The S(1934)

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A possible signal for the S(1934) is found in $\bar{p}p$ backward-elastic-scattering data when compared to a model for $\bar{N}N$ scattering. The resonance parameters are found to be $E_R = 1934 \pm 3$ MeV and $\Gamma = 6 \pm 4$ MeV. A clear effect in the backward cross section need not be accompanied by an equally pronounced effect in σ_T.

I. INTRODUCTION

The new experimental possibilities offered by the Low Energy Antiproton Ring (LEAR) at CERN, place the S(1934) meson once again in the center of interest.

The search for the S dates back from 1966 when a structure at $E_{\text{c.m.}} \approx 1930$ MeV was observed in a production experiment.[1] Since that time in several (photo)production experiments[2] and in formation experiments[3] measuring the total antiproton-proton ($\bar{p}p$) cross section σ_T and annihilation cross section σ_A the S meson was seen. One of the most pronounced indications for the S was found by Brückner *et al.*[4] in 1977.

However, since about 1977 a whole sequence of experiments[5] failed to show any sign of the S and others gave only a weak signal.[6] A critical review on several of the formation experiments can be found in Ref. 7. In a recent experiment[8] at LEAR measuring σ_T, no evidence was found for the S. The conclusion is that despite all the experimental effort, the mere existence of the S remains questionable.

The search for the S stimulated and was stimulated by theoretical investigations. It was speculated that indeed an S meson might exist, pictured either as a "nuclear resonance" of the antinucleon-nucleon ($\bar{N}N$) system[9] or as an antidiquark-diquark state, called baryonium.[10]

In the various models many states are predicted, above and below the $\bar{p}p$ threshold. However, no agreement exists concerning their positions and widths.

One of the experiments specifically designed to look for a structure in the S region, i.e., around $p_{\text{lab}} = 509$ MeV/c or $E_{\text{c.m.}} = 1940$ MeV, was an accurate measurement of the $\bar{p}p$ backward-elastic cross section by Alston-Garnjost *et al.*[11] The cross section in the backward direction was chosen because it is small compared to the cross section in more forward directions and a (weak) resonance signal might then have a relatively large influence there. Unfortunately, at $p_{\text{lab}} \approx 509$ MeV/c, the backward cross section reaches, as a function of momentum, its first diffraction maximum. Any possible resonant structure in the S region would then sit on top of this broad bump. In Sec. II we investigate in more detail whether or not a resonance can be seen in these data. This is done by comparing the results of this experiment to a model for $\bar{N}N$ scattering. The comparison suggests that possibly a resonance is present. In order to characterize the features of a resonance we use a new resonance parametrization which is briefly described in Sec. III. The resulting resonance parameters for the S are discussed in Sec. IV and the influence on cross sections of a resonance is discussed in Sec. V. Finally we make some suggestions for future experiments.

II. BACKWARD CROSS SECTION

In the experiment of Alston-Garnjost *et al.*[11] the differential elastic cross section $d\sigma_{\text{el}}/d\Omega$ at $\cos(\theta_{\text{c.m.}}) = -0.994$ was measured at 30 momenta between 406 and 922 MeV/c. The experimentalists fitted the data with a fifth-order polynomial in p_{lab}, obtaining $\chi^2/\text{DF} = 0.711$. They find no evidence at the 0.1 mb/sr level for a narrow ($\Gamma < 10$ MeV) resonance in the S region.

Recently we have developed a coupled-channels model for $\bar{N}N$ scattering,[12] which provides a good fit ($\chi^2/\text{data} = 1.39$) to an extensive set (977 data points) of $\bar{p}p$

