# PHENOMENOLOGY OF COMPLEX SPIN TACHYONS

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A preliminary formulation of a phenomenology of negative mass squared resonances (NMSR) is described. The angular distribution of pion-nucleon charge exchange scattering is interpreted in terms of these objects. Negative mass squared resonances have as their spin projection operator a member of the principal series $j = -\frac{1}{2} + i\sigma$ of irreducible representation of the little group 0(2,1). A fit of the experimental data for laboratory momenta from 5.9 to 18.2 GeV/c requires a NMSR with $-m^2 = 1.0\ (\mathrm{GeV/c})^2$, a total width $\Gamma = 0.3$ GeV and $\sigma = 1.1$.

Several physical problems of great interest persuade us to consider the possibility of complex mass particles. The most familiar one is the description of unstable particles by poles in the complex energy plane. Attempts to construct a finite quantum electrodynamics lead to the introduction of complex mass particles, where the occurrence of physical complex mass states in the physical region is avoided by the use of an indefinite matrix which enables one to represent them by null vector.

Here we wish to discuss the possibility of observing particles with negative squared mass. We include the possibility that such states may be unstable and therefore refer to them as negative mass squared resonances (NMSR). Such NMSR's would be identical to particles that travel faster than light which were proposed a long time ago [1]. The existence of such particles is possible is we agree that both the total energy (squared), $E^2$, and the three momentum $\underset{\sim}{p}^2$ are observables. Their difference, $(E^2 - \underset{\sim}{p}^2)$ is defined as the squared rest mass, $m_0^2$ :

$$E^2 - \underline{p}^2 = m_0^2 \quad \begin{array}{ll} = 0 & \text{Luxon } (v = c) \text{ Luminal} \\ > 0 & \text{Tardyons } (v < c) \text{ Subluminal} \\ < 0 & \text{Tachyon } (v > c) \text{ Superluminal} \end{array} \tag{1}$$

The rest mass itself need not be a directly observable quantity; for the photon it is not. For ordinary particles $m_0^2$ is positive. For photons we get a consistent description if we put $m_0 = 0$. In a similar way we obtain consistency with the equations of relativity if we introduce a purely imaginary rest mass $m_0 = i\mu$ (which implies $m_0^2 < 0$) for particles that go faster than light. Specifically we retain the energy

$$E = \frac{m_0 c^2}{\qquad} = \frac{i\mu c^2}{\qquad} \tag{2}$$

as a real quantity. The first member of this equation is valid for all slower than light particles (tarydons). The second member is valid for particles with $\beta = v/c > 1$. Note that as the velocity of a superluminal particle increases its energy decreases and eventually goes to zero. In passing we note that the momentum approaches the constant value $\mu c$ as the speed goes to infinity.

$$P = mv = \frac{\beta E}{c} = \frac{\mu c \beta}{\sqrt{\beta^2 - 1}} \xrightarrow{\beta \to \infty} \mu c, \tag{3}$$

At present we know of no argument that would exclude the existence of such particles nor of any direct evidence for their existence. Therefore this becomes an *experimental question*. So far experimenters must grope very much in the dark, as nothing is known about the interaction of NMSR's.

Since the proposal for the existence of particles that travel faster than light several ingenious experiments were undertaken to detect stable particles of this nature [2,3]. The first one tried to detect charged tachyons either by their electromagnetic bending or by the Cerenkow radiation which would be emitted by a superluminal particle. The second group of experimenters searched for negative missing masses squared [4] in the reaction $K^- p \to \Lambda \tau^0$ or $K^- p \to \Lambda \tau \bar{\tau}$ . ( $\tau^0$ = neutral tachyon ).

## Phenomenology of Complex Spin Tachyons

We assume the existence of strongly interacting NMSR's and show that they can appear as secondary peaks in the angular distribution of many of the reactions which have already been studied experimentally. This comes about because for the exchange of a negative $m_0^2$ resonance the propagator will have a sharp maximum in the differential scattering cross section. Indeed a common feature of the data available is the appearance, for a wide range of processes and energies, of a secondary maximum at a negative mass squared or $t = -1.0\ (\mathrm{GeV}/c)^2$. It is possible to give this secondary maximum a resonance interpretation. It is hoped that a systematic study of the position and quantum numbers of such enhancements would furnish useful hints for planning a production experiment.

In the following we will always describe the process in terms of the incident energy (squared) which we associate with the $s$ variable and in terms of the square of the four momentum transfer as the $t$ variable. An immediate consequence of the resonance interpretation of the secondary maximum is that the position of the peak should be independent of the incident energy. As for positive $m_0^2$ particles, we describe the data in the $t$ resonance region by a Breit-Wigner form. As in Regge theory, the energy dependence of the height of the peak will be determined directly by the spin structure of the NMSR.

