LNF–88/74

M.H. Tixier, Z. Ajaltouni, A. Falvard, J. Jousset, B. Michel, J.C. Montret, D. Pallin, A. Antonelli, R. Baldini, J.E. Augustin, G. Cosme, F. Couchot, F. Fulda, G. Grosdidier, B. Jean–Marie, V. Lepeltier, F. Mane, G. Szklarz, D. Bisello, G. Busetto, L. Pescara, P. Sartori, L. Stanco

LOOKING AT *CP* INVARIANCE AND QUANTUM MECHANICS IN $J/\psi \rightarrow \Lambda\bar{\Lambda}$ DECAY

Estratto da: Phys. Lett. B212, 523 (1988)

LOOKING AT *CP* INVARIANCE AND QUANTUM MECHANICS IN $J/\psi \to \Lambda\bar{\Lambda}$ DECAY

DM2 Collaboration

M.H. TIXIER, Z. AJALTOUNI, A. FALVARD, J. JOUSSET, B. MICHEL, J.C. MONTRET, D. PALLIN
Laboratoire de Physique Corpusculaire, Université Blaise Pascal, BP 45, F-63170 Aubière, France

A. ANTONELLI, R. BALDINI
Laboratori Nazionali di Frascati dell'INFN, CP 13, I-00044 Frascati, Italy

J.E. AUGUSTIN, G. COSME, F. COUCHOT, F. FULDA, G. GROSDIDIER, B. JEAN-MARIE, V. LEPELTIER, F. MANE, G. SZKLARZ
Laboratoire de l'Accélérateur Linéaire, Université de Paris-Sud, F-91405 Orsay, France

D. BISELLO, G. BUSETTO, L. PESCARA, P. SARTORI and L. STANCO
Dipartimento di Fisica dell'Università di Padova, e INFN, Sezione di Padova, I-35131 Padua, Italy

Received 2 June 1988

The $J/\psi \to \Lambda\bar{\Lambda} \to p\pi^- \bar{p}\pi^+$ decay is used to test the *CP* invariance in the Λ hyperon decays by measuring $A=(\alpha_\Lambda+\alpha_{\bar{\Lambda}})/(\alpha_\Lambda-\alpha_{\bar{\Lambda}})$ where α_Λ ($\alpha_{\bar{\Lambda}}$) is the decay asymmetry parameter of the Λ ($\bar{\Lambda}$). The obtained value $A=0.01\pm0.10$ is in agreement with *CP* invariance. The used formalism would permit to check quantum mechanics, assuming *CP* invariance.

1. Introduction

Quantitative predictions [1,2] were published two years ago for *CP* violation in hyperon decays indicating that $A=(\alpha_\Lambda+\alpha_{\bar{\Lambda}})/(\alpha_\Lambda-\alpha_{\bar{\Lambda}})$ should be in the range $[-2\times10^{-5}, -1\times10^{-4}]$. Present experimental results [3,4] do not have a sufficient sensitivity to observe such a small effect, but give possible scenarios for future experiments with very large statistics.

The present paper develops the idea of looking for *CP* violation in the two-body decays $J/\psi \to \Lambda\bar{\Lambda}$. The advantage of this decay is to provide a test without assumption on the relative polarization of the Λ and the $\bar{\Lambda}$ which are postulated to be equal in other experiments [3,4].

However it was noticed recently [5] that the distribution of the angle between p and $\bar{p}$ directions in the Λ and $\bar{\Lambda}$ rest frames is also strongly connected to the validity of quantum mechanics. Both aspects will be discussed in the following section from a theoretical point of view and finally compared to data.

A statistics of 1847 $\Lambda\bar{\Lambda}$ events coming from $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda} \to \pi^- p \pi^+ \bar{p}$ has been observed in the DM2 detector [6] at DCI. It has been obtained from a sample of 8.6×10^6 J/ψ decays. In ref. [7], these data were analysed to test the first-order QCD prediction in the angular distribution of the Λ: good consistency was observed.