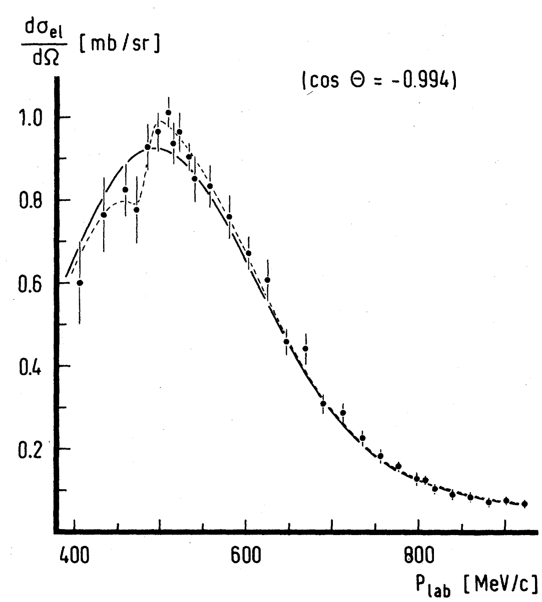

FIG. 1. $\bar{p}p$ backward elastic cross section. Solid curve: fit of Ref. 12 to the $\bar{p}p$ $d\sigma_{el}/d\Omega(180°)$ data of Ref. 11. Dashed curve: fit including a resonance in the $^{11}D_2$ partial wave, with parameters $E_R = 1934$ MeV ($p_{\text{lab}} = 482.3$ MeV/c), $\Gamma = 6$ MeV, $\alpha = 1.65$, $\beta = 0.75$.

total, charge-exchange, and differential elastic and exchange cross sections.

One of the sets also included in this fit is the above-mentioned backward cross section.[11] These 30 data points (see Fig. 1) have with respect to our model a total $\chi^2_{\rm tot}=29.4$ or $\chi^2/\text{data}=0.98$. Our model curve (the solid curve in Fig. 1) is, of course, also constrained by the fit to the other 947 $\bar{p}p$ scattering data.

A detailed comparison of the experimental backward cross section points and our model curve shows that the five neighboring points at 498, 510, 516, 523, and 534 MeV/c contribute 10.3 to this total $\chi^2_{\rm tot}$ of 29.4. A bump structure (or dip-bump when including lower momenta) seems to be present, suggestively located at the same momentum as enhancements seen in σ_T and σ_A (Refs. 3, 4, and 6).

We tried to test the significance of this structure as follows. First we would like to be reasonably sure that the data points (excluding the structure) are spread around our model curve according to an assumed (in our case Gaussian) probability distribution.

When we leave out the above-mentioned five points (or eight points between 460 and 534 MeV/c), we find that the deviations from the curve (scaled by the experimental error) have an average value $\overline{m}=-0.226$ (or -0.379), which shows that the model curve is systematically somewhat too low compared to experiment. The variance of these scaled deviations is $\bar{\sigma}=0.846$ (or 0.738). Ideally the mean and variance would be $m=0.0$ and $\sigma=1.0$.

When we assume that 4 out of the 14 parameters of our model[12] are needed to fit the backward elastic cross section, the probability that we find this $\bar{\sigma}$ or one with a larger deviation from 1 is about 70% (or 50%). The Shapiro-Wilk test[13] gives 86% (or 60%) reliability that the points are spread according to a Gaussian distribution (with mean $\overline{m}$ and variance $\bar{\sigma}$). One can also use the Kolmogorov-Smirnov test[13] to test the assumption of normal distribution with $\sigma=1$ (and mean $\overline{m}$). It yields a reliability of 72% (or 55%). These numbers show that the assumption of a Gaussian probability function was reasonable.

Assuming then that the model curve may be shifted over $\overline{m}$ and that we can use a Gaussian probability function (with $\sigma=1$) we calculated[14] the probability that 5 (or 8) consecutive points with these deviations occur. The probability turned out to be 0.8% (or 0.1%). Other groups of 4 to 6 points on a row which lie above or below the model curve have a probability of appearance larger than 7%.

Summarizing, we believe it is unlikely that the observed deviations around $p_{\rm lab}=509$ MeV/c are of statistical origin only. Besides, it is striking that these deviations occur right at the point where in other experiments the S was seen.

The result of our model[12] suggests that the fit of the experimentalists, with a six-parameter polynomial through the 30 data points is probably overparametrized. Our more realistic model for a smooth backward cross section gives a reasonable fit to all points apart from those around $p_{\rm lab}=509$ MeV/c, where a dip-bump or bump structure might be present. In another model for $\overline{N}N$ scattering[15] a comparable situation in the backward cross section can be seen.

III. PARAMETRIZATION

Let us now assume that indeed a resonance is present. Can the data tell us then something more about it? In order to find this out we tried to fit this remaining structure by including a resonant amplitude in a certain partial wave. We briefly sketch the way in which the resonance is parametrized. A detailed description of this parametrization can be found elsewhere.[16]

