (3)$$

where $|R\gamma\rangle$ ($|L\gamma\rangle$ and $|m_A = +1\rangle$ ($|m_A = -1\rangle$) denote the circular polarization of the emitted photon and the component of J of the decayed atom along the direction of relative motion respectively.
Substituting:

$$|m = +1\rangle = |R\rangle = {}^1/\sqrt{2}\,(|x\rangle + i|x\rangle) \quad (4a)$$

and

$$|m = -1\rangle = |L\rangle = {}^1/\sqrt{2}\,(|x\rangle - i|y\rangle) \quad (4b)$$

we get (with obvious notation):

$$|\Psi\rangle = {}^1/\sqrt{2}\,(|x_\gamma\rangle\,|x_A\rangle - |y_\gamma\rangle|y_A\rangle) \quad (5)$$

which gives us, effectively, a linear polarization basis for the atom-photon system. Since (5) cannot be factored to the form (2), a beam of such photons thus constitutes an improper mixture.

Hyperfine structure is usually left unresolved, and would introduce contamination by proper mixtures. Thus, $F = 0 \rightarrow F = 1$ with $I = 0$ is the necessary condition for the resulting photon mixture to be completely improper. Although this restriction severely limits the possible sources, a suitable choice appeared to be an electrodeless discharge lamp filled with an artificially enriched sample of 92.8% Hg^{202} ($I=0$).

We performed two successive linear polarization measurements on the improper mixture of photons resulting from the $7^1S_0 \rightarrow 6^3P_1$ transition of Hg^{202} occuring at 4077.83 Å. The experimental configuration is depicted in Fig. 1. The discharge was excited in a microwave cavity driven by a QK-62 magnetron. An Ebert monochromator (.25m Jarrell Ash) was used to select the spectral line.

The monochromator entrance and exit slits were replaced by pinholes to produce a narrow, axially symmetric beam. A third pinhole was placed at the entrance to the first polarizer to further restrict the angular extent of the beam. The polarizers were of the pile of plates variety and were very nearly ideal measuring apparatuses, transmitting 94.0% of parallel componants and rejecting 0.78% of perpendicular components. Each polarizer consisted of fifteen 0.010-inch thick glass plates all inclined at approximately Brewster's angle and mounted together in a rotatable frame. The beam passed successively through both polarizers to a photomultiplier tube (RCA 8575). The photomultiplier anode current was integrated and displayed by a microammeter.

Adjacent to the 4077.83Å line is a brighter line at 4046.56Å. This line is produced by the transition $7^3S_1 \rightarrow 6^3P_0$ and is a proper mixture, providing a convenient reference. The improper mixture (4077.83Å) was given a definite polarization by the first polarizer, and the second polarizer was rotated with respect to the first. The intensity of the exiting beam was recorded for various polarizer angles. This proceedure was then repeated on the proper mixture at 4046.56Å using a neutral density filter to reduce the beam intensity to comparable values. The intensities at equal relative polarizer angles for the two lines were plotted and a computer fit to a straight line was performed.[14] The results are shown in Fig. 2. The computer fit yielded a standard deviation of 0.5% of the mean data value. This was well within the 0.8% expected error. To this accuracy we conclude, then, that the experiment failed to reveal any difference between proper and improper mixtures.

The error limitations were due to source drift, inaccuracy in the angle measurements, and the ammeter's integration time. Improved results could have been obtained by employing lock-in modulation of the beam, a longer integration time, and a reference phototube monitoring the source intensity to compensate for drift. However, due to the lack of a specific competitive prediction, these improvements were not considered warranted.

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[1] In the case examined, the observable's operator commuted with the Hamiltonian; however any observable would serve, providing the measurements are made in rapid succession.

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[13] M. A. Horne and J. F. Clauser (to be published).

[14] This procedure minimized the effects of a polarization dependence of the monochromator and photomultiplier.

Figure Captions

Fig. 1 Diagram of apparatus.

Fig. 2 Experimenteal and theoretical relationship between intensities for the two spectral lines. Units are normalized to values at the maximum polarizer transmissions.