2. Description of the formalism

The differential cross section of the $J/\psi \to \Lambda\bar{\Lambda} \to p\pi^- \bar{p}\pi^+$ decay can be expressed as [8]

$$\frac{\partial\sigma}{\partial\Omega\,\partial\Omega'\,\partial\Omega''} \propto \sum_{M}\sum_{\lambda_p}\sum_{\lambda_{\bar{p}}} |T_{M\lambda_p\lambda_{\bar{p}}}|^2 ,$$

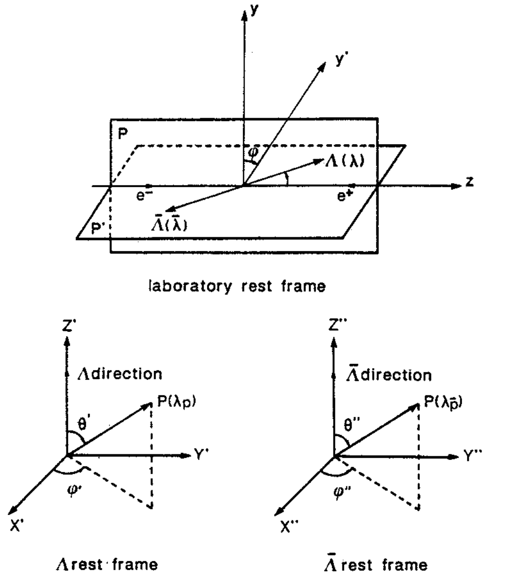

Fig. 1. Λ, $\bar\Lambda$, p, $\bar p$, π^+ and π^- angles.

where

$$T_{M\lambda_p\lambda_{\bar p}} = \sum_{\lambda,\bar\lambda} A_{\lambda\bar\lambda} D^{*1}_{M,\lambda-\bar\lambda}(\phi,\theta,-\phi)$$

$$\times D^{*1/2}_{\lambda,\lambda_p}(\phi',\theta',-\phi') D^{*1/2}_{\bar\lambda,\lambda_{\bar p}}(\phi'',\theta'',-\phi'') B_{\lambda_p}\bar B_{\lambda_{\bar p}}$$

and (fig. 1) λ, $\bar\lambda$, M, λ_p, $\lambda_{\bar p}$ are respectively the Λ, $\bar\Lambda$, J/ψ, p, $\bar p$ helicities, θ, ϕ the Λ emission angles versus e^+ beam direction, θ', ϕ' the proton angles in the Λ rest frame, θ'', ϕ'' the antiproton angles in the $\bar\Lambda$ rest frame, $A_{\lambda\bar\lambda}$ is the helicity amplitude for J/ψ $\to\Lambda\bar\Lambda$, B_{λ_p} is the helicity amplitude for $\Lambda\to\pi^-p$, $\bar B_{\lambda_{\bar p}}$ the helicity amplitude for $\bar\Lambda\to\pi^+\bar p$, and $D^j_{m'm}$ is the standard rotation matrix.

As the J/ψ $\Lambda\bar\Lambda$ vertex involves only electromagnetic and strong interactions, parity conservation holds, which implies

$$A_{-\lambda,-\bar\lambda}=\eta_{J/\psi}\eta_\Lambda\eta_{\bar\Lambda}(-1)^{S_{J/\psi}-S_\Lambda-S_{\bar\Lambda}}A_{\lambda\bar\lambda}=A_{\lambda\bar\lambda}\,,$$

where η_i and S_i are the intrinsic parity and spin of the ith particle.

Consequently only two amplitudes are independent: A_{++} and A_{+-} are chosen in the following.