The partial-wave background S matrix for n channels is a unitary and symmetric matrix and can be written as[17]

$$\mathscr{S}_{\rm bg}=\mathscr{U}\tilde{\mathscr{U}}\ , \tag{1}$$

where $\mathscr{U}$ is an $n\times n$ unitary matrix. The elastic matrix element is usually parametrized as

$$S_{\rm bg}=(\mathscr{S}_{\rm bg})_{11}=\eta\exp(2i\delta)\ .$$

The multichannel S matrix, with a resonance included, is written as

$$\mathscr{S}=\mathscr{U}\mathscr{S}_{\rm BW}\tilde{\mathscr{U}}\ , \tag{2}$$

where $\mathscr{S}_{\rm BW}$ is the multichannel Breit-Wigner formula:

$$\mathscr{S}_{\rm BW}=\mathbb{1}_n-\frac{2i\gamma\tilde{\gamma}}{(2/\Gamma)(E-E_R)+i}\ , \tag{3}$$

where the fractions γ_i are real and satisfy

$$\sum_{i=1}^{n}{\gamma_i}^2=\tilde{\gamma}\gamma=1\ . \tag{4}$$

Writing the S matrix as in Eq. (2) automatically guarantees unitarity and symmetry. For the one-channel elastic part of $\mathscr{S}$ one then obtains from (2)

$$S_{\rm el}=(\mathscr{S})_{11}=S_{\rm bg}+z(S_R-1)\ , \tag{5}$$

with

$$S_R=\frac{E-E_R-i\Gamma/2}{E-E_R+i\Gamma/2}\ , \tag{6}$$

and

$$z=e^{2i\delta}\left[\left[\frac{1+\eta}{2}\right]^{1/2}\cos\alpha+i\left[\frac{1-\eta}{2}\right]^{1/2}\sin\alpha\cos\beta\right]^2 . \tag{7}$$

Here

$$\Gamma_{\rm el}=\Gamma\cos^2\alpha$$

is the width to the elastic channel, and

$$\Gamma_{\rm in'}=\Gamma\sin^2\alpha\cos^2\beta$$

is the width to the channels to which also the elastic channel decays. Since the resonance can also decay to channels to which the elastic channel is not coupled directly via the background, but only with the resonance as an intermediate state, one also has a "missing width" $\Gamma_{in''}$, i.e.,

$$\Gamma=\Gamma_{\rm el}+\Gamma_{\rm in'}+\Gamma_{\rm in''}\ .$$

The elastic and charge-exchange amplitudes are

$$f_{\rm el}=[f(I=0)+f(I=1)]/2\ ,$$
$$f_{\rm CE}=[f(I=0)-f(I=1)]/2\ , \tag{8}$$

from which the elastic $\bar{p}p$ partial-wave amplitude $f_{\rm el}$ follows as

$$f_{\rm el}=f_{\rm bg,el}+\frac{zf_R}{2}\ ,$$

where

$$f_R=(S_R-1)/2i\ , \tag{9}$$

and the charge-exchange amplitude ($\bar{p}p\to\bar{n}n$)

$$f_{\rm CE}=f_{\rm bg,CE}\pm\frac{zf_R}{2}\ . \tag{10}$$

An isospin $I=0$ or an $I=1$ resonance gives the plus or minus sign in (10).

For characterizing the resonance one has four parameters: E_R, Γ, $\Gamma_{\rm el}$, and $\Gamma_{\rm in'}$. Of course, these parameters can still be momentum dependent. That there are four parameters can also be seen in the Argand diagram of the elastic amplitude. In such a diagram, a resonance is represented by a circle attached to the point $f_{\rm bg}$. The circle has in general the following four characteristics. In the first place, the energy E_R is the energy corresponding to the point on the resonance circle right across the point $f_{\rm bg}$. Second, the total width Γ is related to the speed at which the circle is traversed at E_R. Third, the resonance circle has a certain radius, given by $|z|$. And finally it has an orientation, which is given by the phase of z [Eq. (7)]. It will be clear that unitarity imposes restrictions upon the values that the radius and orientation can have. They have to be such that the resonance circle always lies completely within the unitarity circle. The key feature of our parametrization is that it automatically guarantees unitarity (and symmetry) of the S matrix, and at the same time allows one to describe all possible resonance circles. No additional unitarity constraints, as in other parametrizations, are needed.

IV. RESONANCE PARAMETERS

We now use the resonance parametrization of the preceding section and apply it to the data described in Sec. II in order to find out whether we can determine the parameters of the presumed resonance. The smooth background S matrix is given by our coupled channels model for $\bar{N}N$ scattering. We include a single resonance in a specific partial wave (J,L,S,I). In this way we investigate systematically for all the relevant partial waves whether there might be a resonance in this wave. It seems a reasonable assumption to take E_R, Γ, $\Gamma_{\rm el}$, and $\Gamma_{\rm in'}$ energy-independent, since the structure extends only over a small region of energy compared to the distance to the $\bar{p}p$ threshold.