Positive mass squared resonances appear as peaks in the distribution corresponding to the energy variable. The little group of the Poincaré for particles of positive mass squared is 0(3). If the scattering is to go through this state then the angular distribution must be described in terms of Legendre functions of integer order.

Negative mass squared particles would be classified according to irreducible representations of the Poincaré group corresponding to the little group 0(2,1). If the scattering is to go through the negative mass squared state it must be described in terms of an irreducible representation of 0(2,1). The scattering amplitude in the resonance region is then given by the little group decomposition shown below [7].

$$\langle P_3\lambda_3, P_4\lambda_4 \,|T|\, P_1\lambda_1, P_2\lambda_2\rangle = \sum_{\mu_1\mu_3} A_s(\mu_1, \mu_3)$$

$$\int_{-\frac{1}{2}-i\infty}^{-\frac{1}{2}+i\infty} dj\ \frac{2j+1}{\tan \pi i}\ \langle\lambda_2\lambda_4 \quad T^j(t)| \quad |\lambda_1\lambda_3\rangle\, d^{j}_{\lambda_4-\lambda_{\cdot},\ \ -\mu_3}(\cosh\beta) \tag{4}$$

$$+ \sum_{0<j<M-1} (2j+1)\langle\lambda_2\lambda_4 \quad T^{j\pm}(t) \quad |\lambda_1\lambda_3\rangle\, d^{j\pm}_{\lambda_4-\lambda_2,\,\mu\,-\mu_3}(\cosh\beta)$$

Here $d^{j}_{\lambda_4-\lambda_2,\lambda_1-\lambda_3}$ is the d function for the principal series, $d^{j\pm}_{\lambda_4-\lambda_2,\lambda_1-\lambda_3}$ is that for the discrete series with $d^{j+}$ appearing when both $\lambda_4-\lambda_2$ and $\lambda_1-\lambda_3$ are positive and $d^{j-}$ appearing when both are negative. Further, we have above

$$\cosh\beta = \frac{2(s-m_1^2-m_2^2)+t}{[(4m_1^2-t)(4m_2^2-t)]^{1/2}}, \quad M=\min(|\mu_1-\mu_3|,|\lambda_4-\lambda_2|), \tag{5}$$

and $A_s(\mu_1,\mu_3)$ consist of spin rearrangement factors as given in [7]. Our interpretation of the NMSR requires that the reduced matrix element above be of the form

$$\langle\lambda_4\lambda_2\,|\,|T^{(j)}|\,|00\rangle = \frac{\text{Residue}\,[\![\langle\lambda_4\lambda_2\,|\,|T^{(j_0)}|\,|\lambda_3\lambda_1\rangle]\!]}{t+m_0^2-i\,|m_0|\Gamma}\,\delta(j-j_0) \tag{6}$$

where $\Gamma$ is the full width at half maximum and the resonance has a definite spin.

The relative contribution of the NMSR to the full amplitude depends strongly upon the competing processes present which determine the background to the NMSR peak. We have chosen as a test fit for the NMSR parameterization, high energy $\pi N$ charge exchange, where for us, the rho meson exchange is the only competing process.

## ANALYSIS OF $\pi$N CHARGE EXCHANGE

In this case $p_1,p_2$ corresponds to the CM four momenta of the initial $\pi$ and proton while $p_3,p_4$ specify the CM four momenta of the final $\pi^0$ and neutron, respectively ($M_N$ and $M_\pi$ denote the nucleon and pion masses respectively). Here $s=(p_1+p_2)^2$ and $t=(p_1-p_3)^2$.

Taking $f_{++}(t)$ and $f_{+-}(t)$ to designate the t-reaction channel helicity non-flip and flip amplitudes, respectively, $\pm$ denoting proton helicities $\lambda=\pm 1/2$, the spin averaged differential cross section $\frac{d\sigma}{dt}$ and polarization P are given by

$$\frac{d\sigma}{dt} = \frac{1}{\pi}\,\frac{1}{\Delta^2(s,M_P^2,M_\pi^2)}\,[\![\,|f_{++}|^2+|f_{+-}|^2\,]\!], \tag{7}$$

$$P\frac{d\sigma}{dt} = \frac{1}{\pi}\,\frac{1}{\Delta^2(s,M_P^2,M_\pi^2)}\,2\,\mathrm{Im}\,(f^*_{+-}f_{++}), \tag{8}$$

where $\Delta^2(a,b,c)=a^2+b^2+c^2-2ab-2ac-2bc$.

