Comparison of π^+ and π^- Lifetimes*

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A check on *CPT* invariance has been made by comparing the lifetimes of the charged pion and its antipion. The fraction of surviving pions in beams of π^+ and π^- which were nearly identical in their spatial and momentum distributions were measured at ten positions along the beam using a liquid-hydrogen differential Čerenkov counter. Over 100 successive π^+-π^--π^+ comparisons were made. Because of the method used, many possible systematic errors which affect an absolute lifetime measurement cancel out in determining the ratio of the lifetimes. The ratio measurement gave $(\tau_+/\tau_-)-1=0.0056\pm0.0028$ and the absolute π^+ lifetime was found to be 26.6 ± 0.2 nsec.

INTRODUCTION

INVARIANCE of the Hamiltonian under *CPT* is a sufficient but not necessary condition for the equality of the total lifetimes and masses of particle and antiparticle. An experiment has been performed to check *CPT* invariance in weak interactions by looking for any difference between the total lifetimes of positive and negative pions. This was done in such a manner that the absolute lifetimes of both were also determined directly. The lifetimes were measured by finding the fraction of surviving pions as a function of distance in vacuum in nearly identical momentum-analyzed beams of π^+ and π^- mesons.

Pions were produced in collisions of the external proton beam of the Lawrence Radiation Laboratory's 184-in. synchrocyclotron with a 6-in.-long Be target (Fig. 1). The pion beam was momentum-analyzed by the bending magnets, M_1 and M_2, and geometrically defined by the collimator C, five thin scintillators S_1 to S_5, and four annular anticoincidence scintillators A_1 to A_4. After S_2, the entire trajectory was in vacuum except for the 36-in.-long, $\frac{2}{3}$-atm, CO_2 Čerenkov counter located between S_4 and S_5 to veto electrons in the beam.

The counters and magnets described so far provide (1) a nearly parallel beam of small momentum spread ($\Delta p/p=\pm0.4\%$), and (2) a monitor of the intensity of that beam. Pions were actually selected by a differential, liquid-hydrogen Čerenkov counter which was positioned successively at various points along the decay path up to 17 ft past A_4 without the quadrupole Q, and with Q in place, up to 36 ft beyond its exit end. Hydrogen was used because operation at cyclotron momenta required a refractive index of about 1.1, and multiple scattering had to be kept to a minimum. In the counter[1] (Fig. 2), 11-deg Čerenkov light from paraxial particles is focused by the quartz doublet onto a ring aperture. In order to reject particles with off-angle trajectories, such as δ rays or decay muons, more efficiently, the ring aperture is surrounded by an anticoincidence ring. The angular resolution of the counter was ±3 deg, while the velocity resolution ($\Delta\beta/\beta$) was ±0.005. The desired pions had $\beta=0.912$, muons in the beam had $\beta=0.947$, and muons from the decay of pions had a range of velocities including $\beta=0.912$. However, these decay muons were emitted at 7 deg with respect to the beam direction, and hence were rejected.

Complete separation of pions from decay muons is important for correct absolute lifetimes, although it should make no difference in establishing the equality of π^+ and π^- lifetimes. It is important, however, to ascertain (a) that there is no change in the nature of the monitor counts with time, and that there are no important differences between π^+ and π^- with respect to (b) beam geometry, (c) momentum, and (d) Čerenkov counter response with distance. These items are now discussed in order.

I. MONITOR

Although it is not necessary that monitor counts, $S_1S_2S_3S_4S_5\bar{A}_e\bar{A}_1\bar{A}_2\bar{A}_3\bar{A}_4$, arise from pions alone, it is important that the fraction due to pions not change, or at least (for relative measurements) that changes be the same for the positive and negative beams. Since the fraction of electrons did change when the proton beam wandered across the Be target, an electron veto counter (of 95% efficiency) was installed, and a split ion chamber was placed in front of the target to permit controlling the proton-beam position to better than 1 mm. These kept changes in the fraction of electrons (27% for π^- and 4.6% for π^+) to <0.1% for the negative beam and <0.02% for the positive. The muon contamination at counter A_4, as determined from integral range curves in Cu, was 6% for both polarities.