Defining α_Λ ($\alpha_{\bar\Lambda}$) the asymmetry decay parameter of the Λ ($\bar\Lambda$) by

$$\alpha_\Lambda=\frac{|B_+|^2-|B_-|^2}{\sqrt2}\,,\quad \alpha_{\bar\Lambda}=\frac{|\bar B_+|^2-|\bar B_-|^2}{\sqrt2}\,,$$

one obtains by integrating over ϕ:

$$\frac{\partial\sigma}{\partial\cos\theta\,\partial\Omega'\,\partial\Omega''}\propto 2|A_{++}/A_{+-}|^2\sin^2\theta$$
$$\times\{1-\alpha_\Lambda\alpha_{\bar\Lambda}[\cos\theta'\cos\theta''$$
$$-\sin\theta'\sin\theta''\cos(\phi'-\phi'')]\}$$
$$+(1+\cos^2\theta)(1+\alpha_\Lambda\alpha_{\bar\Lambda}\cos\theta'\cos\theta'')\,. \qquad (1)$$

CP invariance at the $\Lambda\pi^-p$ and $\bar\Lambda\pi^+\bar p$ vertices gives

$$\bar B_{-\lambda_{\bar p}}=\eta_\Lambda\eta_\pi\eta_p(-1)^{S_\Lambda-S_\pi-S_p}B_{\lambda_p}=-B_{\lambda_p}\,,$$

and

$$\alpha_{\bar\Lambda}=-\alpha_\Lambda\,.$$

The ratio A_{++}/A_{+-} which is connected to G_E and G_M, the electric and magnetic Λ form factor [#1], is determined from the θ angular distribution [7] after integrating over Ω', Ω''. This was done in ref. [7] in which

$$|G_E^\Lambda/G_M^\Lambda|=|A_{++}M_{J/\psi}/A_{+-}\sqrt2 M_\Lambda|=0.67\pm0.23$$

was measured.

Tornquist [5] demonstrated that the decays $\eta_c\to\Lambda\bar\Lambda$, J/ψ$\to\Lambda\bar\Lambda$ are the experimental realization of Bell's [9] conceptual proposition to test quantum mechanics versus local hidden variable theories. In fact, these $\Lambda\bar\Lambda$ decays can be conceptually described quite similarly to traditional experiments involving photons and polarimeters [#2]. The initial state is well known and due to parity symmetry breaking, the Λ decay works as a spin analyser. The proton direction plays the same part as the direction of the external polarimeter in classical experiments [10] (see fig. 2). Then, the important quantity, sensitive to the nature of the theory, is the scalar product of p and $\bar p$ momenta $\boldsymbol{a}$ and $\boldsymbol{b}$ in the Λ and $\bar\Lambda$ rest frames.

Due to the pseudoscalar nature of the η_c, the differential cross section of the decay $\eta_c\to\Lambda\bar\Lambda$ is directly proportional to $\boldsymbol{a}\cdot\boldsymbol{b}$. So it is the most sensitive test of quantum mechanics since this scalar product can be compared to Bell's inequality. Only 100 events would

[#1] Strictly speaking, the terms electric and magnetic form factors or coupling are misused here, since baryon pair production is dominated by strong interaction in the J/ψ decay. But the structure of the proton current is the same in the coupling to J/ψ and this standard notation is used for convenience.

[#2] See ref. [10] for a recent example.

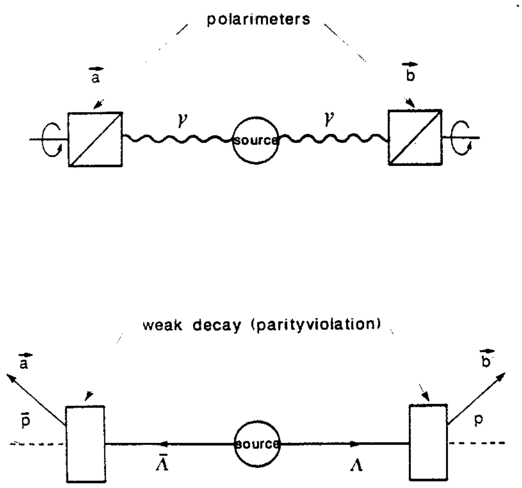

Fig. 2. Analogy between $\Lambda\bar{\Lambda}$ decays and traditional EPR experiments.

already give very interesting results. Unfortunately, this decay has not yet been observed and only an upper limit exists [11] which does not conflict with the SU(3) prediction.