By adjusting the four parameters for each case, we make a best fit to the backward-elastic-cross-section data between 406 and 534 MeV/c.

We find that the data are not restrictive enough to allow a determination of the quantum numbers of the resonance. Each partial wave (up to $L=4$) can support equally well a resonance. In all cases the χ^2 of the fit to the backward cross section is much improved when a resonance is included: typically it is lowered from $\chi^2{}_{\rm tot}=29.4$ to $\chi^2{}_{\rm tot}\lesssim 17.0$, an improvement of more than 12 with only four additional parameters. This is another demonstration of the above-mentioned significance of the structure. In Fig. 1 an example of such a fit is given for the case where a resonance is put in the ${}^{11}D_2$ wave (dashed curve). However, the other waves give a similar plot.

The parameters E_R and Γ turn out to be almost independent of the particular partial wave in which the resonance is put. They are

$$E_R=1934\pm3\ \text{MeV},\quad \Gamma=6\pm4\ \text{MeV}\ .$$

These numbers are far from unrealistic. In Ref. 18 a value of $E_R=1935.3\pm1.0$ MeV is quoted, whereas no value for Γ is given.

The partial widths $\Gamma_{\rm el}$ and $\Gamma_{\rm in'}$ have widely different values among the partial waves. However, in all cases we find $\Gamma_{\rm el}/\Gamma<0.5$. This ratio between elastic and total width is given by α, which was always well determined by the fit to the data. The parameter β has in general a large error, which implies that the "missing width" $\Gamma-\Gamma_{\rm el}-\Gamma_{\rm in'}$ is not well fixed by the data.

V. CROSS SECTIONS

Some almost model-independent observations can be made about the difference in the total cross sections between the cases with and without a resonance. We denote this difference by $\Delta\sigma_T$, where $\Delta\sigma_T=(\sigma_T$ with a resonance)-(σ_T without a resonance).

The $\bar{p}p$ backward-elastic cross section is expressed in terms of the elastic partial-wave amplitudes $f_{\rm el}(J,L',L,S)$ for unpolarized $\bar{p}$ and p, as (leaving out the Coulomb-phases)

$$\frac{d\sigma_{\rm el}}{d\Omega}(180^\circ)=\tfrac{1}{4}\sum_{sm}\left|\sum_{JLL'}[(2L+1)(2L'+1)]^{1/2}C^{L\,S\,J}_{0\,m\,m}C^{L'S'J}_{0\ m\,m}f_{\rm el}(J,L',L,S)(-)^L\right|^2 \tag{11}$$

with $f_{\rm el}$ given in (8).

As one observes in Fig. 1, the best fit to the backward cross section, including a resonance, shows a dip-bump structure as a function of the momentum. In order to obtain for different partial waves (about) the same behavior of the backward cross section, it is clear that, due to the factor $(-)^L$, the partial-wave resonant amplitude $(zf_R/2)$ has to change sign between even-L and odd-L waves.

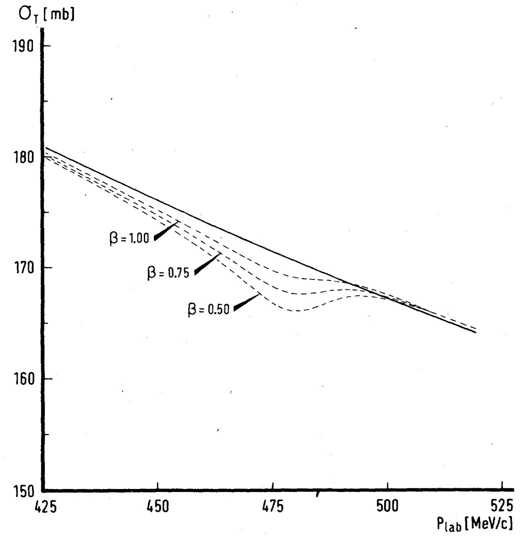

FIG. 2. $\bar{p}p$ total cross section. Solid curve: result of Ref. 12. Dashed curves: σ_T for a resonance in the ${}^{11}D_2$ wave. $\beta=0.75$ corresponds to the best fit to $d\sigma_{el}/d\Omega(180°)$. $\beta=0.50$ and $\beta=1.00$ increase the χ^2 of this fit by 1.5.