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[1] The optical system is the same as that described by D. A. Hill, D. O. Caldwell, D. H. Frisch, L. S. Osborne, D. M. Ritson, and R. A. Schluter [Rev. Sci. Instr. **32**, 111 (1961)]. Further details on this counter are given by R. W. Kenney, D. O. Caldwell, E. F. McLaughlin, W. L. Pope, R. V. Schafer, and B. F. Stearns [Proceedings of the 1966 International Conference on Instrumentation for High Energy Physics, Stanford, p. 201 (unpublished); Lawrence Radiation Laboratory Report No. UCRL-17129, 1966 (unpublished)].

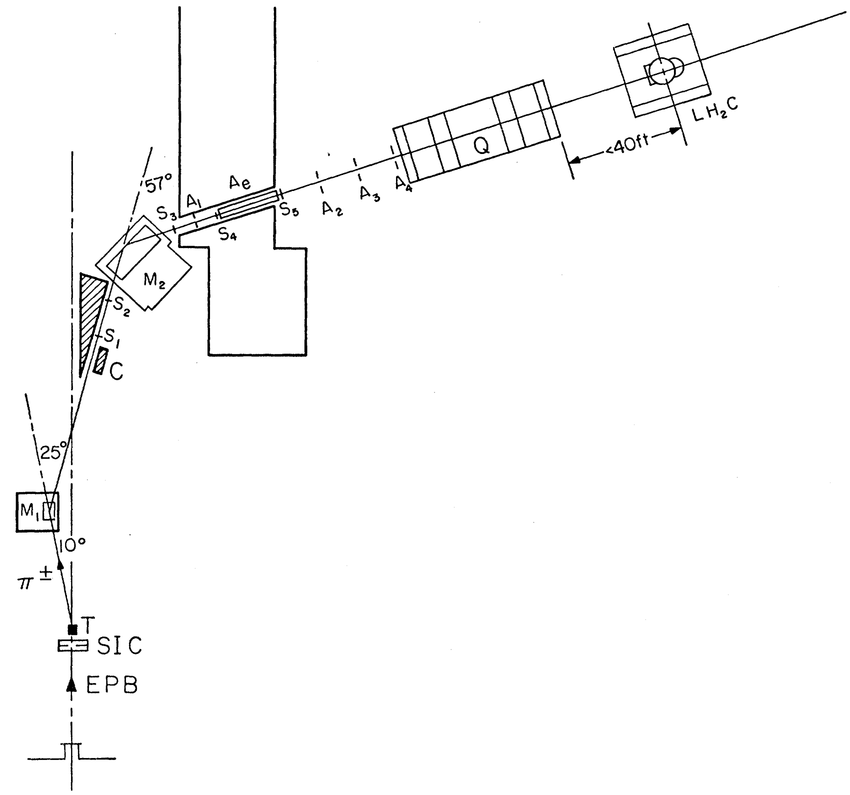

FIG. 1. Experimental arrangement. EPB: 732-MeV external proton beam. SIC: Split ion chamber. T: 6-in. Be target. M_1: 9×12-in. C magnet. C: 1.5-in.-diam Pb collimator. M_2: 12×36-in. C magnet. Q: 16×32×16-in. quadrupole triplet. S_1–S_5: 0.02-in.-thick scintillators. A_1 through A_4: Ring anticoincidence scintillators. A_e: 36-in.-long CO_2-gas Čerenkov counter (10 psi). LH_2C: Movable liquid-hydrogen Čerenkov counter.

Fluctuations in the data could be caused by accidental coincidences, as well as by changes in beam composition. The low monitor counting rate helped make the effect of accidentals unimportant. The positive flux averaged 35/sec, while the negative beam averaged 7/sec, the difference stemming from the quite different production cross sections. The only significant accidental coincidence rate, caused by particles getting by the edge of S_3 in coincidence with random counts in S_3, gave a mean fraction of 0.0028 for positives and 0.0023 for negatives. The beam conditions were quite reproducible and stable, and this resulted in making these rates very constant with time, so that it was unnecessary to correct for them in the monitor counts. There were *no* measurable accidentals in the pion counts (monitor-Čerenkov coincidences).

The fraction of monitor counts per $S_1S_2S_3\bar{A}_1$ coincidence, the fraction of electrons vetoed, and the fraction of accidentals were all monitored continuously. The distribution of each of these quantities for the 1200 individual readouts was Gaussian with the expected variance. Thus there was no indication of systematic fluctuations in the monitor system.