Extending the calculation to the $J/\psi\to\Lambda\bar{\Lambda}$ study and assuming *CP* invariance and $G_E=G_M$ [12] [#3]. Tornquist reformulates the differential cross section (1) as

$$\frac{\partial\sigma}{\partial\cos\theta\,\partial\Omega'\,\partial\Omega''}$$
$$\propto 2[1-(p_{\bar{\Lambda}}^2/E_{\bar{\Lambda}}^2)\sin^2\theta](1-\alpha_{\bar{\Lambda}}^2 a_n b_n)$$
$$+(p_{\bar{\Lambda}}^2/E_{\bar{\Lambda}}^2)\sin^2\theta[1-\alpha_{\bar{\Lambda}}^2(\boldsymbol{a}\cdot\boldsymbol{b}-2a_x b_x)]\,, \qquad (2)$$

where $\boldsymbol{a}$ and $\boldsymbol{b}$ are the proton and antiproton momentum, respectively in the Λ ($\bar{\Lambda}$) rest frame, x is the direction orthogonal to the $\Lambda\bar{\Lambda}$ direction and to the e^+e^- beam axis and $\boldsymbol{n}$ is an axis defined to take into account the suppression of 0 spin projection in the J/ψ decay; it is degenerated with z, when $\theta=0^0$ or $90°$. This expression highlights the $\boldsymbol{a}\cdot\boldsymbol{b}$ contribution which is important for the test of quantum mechanics. The contribution of the $\boldsymbol{a}\cdot\boldsymbol{b}$ term is maximum when $p_{\bar{\Lambda}}^2/E_{\bar{\Lambda}}^2\to 1$ corresponding to the ultrarelativistic limit and when $\theta=90°$. Unfortunately $p_{\bar{\Lambda}}^2/E_{\bar{\Lambda}}^2$ at the J/ψ mass is only equal to 0.48 and $\alpha_{\bar{\Lambda}}^2$ to 0.412 [12] which reduce the contribution of the $\boldsymbol{a}\cdot\boldsymbol{b}$ term in the experimental measurement.

Other terms, containing $a_n\cdot b_n$ or $a_x\cdot b_x$ only reduce the sensitivity of the test since they do not depend on the nature of the theory: as mentioned in ref. [13], the x and n direction play the same role as hidden parameters.

The possibility of *CP* violation can be included in formula (2) by substituting $-\alpha_\Lambda\alpha_{\bar{\Lambda}}$ to $\alpha_{\bar{\Lambda}}^2$. Then we notice that the product $\alpha_\Lambda\alpha_{\bar{\Lambda}}\boldsymbol{a}\cdot\boldsymbol{b}$ is connected to both effects, *CP* invariance and the test of quantum mechanics, and shows the correlation between the two assumptions. Assuming the validity of quantum mechanics, $\alpha_{\bar{\Lambda}}$ is extracted from the $\boldsymbol{a}\cdot\boldsymbol{b}$ distribution. On the other hand, there is no test of quantum mechanics, using the $\boldsymbol{a}\cdot\boldsymbol{b}$ distribution, without supposing $\alpha_{\bar{\Lambda}}=-\alpha_\Lambda$ (*CP* invariance).

[#3] In ref. [12] $G_E=G_M$ is assumed. This is not in disagreement with our data.

3. Experimental set up, analysis and results

The DM2 [6] detector is a large solid angle spectrometer operated at the Orsay e^+e^- colliding ring DCI. Only the interesting features for this analysis will be described here.