Our assumption is that for t up to and including the secondary maximum region in $\frac{d\sigma}{dt}$, the NMSR region, one can describe $f_{++}$ and $f_{+-}$ as sum of the

NMSR part, denoted $f^{\tau}$, plus the competing phenomenological background contribution denoted by $f^{\rho}$.

$$f_{++} = f^{\rho}_{++} + f^{\tau}_{++}; \quad f_{+-} = f^{\rho}_{+-} + f^{\tau}_{+-} \tag{9}$$

$f^{\rho}$ dominates in the near forward region while $f^{\tau}$ dominates in the region of the secondary peak.

The phenomenological form for $f^{\rho}$ is based on the identification of the competing process as peripheral rho meson exchange. This requires that $f^{\rho}$ have the t dependence of the rho meson pole. There are additional t factors which are derived from kinematic constraints. For the s dependence of the background we utilize $s^{\alpha(t)}$ which is consistent with the observed shrinkage of the forward peak. The forward peak is well described by $\alpha$ (t) which is a $\alpha(t) = \alpha(0) + t\,\alpha'(0)$ with $\alpha'(0) = 1.0\ (\mathrm{GeV/c})^{-2}$ and $\alpha(0) = 0.58$. The background amplitudes are

$$f^{\rho}_{++} = \frac{b_{++}(s/s_0)^{\alpha(t)}}{\sqrt{t - 4M_p^2} \quad t - M_\rho^2} \tag{10}$$

$$f^{\rho}_{+-} = ib_{+-}\ \sqrt{t(t - 4M_\pi^2)} \quad \frac{(s/s_0)^{\alpha(t)}}{t - M_\rho^2} \tag{11}$$

The value of $s_0$, $b_{++}$ and $b_{+-}$ are fit to the data. Two cases were tested. In the first $b_{++}$ and $b_{+-}$ were assumed to be real constants, while in the second $b_{+-}$ was assumed to be proportional to $\alpha(t)$, thus producing an effective nonsense wrong signature dip.

The NMSR contribution $f^{\tau}$ for this process is obtained from Eq. (1) and (3). Using $j_0 = -\frac{1}{2} + i\sigma$, $\lambda_1 = \lambda_3 = 0$ and $\lambda_2 = \frac{1}{2}$; $f^{\tau}_{++}$ becomes

$$f^{\tau}_{++} = \frac{2\sigma}{\cosh \pi\sigma} \quad \frac{\lambda_{++}}{t + m_0^2 - i\Gamma|m_0|} \quad d^{-\frac{1}{2}+i\sigma}_{0,0}(\cosh\beta), \tag{12}$$

$$f^{\tau}_{+-} = \frac{2\sigma}{\coth \pi\sigma} \quad \frac{\lambda_{+-}}{t + m_0^2 - i\Gamma|m_0|} \quad d^{-\frac{1}{2}+i\sigma}_{1,0}(\cosh\beta). \tag{13}$$

In the above $\lambda_{++}$ and $\lambda_{+-}$ are real constants that are fitted to the data.

The fit to the data [8,9] of this model for $d\sigma/dt$ and the polarization P(t) are given in Figs. 1 and 2. Several interesting points regarding the fit were discovered. The different forms of $b_{+-}$ used in the two cases resulted in minor changes in the angular distribution. The dip at $t \cong 0.6$ occurs with or without the nonsense wrong signature zero. In Fig. 1, we show only the fit for the first case. The NMSR parameters are found to be effectively the same in the two cases. The polarization differs markedly and shows that while the prediction of a polarization is directly related to the existence of the NMSR, its detailed form is strongly dependent upon the form of the background. The solution corresponding to the first case, $b_{+-}$ constant, was favored on the basis of chi squared probability. Another fit is possible with a smaller imaginary spin part, i.e. $\alpha \simeq 0.1$. This fit had a slightly higher chi square than the fit corresponding to the larger $\alpha$ used in Figures 1 and 2.