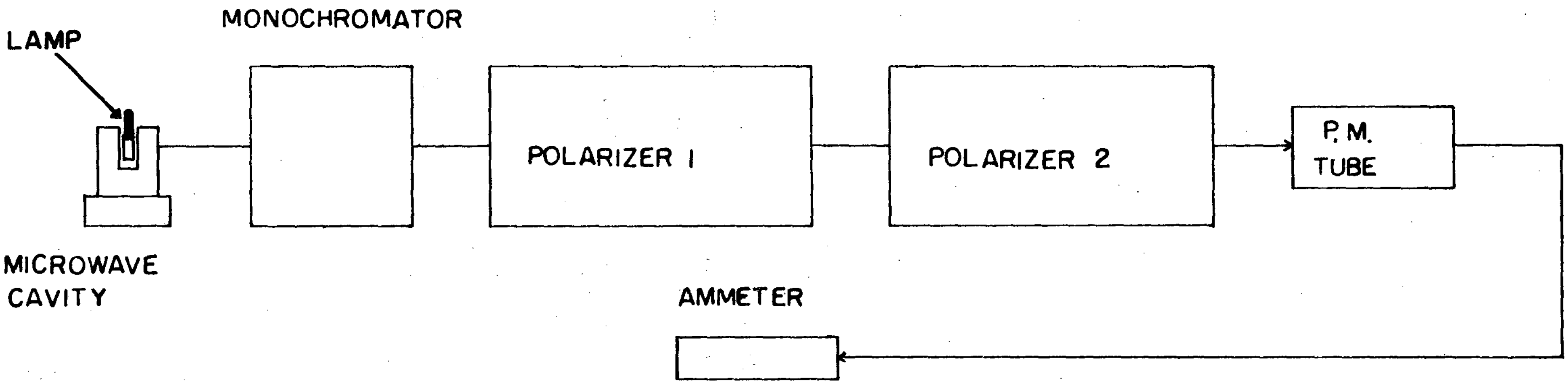
MONOCHROMATOR
LAMP
POLARIZER 1
POLARIZER 2
P. M.
TUBE
MICROWAVE
CAVITY
AMMETER

Fig. 1

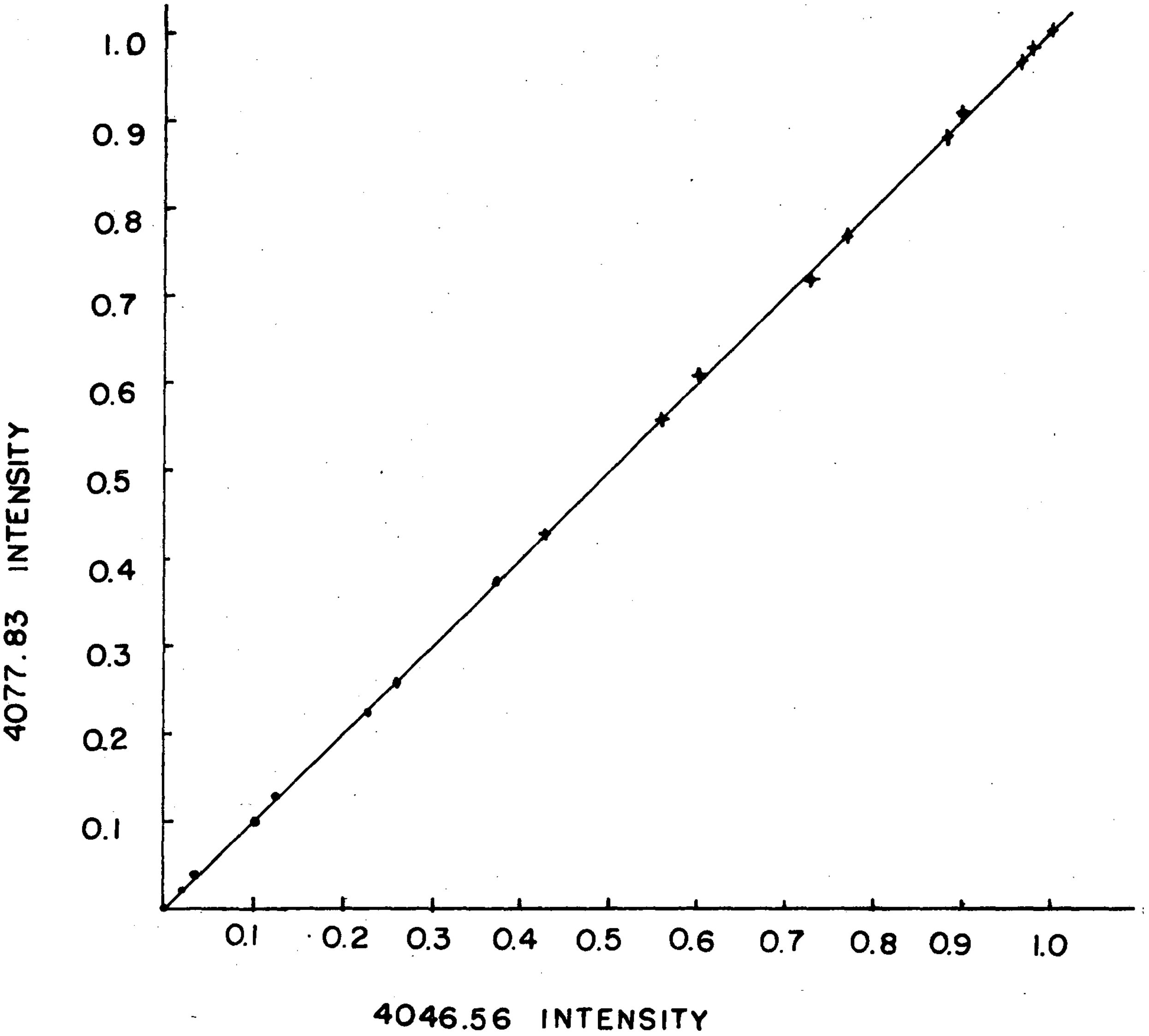
4077.83 INTENSITY
4046.56 INTENSITY
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

Fig. 2

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