II. BEAM GEOMETRY

Detailed beam profiles, as shown in Fig. 3, were taken with a digitized spark chamber[2] at all positions along the beam trajectory at which data were obtained, in order to be certain that the beam was sufficiently well contained and that the positive and negative beams were similar. The beams were nearly identical in shape but their centers became gradually displaced along the decay path because of the small ($\sim$3 G) stray cyclotron field. The centering and containment of the beam was also checked at each position by taking counts with the Čerenkov counter moved off center horizontally and vertically. In addition, the angular alignment with respect to the beam axis was tested by rotating the counter in the horizontal and vertical planes. A substantial fraction of the data-gathering time was spent in this type of check.

That no evidence was found for particles outside the expected beam area may be attributed to having three final anticoincidence counters, $\bar{A}_2$ to $\bar{A}_4$, and to having very little scattering material in the beam. The S counters were only 0.025-in. thick, there was no edge wrapping on the A counters because they were in a vacuum, and there were no windows between the electron veto counter and the moveable Čerenkov counter. It is worth noting that because of the larger π^+ cross section, such scattering would make the π^- lifetime appear longer.

III. MOMENTUM

The field at the position of the gaussmeter in each of the magnets M_1 and M_2 was held constant and the same for both polarities to within 0.1%. In the data reported

[2] H. Weisberg and V. Perez-Mendez, Lawrence Radiation Laboratory Report No. UCRL-16704, 1966 (unpublished); Nucl. Instr. Methods 46, 233 (1967).

here there were 125 π^+-π^--π^+ sequences, so that any errors in field settings tended to average out. While fields in the beam-transport magnets were reversed in order to change polarity, the stray magnetic field from the cyclotron was constant. From measurements of that field it is estimated that this could have accounted for a momentum difference of at most 0.1%.

Several methods were used to check for a momentum difference. A time-of-flight measurement assured equality only to about 1%. A range measurement gave $(\langle p_+\rangle/\langle p_-\rangle)-1=-0.002\pm0.004$. The most accurate determination of the relative mean momenta was provided by measuring for each sign of particle the efficiency of the Čerenkov counter as a function of beam momentum, which was varied by changing the fields in M_1 and M_2. The resulting steep-sided curves, which were a fold of beam momentum spread and counter response, matched closely and gave $(\langle p_+\rangle/\langle p_-\rangle)-1=0.001\pm0.001$. Another momentum comparison was made at the end of the experiment by bending the beams through 78 deg with an analyzing magnet placed after counter A_4. This field was monitored by a nuclear-magnetic-resonance probe throughout both the momentum analysis and an extensive field mapping. The entrance and exit beam trajectories were determined by profiles taken with the digitized spark chamber at six positions. The vacuum system was extended at each position so that no multiple-scattering material was placed in the beam. The

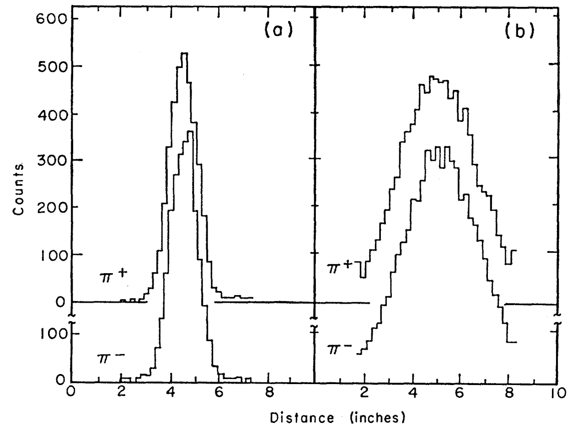

FIG. 3. Beam profiles taken with a digitized spark chamber. Data were taken in 0.1-in. intervals, but pairs of channels have been added together here for clarity. (a) Profiles at the end of the 36-ft decay path for π^+ and π^-, showing the similarity in their beam shapes. The relative horizontal scale has been shifted to permit easier comparison. Note that the tails of the profiles, which are the same for positives and negatives, are not due to pions, since the Čerenkov counter gives no counts in those regions; (b) profiles 12 ft beyond a 78-deg bend, showing the similarity in central momentum and momentum spread for the π^+ and π^- beams.