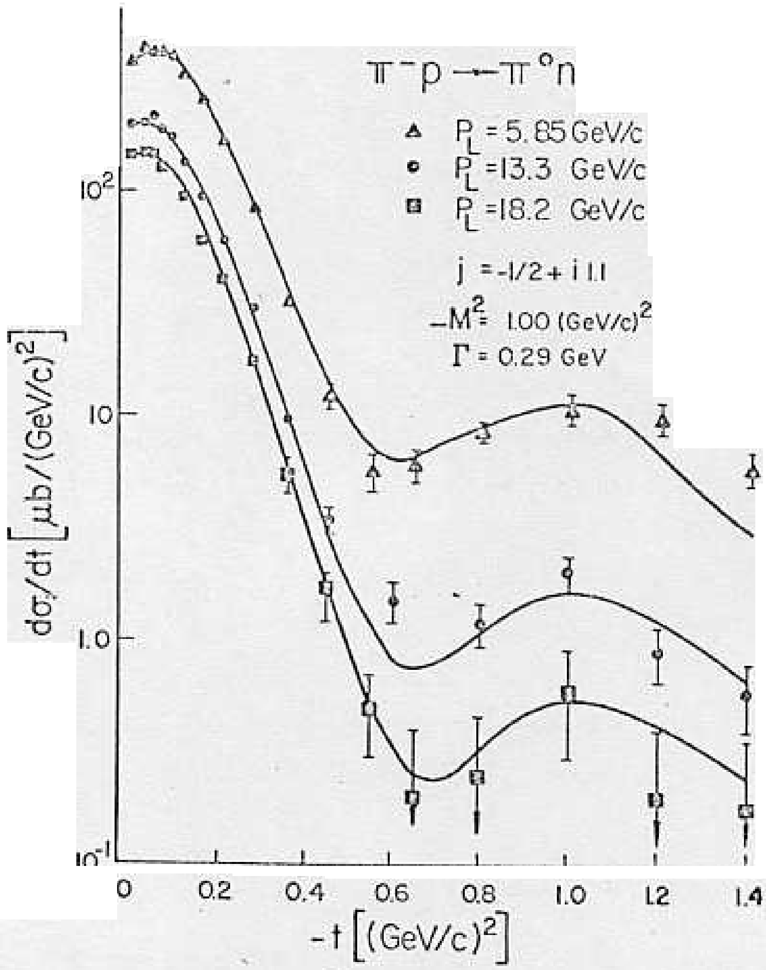


Figure 1. Differential cross section $\frac{d\sigma}{dt}$ as a function of t for laboratory momenta of the pion $P_L$=5.85, 13.3, 18.2 Ge V/c. Data points are from [8]. The smooth curve represents a best fit to the data as described in the text. The parameters for the background contribution depend somewhat upon the form of amplitude used.

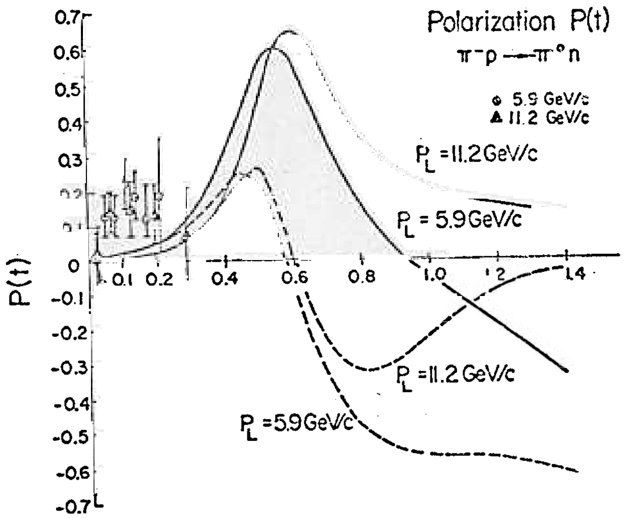


Figure 2. Polarization P(t) for laboratory momentum $P_L$ of 5.9 and 11.2 GeV/c. Data points are from [9]. The solid curve corresponds to case 1 where $b_{+-}$ is constant and the dashed line to case 2 where $b_{+-} \propto \alpha(t)$.

## CONCLUSIONS

Figs. 1 and 2 show that the NMSR provides a consistent interpretation of the secondary peak in the angular distribution of pion nucleon charge exchange scattering with no more parameters than most Regge models. Our use of NMSR's for the π-N charge exchange process provides an alternative and probably not contradictory approach to the usual Regge fits with linear trajectories. The latter approach cannot simultaneously explain the forward and secondary peaks, as well as the polarization, without introducing a secondary trajectory corresponding to particles which do not seem to be present in a well searched region of the meson spectrum.