Within a 0.5 T magnetic field produced by a 2 m diameter and 3 m long solenoid and from the point of interaction, the detector consists of:

(i) 2 proportional chambers to provide the fast level trigger and to improve the precision measurement of secondary vertices. In this analysis, the Λ ($\bar{\Lambda}$) signal is sufficiently well isolated by a mass cut. So a secondary vertex requirement which would only reduce the number of events has not been applied.

(ii) 13 drift chambers to measure charged track momenta. The momentum accuracy is 35 MeV/*c* at 1 GeV/*c*.

(iii) 36 scintillator counters to measure the charged particle time of flight. A 3σ π/K separation is obtained up to 420 MeV/*c* and a 3σ π/p separation up to 830 MeV/*c*.

The $J/\psi\to\Lambda\bar{\Lambda}\to\pi^+\pi^-p\bar{p}$ decay is studied from events with three and four tracks detected in the apparatus which are used in this analysis.

Fig. 3 shows the $\Lambda\bar{\Lambda}$ signal from fully reconstructed $J/\psi\to\pi^+\pi^-p\bar{p}$ events selected with a cut on missing momentum equal to 100 MeV/*c* and on total energy

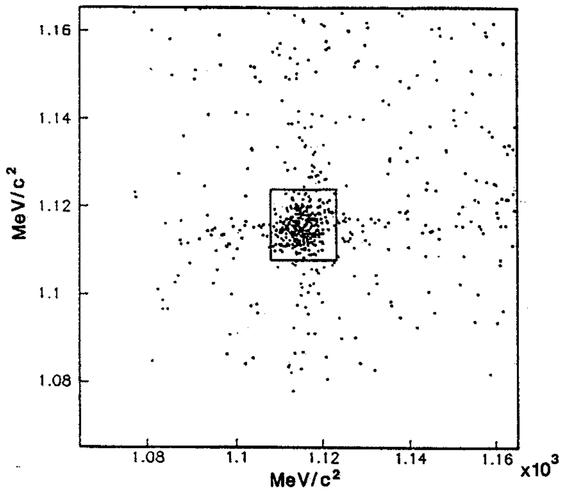

Fig. 3. The $\Lambda\bar{\Lambda}$ signal, $p\pi^-$ versus $\bar{p}\pi^+$ mass. The square area corresponds to the selected signal ($1107 \leqslant m_{\pi p} \leqslant 1123$).

in the range [2996,3196] MeV. Fig. 4 shows the Λ signal by computing the $M_{\pi p}$ invariant mass for a sample of $J/\psi \to p\bar{p}\pi^+\pi^-$ events. It is fit to a gaussian distribution added to a quadratic polynomial. As an RMS equal to 3.5 MeV/c^2 is obtained for the peak, a ± 8 MeV/c^2 cut is applied around 1115 MeV/c^2 to select Λ ($\bar{\Lambda}$). The kinematical signature of each particle is required to be consistent within 3σ with the TOF information, if any. The contamination from phase space events $J/\psi \to 2\pi p\bar{p}$ or from a $\Delta^{++}\Delta^{--}$ dynamics has been found to be negligible by a Monte

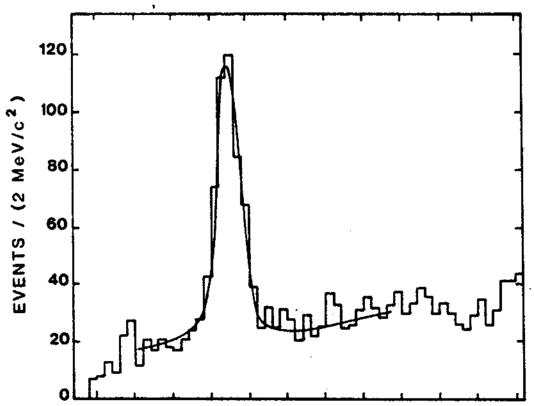

Fig. 4. $\pi^- p$ mass distribution in the decay $J/\psi \to \pi^+\pi^- p\bar{p}$. The fit is described in the text.