positive and negative profiles were taken alternately, and their centroids and shapes were determined with high accuracy, as shown in Fig. 3, permitting a good relative momentum determination, $(\langle p_+\rangle/\langle p_-\rangle)-1=-0.002\pm0.001$. Since the chamber positions were not known with comparable accuracy, the absolute momentum, 311.2 ± 1.0 MeV/c was determined much less precisely. The full momentum width at half-maximum of both beams was 2.5 MeV/c. As an average in determining lifetime ratios, we have used

$$(\langle p_+\rangle/\langle p_-\rangle)-1=-0.0005\pm0.0007.$$

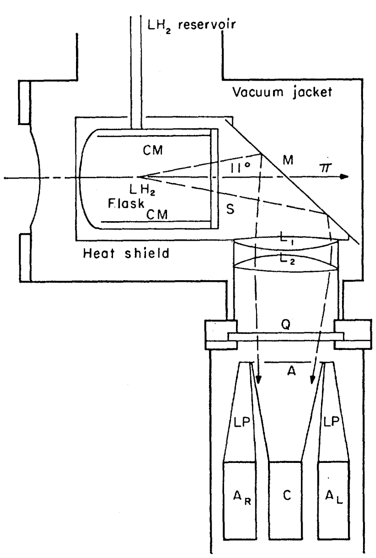

FIG. 2. Schematic drawing of the liquid-hydrogen differential Čerenkov counter. Note that the diameter of the ring focus depends on the angle of emission of the Čerenkov light (and hence the velocity of the particle), while the lateral position of the ring focus with respect to the ring aperture depends on the direction of the particle. The optically coaxial cylindrical mirror provides full efficiency across the 4-in. diameter of the radiator. LH_2: 4×8-in.-long liquid-hydrogen radiator. S: $\frac{1}{4}$-in. sapphire window. M: 45-deg mirror. L_1, L_2: quartz lenses. Q: quartz vacuum window. A: ring aperture. LP: anticoincidence-ring light pipes. C: coincidence photomultiplier. A_R, A_L: anticoincidence photomultipliers. CM: cylindrical mirror.

IV. ČERENKOV COUNTER RESPONSE

It is an important feature of our method that the efficiency of the movable Čerenkov counter neither has to be known nor does it have to be the same for π^+ and π^-. For absolute lifetime measurements the efficiency must not change over one sequence of counter positions. However, for the lifetime difference it is required only that the efficiency, if it changes, do so approximately linearly over the time required for one π^+-π^--π^+ sequence (about 3h). In the data reported here,[3] the order of the ten positions along the beam was shuffled, and two or more π^+-π^--π^+ sequences were taken at each position.

[3] Data reported by D. S. Ayres, R. D. Eandi, A. J. Greenberg, R. W. Kenney, R. J. Kurz, and B. Macdonald [*Proceedings of the Williamsburg Conference on Intermediate Energy Physics, 1966* (College of William and Mary, Williamsburg, Virginia, 1966), Vol. 1, p. 419] are not included here, although the results are quite similar, because counter A_e was not installed. Data reported by R. J. Kurz, D. S. Ayres, R. D. Eandi, A. J. Greenberg, R. W. Kenney, B. Macdonald, D. O. Caldwell, and B. F. Stearns [Bull. Am. Phys. Soc. 11, 309 (1966)] include only a small part of the data used here.

If the counter had a velocity response which was different for π^+ and π^-, this could produce an apparent lifetime difference. Such a systematic effect might occur because of the difference in π^+ and π^- interactions in hydrogen and their momentum dependence near the $\frac{3}{2}$-$\frac{3}{2}$ resonance. Calculations show this effect to be negligible, and the measured equality of the momentum response of the counter to positive and negative beams limits such an effect to 0.1% of the lifetime ratio.

Two difficulties arose in the counter operation. First, despite its being in vacuum, condensation accumulated slowly on the outer surface of the sapphire window, which was at 20°K. After about 24 h of operation, there was enough scattering of Čerenkov light into the anticoincidence ring to decrease the counter efficiency by about 1%. The counting rate in the ring aperture without anticoincidence was not changed.

The second difficulty was that the counter had an efficiency of 0.6% for both π^+ and π^- without liquid hydrogen. The source of counter-empty counts might have been light produced in the window by weak scintillation of the sapphire or by scattering from surface imperfections of Čerenkov radiation which should have been trapped in the window by total internal reflection. Range measurements, beam profiles, and attenuation with distance measurements all indicated that this counting rate was simply a constant fraction of the counter-full rate, and hence the correction for this effect is negligible. Another possible consequence of light from the window was the appearance of long tails on the measured distribution of counter response as a function of momentum.