If NMSR's exist, we should expect to see their contribution in other related processes where the exchanged quantum numbers are appropriate. Ror example, we would expect to find the same NMSR that was responsible for the secondary peak in π N charge exchange also occuring in $K^0$ n, $K^-$p, np and $\bar{p}$p charge exchange. These latter processes would be expected to have secondary peaks in $d\sigma/dt$ at $t \cong -1.0$ (GeV/c) with the same energy dependence and width as in π-p charge exchange scattering. In fact, a secondary maximum occurs at $t \cong -1.0$ (GeV/c) in

$K^- p \to K^0 n$ [10] and there are indications for similar effects in np charge exchange [11] and possibly pp charge exchange as well [12]. A more detailed study of these processes is indicated. Baryonic NMSR's would show up as peaks in the backward scattering differential cross sections.

In general, there may be other dynamical mechanisms which operate independently of the NMSR contribution and consequently the extent to which secondary peaking in t would be visible varies. This condition prevails in some elastic scattering processes where background may obscure the NMSR contribution and, or, the presence of more than one NMSR may make the secondary peaking less distinct. For example, in elastic scattering, in addition to the background produced by the vector meson exchange there is Pomeranchuk exchange.

We would also like to review the failure of experiments using missing mass spectroscopy to detect NMSR's. One notes immediately that the region searched in these experiments corresponds to absolute values of squared mass which are much too low for the production of a -1 $(GeV/c)^2$ NMSR. The calibration of missing mass spectrometer experiments [4] is such a case. Here for the values of $m_0^2 > -0.1\ (GeV)^2$ no indications of NMSR's have been found. Similarly the Columbia experiment [5] searched in the vicinity of $m_0^2 > -0.15\ (GeV)^2$ and found no events.

A more basic reason why these experiments do not apply to our indentification of NMSR's is that they were intrinsically restricted to searching for stable negative mass squared particles. The resonance nature of the state requires that it can not propagate freely for distances large compared to the inverse width. This requires that there be another hadronic particle within nuclear dimensions to which the NMSR can "attach" itself. If a stable tachyon with appropriate quantum numbers exist then the NMSR can decay into it plus some tardyon. If stable tachyons do not exist then the missing mass spectrometer experiments performed to date would not detect NMSR's even if they existed. Even if no stable tachyons existed, the search for NMSR's can be performed in two ways. When it is observed as an exchanged resonance in a process similar to the $\pi$ P charge exchange which we have analyzed above. It can also be observed in missing mass spectrometer experiments involving targets of deuterons or more complicated nuclei which should include values of missing mass squared of -1.0 $(\mathrm{GeV})^2$.

The situation is entirely different for the detection of tachyon pairs. We recall that independent of the rest mass the energy of a NMSR can become arbitrarily small as its speed grows larger. In particular the two momenta, which remain finite, can balance each other as vectors. In such a case we will see all possible "missing masses" including zero missing mass stretching from $-4\,|M|^2$ to $+\infty$, provided such a continuous spectrum can be disentangled from an instrumental background.

## REFERENCES

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1. O.M. Bilaniuk, V. K. Deshpande, E. C. G. Sudarshan; American Journal of Physics 30, 718 (1962).
2. T. Alväger and P. Erman, Nobel Institute Report, Stockholm (1966). T. Alväger and M. N. Kreisler, Phys. Rev. 171, 1357 (1968).
3. G. Feinberg, Scientific American 222, 68 (1970). C. Baltay, G. Feinberg, N. Yeh, R. Linsker, Phys. Rev. (to be published).
4. E. C. G. Sudarshan, Arkiv för Fysik 39, 585 (1969).
5. H. Brody, B. Maglic and R. Schluter, proposal to PPA.
6. G. Pinski, E. C. G. Sudarshan, K. T. Mahanthappa, 173, Proceedings of Tenth Rochester Conference (1960); B. C. Maglic, L. W. Alvarez, A. H. Rosenfeld and M. L. Stevenson, Phys. Rev. Letters 7, 178 (1961); A. R. Erwin, R. March, W. D. Walker and E. West, Phys. Rev. Letters 6, 628 (1961).
7. We assume that the NMSR can be described in terms of the principle and discrete series alone following J. F. Boyce, R. Delbourgo, A. Salam and J. Strathdee, International Center for Theoretical Physics, Trieste report IC/67/9 (1967), unpublished.
8. A. V. Stirling et al., Phys. Rev. Letters 14, 763 (1965); P. Sonderegger et al., Phys. Letters 20, 75 (1966).
9. P. Bonamy et al., Phys. Rev. Letters 23, 501 (1966).
10. P. Astbury, et al., Phys. Rev. Letters 23, 396 (1966).
11. R. Good, N. Xuong, Phys. Rev. Letters 14, 191 (1965).
12. P. Astbury, B. Gobbi, M. Pepin, Phys. Letters 23, 160 (1966).

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