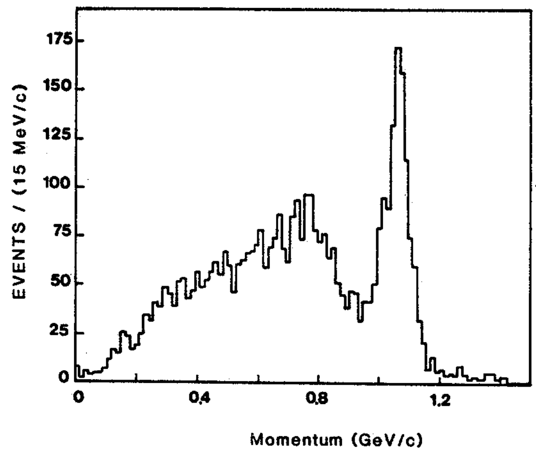

Fig. 5. Λ momentum for the three charged track events.

Carlo simulation. 1077 $J/\psi \to \Lambda\bar{\Lambda}$ events are obtained.

The events with only three reconstructed tracks are included in the analysis since they increase the available statistics and reduce small systematical errors. The Λ or $\bar{\Lambda}$ fully reconstructed in the event is selected by the cut on $M_{\pi p}$ previously given. Fig. 5 gives the momentum of the reconstructed $\Lambda(\bar{\Lambda})$. A clear signal appears around 1074 MeV/c corresponding to the process $J/\psi \to \Lambda\bar{\Lambda}$. However, this signal is contaminated on the low-momentum side by $J/\psi \to \Sigma\bar{\Sigma}^0$ which contributes up to 1050 MeV/c. So, only 770 events whose momentum lies between 1035 MeV/c and 1160 MeV/c are retained for this analysis.

As mentioned previously, *CP* invariance can be looked for, assuming the validity of quantum mechanics, by studying the $\boldsymbol{a}\cdot\boldsymbol{b}$ distribution, $\boldsymbol{a}$ and $\boldsymbol{b}$ defining the proton and antiproton direction in the Λ and $\bar{\Lambda}$ rest frame. The comparison of the observed distribution with the theoretical one depends strongly on a correct simulation of the momentum spectra and special attention was paid to this particular aspect of the Monte Carlo simulation (fig. 6). Monte Carlo events are generated from the angular distribution (1) where we introduce our measurement for G_E/G_M. It was verified that a modification of G_E/G_M within errors does not sensitively modify the determination of the A parameter.

The $\boldsymbol{a}\cdot\boldsymbol{b}$ distribution is plotted in fig. 7 and compared with that expected from standard physics (quantum mechanics and *CP* invariance). The agreement is very good by taking the PDG value

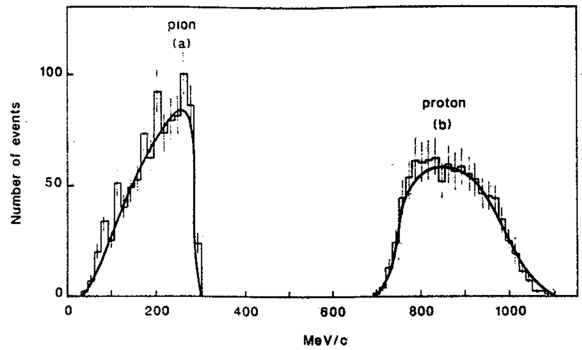

Fig. 6. The proton and pion momentum distribution. The superimposed curves show the MC simulation.

$\alpha_\Lambda = -\alpha_{\bar\Lambda} = 0.642 \pm 0.013$. The χ^2 is 7.2 for 9 degrees of freedom.