Having discussed the four items of particular concern in achieving believable results, we now turn to the data analysis. The data, based on 12×10^6 π^+ and 6×10^6 π^-, were analyzed in two ways, both utilizing the measured quantities

$$\frac{\pi^\pm \text{ counts at position } x}{\text{monitor counts}} \equiv R_\pm(x) = \epsilon_\pm f_\pm \times \exp\left[-\left(\frac{mc}{p\tau}\right)_\pm x\right],$$

where $\epsilon_\pm$ is the movable-Čerenkov-counter efficiency for $\pi^\pm$, $f_\pm$ is the fraction of $\pi^\pm$ in the beam at $x=0$, and m, p, and τ are the mass, momentum, and mean lifetime of the pion. In the first method, the slope of a least-squares, straight-line fit to

$$\ln R_\pm(x) = \ln(\epsilon_\pm f_\pm) - (mc/p\tau)_\pm x \qquad (1)$$

gave the $\pi^\pm$ absolute lifetimes, it being required only that the (unnecessary) value of $\epsilon_\pm f_\pm$ be constant over one series of counter positions. In the second method, the slope of a straight-line fit to

$$\ln\frac{R_+(x)}{R_-(x)} = \ln\frac{\epsilon_+ f_+}{\epsilon_- f_-} - \left[\left(\frac{mc}{p\tau}\right)_+ - \left(\frac{mc}{p\tau}\right)_-\right]x \qquad (2)$$

is simply related to the lifetime difference $(\tau_+/\tau_-)-1$. Since $R_+(x)/R_-(x)$ is formed for each π^+-π^--π^+ sequence, any changes in $\epsilon_\pm f_\pm$ that are approximately linear over each sequence will still keep $\epsilon_+ f_+/\epsilon_- f_-$ constant.

Both analyses were done with and without the anticoincidence ring of the Čerenkov counter, and the values obtained for lifetime differences are in good agreement. Only the first method with the anticoincidence ring yields absolute lifetimes. Since the absolute-lifetime analysis is affected by variations of Čerenkov counter efficiency due to condensation on the sapphire window, no data were used for which the counter had been filled with liquid hydrogen for more than 12 h.

The relative lifetime analysis is shown in Table I. Note that data taken with the quadrupole Q out (0.04–0.23 mean lifetime) indicate $\tau_- > \tau_+$, but when these are fitted together with the Q-in data (0.20–0.78 lifetime) one gets $\tau_+ > \tau_-$ by a greater amount than is the case for the Q-in data by itself. The Q-in data were collected over 3 months with more than 100 π^+-π^--π^+ sequences and 7 positions, whereas the Q-out data were taken in 3 days at the end of the experiment, utilizing 18 sequences and 3 positions under significantly altered beam conditions. Thus our most reliable estimate of the lifetime difference, shown in Table II, is that given by the Q-in data alone analyzed by the relative method [Eq. (2)] with the anticoincidence ring. The standard deviation given there includes the relative momentum error, while the statistical and consistency errors are the same, since χ^2 per degree of freedom is 1.0 for over 100

TABLE I. π^+/π^- lifetime ratio analysis.

Data selection	Distance range (mean lifetimes)	$(\tau_+/\tau_-)-1$ No anticoincidence ring	With anticoincidence ring
All	0.04–0.78	0.0070±0.0023	0.0074±0.0025
Quad. out	0.04–0.23	−0.015 ±0.009	−0.024 ±0.016
Quad. in	0.20–0.78	0.0058±0.0024	0.0056±0.0028

TABLE II. Comparison of π^+ lifetime values and π^+/π^- lifetime ratios in recent experiments.

Reference	τ_+ (nsec)	$(\tau_+/\tau_-)-1$
Ashkin *et al.*[a]	25.46±0.32	···
Eckhouse *et al.*[b]	26.02±0.04	···
Kinsey *et al.*[c]	26.40±0.08	···
Bardon *et al.*[d]	25.6 ±0.3	0.0040±0.007
Lobkowicz *et al.*[e]	26.67±0.24	{0.0040±0.0018 {0.0023±0.0040
This experiment	26.6 ±0.2	0.0056±0.0028