On the other hand, we have for $\Delta\sigma_T$

$$\Delta\sigma_T=\frac{\pi}{p}(2J+1)\mathrm{Im}\left[\frac{zf_R}{2}\right], \tag{12}$$

where p is the center-of-mass momentum. From this we observe that when $\Delta\sigma_T$ is positive at a certain momentum for $L=$even, then it will be negative for $L=$odd and vice versa. This implies for a dip-bump structure as function of the momentum in the backward cross section that we find in σ_T a dip-bump structure when $L=$even (negative parity) and a bump-dip structure as function of the momentum when $L=$odd (positive parity).

However, one should keep in mind that the actual height and depth of the bump-dip structure is also dependent upon β. This can also be seen in Fig. 2 for the ${}^{11}D_2$ wave. As a matter of fact we observe that in our fits in general only the dip (bump for negative parity) of $\Delta\sigma_T$ corresponding to the dip in the backward cross section might be observable, since the bump in σ_T that corresponds to the bump in $d\sigma_{el}/d\Omega(180°)$ is very weak. This specific feature depends upon the background value of the amplitude.

As a conclusion, we observe that the parity of the resonance can be determined from an accurate measurement of σ_T together with detailed data on the position and shape of the structure in the backward cross section.

In general the maximum value of $|\Delta\sigma_T|$ lies between 2 and 4 mb (depending upon the specific partial wave) for the best fit to the backward cross section. The maximum of $|\Delta\sigma_T|$ is very much dependent upon β (this can also be seen in Fig. 2). As mentioned before, β was not well fixed by the data. In fact, the error on this maximum value of $|\Delta\sigma_T|$ lies between 1 and 3 mb (again depending upon the partial wave). This means that a value of the maximum of $|\Delta\sigma_T|$ of about 1 mb is compatible with our fit to the backward cross section. The most accurate experiments[8] have a statistical error of about 0.9 mb in this momentum region.

Including a resonance, a large change in σ_A of some 10 mb at maximum is in our model only generated by a resonance coupled to the ${}^{31}P_1$ partial wave. Such a large effect is observed by Brückner *et al.*[4] However, in this case we find the change in σ_T also to be large, which is then again not in accordance with other experiments.

Note that a small effect in σ_T, accompanied by a clear effect in the backward cross section, can also be caused by a degenerate pair of resonances, provided they do not have the same parity.

Typically the change in σ_{CE}, due to a resonance, is smaller than 0.5 mb, for several partial waves even less than 0.1 mb. For a resonance coupled to the aforementioned ${}^{11}D_2$ partial wave the charge-exchange cross section is displayed in Fig. 3. The current (statistical) errors on σ_{CE} are about 0.2 mb. Therefore a single resonance with a definite isospin is compatible with no effect seen until now in σ_{CE}. Such a small effect in σ_{CE} might also be obtained with degenerate $I=0$ and $I=1$ resonances.[19] Due to lack of sufficient data in the backward elastic cross section, we could not test whether such a doublet is preferred.

Some years ago R. Tripp suggested[20] measuring carefully the energy dependence of the charge-exchange differential cross section in the backward direction, especially in the region of the S meson. In Fig. 4 we present our prediction for this backward cross section, in the case that a single resonance is included, either in $I=0$ or $I=1$. From all possible J^{PC} combinations we selected a typical example (${}^1D_2$). Because this charge-exchange backward cross section is at $p_{lab}=510$ MeV/c a factor of about 7 smaller than the elastic backward cross section, the relative effect of a resonance is roughly a factor $\sqrt{7}$ larger in the backward charge-exchange cross section. In the J^{PC}

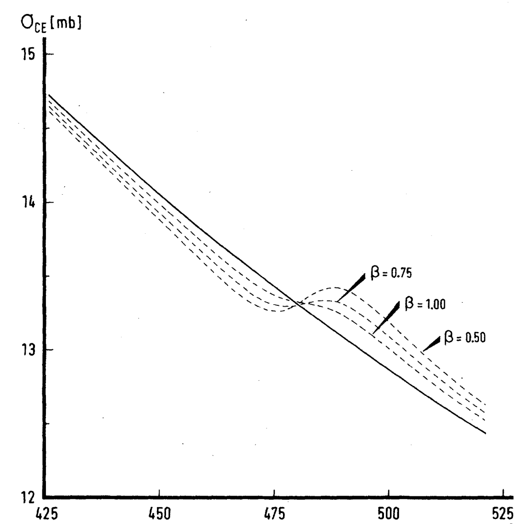

FIG. 3. The $\bar{p}p$ charge-exchange cross section. Solid curve: result of Ref. 12. Dashed curves: σ_{CE} including a resonance in the ${}^{11}D_2$ wave. See Fig. 2 for β.