Fixing the α_Λ parameter to its standard value (0.642), the shape of the theoretical distribution for $\boldsymbol{a}\cdot\boldsymbol{b}$ is varied with $\alpha_{\bar\Lambda}$. From χ^2 minimization one obtains $\alpha_{\bar\Lambda} = -0.63 \pm 0.13$.

This measurement gives the following value of the asymmetry decay parameter:

$$A = (\alpha_\Lambda + \alpha_{\bar\Lambda}) / (\alpha_\Lambda - \alpha_{\bar\Lambda}) = 0.01 \pm 0.10 ,$$

whereas CP invariance implies $A=0$. This determination is obtained with the same sensitivity as recent experiments performed at the ISR [3] ($A = -0.02 \pm 0.14$) and LEAR [4] ($A = -0.07 \pm 0.09$).

The accuracy of all these experiments remains insufficient to observe CP violation at the level predicted by present calculations in the standard model: $A = -2 \times 10^{-5}$ in the Kobayashi–Maskawa model or $A = -1 \times 10^{-4}$ in the Weinberg model [2].

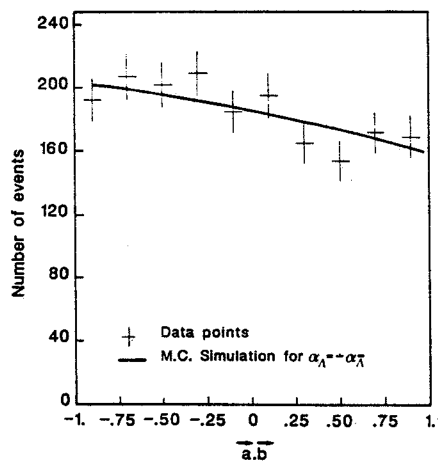

Fig. 7. The $\boldsymbol{a}\cdot\boldsymbol{b}$ distribution. MC simulation and data.

4. Conclusion

The precision of the A parameter measurement does not permit to conclude CP violation. To improve the precision of this measurement by one order of magnitude it would be necessary to study a sample of about 2×10^5 $\Lambda\bar\Lambda$ events.

In the future the same method could be used in an optimal way by studying the channel $p\bar p \to \eta_c \to \Lambda\bar\Lambda$ on a machine as Super-Lear. A well fixed quantum number $J^P = 0^-$ intermediate state should in fact provide a powerful tool to test quantum mechanics and to look for CP violation in hyperon decays.

Acknowledgement

We are very grateful to N.A. Tornquist for communication of his results prior to publication and for many useful comments. We would like to thank F. Selleri for his continuous interest and support. We acknowledge J. Six for his many remarks and advice.

References

[1] J.F. Donoghue et al., Phys. Rev. D 34 (1986) 833; Phys. Lett. B 178 (1986) 319.
[2] L. Wolfenstein, Ann. Rev. Nucl. Part. Sci. 36 (1986) 137.
[3] P. Chauvat et al., Phys. Lett. B 163 (1985) 273.
[4] P.D. Barnes et al., Phys. Lett. B 199 (1987) 147.
[5] N.A. Tornquist, Found. Phys. 11 (1981) 171.
[6] J.E. Augustin et al., Phys. Scr. 23 (1981) 623.
[7] D. Pallin et al., Nucl. Phys. B 292 (1987) 653.
[8] M. Jacob and G.C. Wick, Ann. Phys. (NY) 7 (1959) 404.
[9] J.S. Bell, Physics 1 (1965) 195.
[10] A. Aspect, Phys. Rev. Lett. 49 (1982) 91.
[11] P. Henrard, Thèse de Doctorat de l'Université de Clermont II (1987), unpublished.
[12] N.A. Tornquist, Phys. Lett. A 117 (1986) 1.
[13] N.A. Tornquist, EPR experiments using the decays of η_c or J/ψ into $\Lambda\bar\Lambda \to \pi^- p \pi^+ \bar p$, in: Quantum mechanics versus local realism. The EPR paradox, ed. F. Selleri (Plenum, New York), to be published.