[a] J. Ashkin, T. Fazzini, G. Fidecaro, Y. Goldschmidt-Clermont, N. H. Lipman, A. W. Merrison, and H. Paul, Nuovo Cimento **16**, 490 (1960).
[b] M. Eckhouse, R. J. Harris, Jr., W. B. Shuler, R. T. Siegel, and R. E. Welsh, Phys. Letters **19**, 348 (1965). The numbers quoted differ from the published values in accordance with a communication of the authors to A. H. Rosenfeld.
[c] K. F. Kinsey, F. L. Lobkowicz, and M. E. Nordberg, Jr., Phys. Rev. **144**, 1132 (1966).
[d] Reference 4.
[e] Reference 5.

data points. As a check on data consistency over a longer period, the absolute lifetime analysis using Eq. (1) with the anticoincidence ring gives $(\tau_+/\tau_-)-1=0.0060 \pm 0.0031$ over the same distance (0.20–0.78) lifetime. The corresponding value for the π^+ lifetime is also shown in Table II with a standard deviation that includes statistical and consistency errors as well as that in the absolute momentum. The latter result is in fair agreement with one of the two recent accurate determinations of τ_+, but not with the other.

As shown in Table II, the comparison of π^+ and π^- lifetimes agrees with the other two contemporaneous experiments.[4,5] The three experiments utilized quite different methods, and we should like to emphasize that the present experiment requires no corrections except for the very small one for a difference in the momenta. Using the same method with improved beam and counters, the experiment will be repeated shortly with greater precision[8].

[4] M. Bardon, U. Dore, D. Dorfan, M. Krieger, L. Lederman, and E. Schwarz, Phys. Rev. Letters **16**, 775 (1966).

[5] F. Lobkowicz, A. C. Melissinos, Y. Nagashima, S. Tewksbury, H. von Briesen, Jr., and J. D. Fox, Phys. Rev. Letters **17**, 548 (1966). The two values given for lifetime difference arise from different methods of averaging the data.

ACKNOWLEDGMENTS

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Excited-Droplet Model for $pp \rightarrow pN_{1/2}^*$ at High Energies*

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A surface-excitation droplet model for $N_{1/2}^*$ production in pp collisions at high energy and small momentum transfer is proposed which explains the Δ^2 dependence of the first two observed $I=\frac{1}{2}$ isobars.

IN the coherent-droplet model of Byers and Yang,[1] high-energy exchange reactions with small momentum transfer are pictured in terms analogous to small-angle elastic scattering of partially absorbing nuclei. The reactions are described in terms of a density function $\rho(r)$ which represents the optical-model density of hadron "matter." In this paper, a picture is proposed in which the significance of $\rho(r)$ is extended to a distribution of mass subject to coherent excitation in modes analogous to collective excitation of complex nuclei.

The proton and its excited states with the same isospin will be described in their own center-of-mass (c.m.) system by state functions $f(r)Y_L^M(\theta,\phi)\Psi$, where Ψ is a spinor. It will first of all be postulated that the "intrinsic" helicity component associated with Ψ is conserved in high-energy collisions, while the "spatial" part of the wave function provides a description of the excited states of the proton appropriate for the high-energy limit of the S-matrix elements.[2] The spin functions Ψ will, therefore, be ignored in the following discussion of S-matrix elements.

The second postulate to be made is that of "surface" modes of excitation; the radial wave functions are assumed to be similar in shape for all excited states, and overlap integrals with ground-state wave functions will be peaked at a radius associated with an effective elastic scattering radius. This will enable use of the Austern-Blair[3] approach to connect inelastic and elastic channels.

A third postulate is the diffraction-excitation (or "dissociation")[4] mechanism which suggests that in

* Work performed under the auspices of the U. S. Atomic Energy Commission

[1] N. Byers and C. N. Yang, Phys. Rev. **142**, 976 (1966).

[2] This decoupling of intrinsic and collective excitation components of the angular momentum of the state presumably cannot be a symmetry of the S matrix at rest since in that case there would be a doubling of $N^*_{1/2}$ parities not observed experimentally. The spin and parity of each N^* depends on a coupling of intrinsic (ψ) and collective (Y_L^M) degrees of freedom.

[3] N. Austern and J. S. Blair, Ann. Phys. (N. Y.) **33**, 15 (1965); W. H. Bassichis and A. Dar, *ibid.* **36**, 130 (1966). The form of the matrix element in the model presented here corresponds to a δ-function interaction potential between projectile and the hadronic matter distribution.

[4] M. Ross and L. Stodolsky, Phys. Rev. **149**, 1172 (1966).