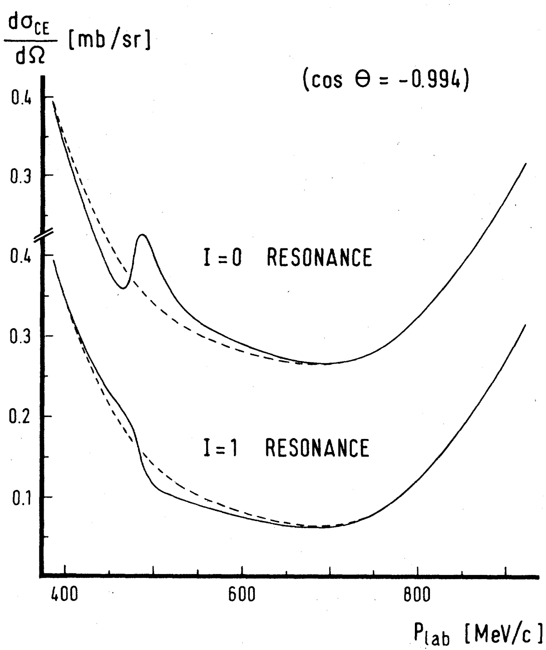

FIG. 4. The $\bar{p}p$ backward charge-exchange cross section. Solid curves: including a resonance in the $^1D_2$ wave. Dashed curves: result of Ref. 12.

cases considered by us an $I=0$ resonance always gives a bump at about 500 MeV/c and an $I=1$ resonance always produces there a dip. A measurement of this backward charge-exchange cross section will be a way to determine the isospin of the resonance.

In Ref. 11 it was argued that a resonance might show up relatively pronounced in the elastic cross section at 180°. We suggest that another good place to look for a resonance is the angle at which the differential cross section has its minimum (provided that the resonance is not exclusively coupled to the $\bar{p}p$ $L=4$ partial wave, since for this wave the Legendre polynomial reaches a zero about in this minimum of $d\sigma_{el}/d\Omega$). In our coupled-channels model we can accurately determine this angle, and the corresponding value of $d\sigma_{el}/d\Omega$.

We find

$$\cos\theta_{min}=0.4610+0.2436\times10^{-2}(p_{lab}-p_0) -0.1515\times10^{-4}(p_{lab}-p_0)^2 , \qquad (13)$$

$$\frac{d\sigma_{el}}{d\Omega}(\theta_{min})=0.3073-0.2012\times10^{-2}(p_{lab}-p_0) +0.1710\times10^{-5}(p_{lab}-p_0)^2 +0.2121\times10^{-7}(p_{lab}-p_0)^3 , \qquad (14)$$

where $p_0=500$ MeV/c and p_{lab} is in MeV/c. These formulas are accurate to 1% for $400<p_{lab}<650$ MeV/c.

Apart from more accurate measurements of $d\sigma_{el}/d\Omega(180°)$ and σ_T (which may provide the parity of the resonance), also a determination of $P(d\sigma_{el}/d\Omega)$, the polarization times the $\bar{p}p$ unpolarized elastic differential cross section, will be instructive. This quantity is equal to[21]

$$P(d\sigma_{el}/d\Omega)_{unpol}=\mathrm{Tr}(MM^\dagger\sigma_y) , \qquad (15)$$

where M is the full scattering amplitude matrix. Conservation of C parity implies that in $\bar{p}p$ the spin S is conserved. A resonance coupled to a singlet $S=0$ $\bar{N}N$ partial wave will then influence the differential cross section, but will leave $P(d\sigma_{el}/d\Omega)$ unaltered.

VI. CONCLUSION

We conclude that there is some evidence for a structure in the $\bar{p}p$ backward-elastic-cross-section data around $p_{lab}=509$ MeV/c. This structure can be fitted very well when a resonance is included with $E_R=1934\pm3$ MeV and $\Gamma=6\pm4$ MeV. Accurate measurements of σ_T together with $d\sigma_{el}/d\Omega$ (180°) can provide the parity of the resonance. However, it remains possible that a structure in the backward cross section is not accompanied by a likewise pronounced effect in σ_T, even with a single resonance. A measurement of the backward charge-exchange cross section can provide the isospin of the resonance.

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