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October 18, 1963

Final-State Interactions in the Decay $\eta \to 3\pi$ [†]

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October 18, 1963

In this Letter we present the results of an analysis of the Dalitz-Fabri plot of 97 eta decays, $\eta \to \pi^+ \pi^- \pi^0$. The etas were produced in the reaction $\pi^+ p \to \pi^+ p \eta$, by using π^+ of 1170 MeV/c (76 events) and 1050 MeV/c (21 events) incident on the Alvarez 72-in. hydrogen chamber. Our sample differs from previously published samples in two important respects.[1] First, our background is negligible.[2] Second, the contaminating decay mode $\eta \to \pi^+ \pi^- \gamma$, which is $26 \pm 8\%$ as probable as the $\pi^+ \pi^- \pi^0$ mode,[3] has been cleanly separated out and removed.[4]

We do not present here the complete Dalitz-Fabri plot,[5] but only its projection on the T_0 axis, where T_0 is the kinetic energy of the π^0. We first compare our spectrum with that given in the compilation of Berley et al.[1] The comparison is shown in Fig. 1. Agreement is only fair. In particular, our data show a more rapid decrease in intensity for T_0 greater than about 30 MeV than does the compilation. Our belief is that the disagreement is due to the unsubtracted background and the unseparated $\pi^+ \pi^- \gamma$ decays contained in the compilation.[1]

We now compare our spectrum with two theories. The first theory we call the linear-matrix-element theory.[6,7] We fit our spectrum to the formula

$$\frac{dN}{dT_0} = C\,|1 + a\,y\exp(i\beta)|^2\,\phi(y) = C(1 + 2a\,y\cos\beta + a^2 y^2)\phi(y),$$

where $y = 2(T_0/T_0^{max})-1$, so that $-1 \leq y \leq +1$; and where $\phi(y)$ is the Lorentz-invariant phase space. The constant C is chosen to normalize the area to 97 counts. We find a minimum $\chi^2 = 6.1$ for $\cos\beta = -1$ and $a = 0.71 \pm 0.09$. The expected χ^2 is 4.0 and the χ^2 probability for a fit as bad or worse is about 20%. The best fit to this theory is the "linear-matrix-element" curve shown in Fig. 2. From these parameters one can predict[6] the branching ratio

$$R \equiv \Gamma_\eta(000)/\Gamma_\eta(+-0) = (3/2)P/[1 + (a^2/4)],$$

where $P \sim 1.1$ corrects for $m_{\pi^0} \neq m_{\pi^+}$. Inserting our best-fit value $a = 0.71$, we obtain the prediction $R = 1.50 \pm 0.04$. This can be compared with the directly measured value,[8]

$$R = 0.83 \pm 0.32. \tag{1}$$

The χ^2 probability for agreement between the predicted and measured values of R is 3.8%. Thus the agreement is poor.

We next compare our spectrum with the theory of Brown and Singer.[9,10] In order to explain the unexpectedly large competition of the isospin-violating decay $\eta \rightarrow \pi^+\pi^-\pi^0$ with the electromagnetic decay $\eta \rightarrow \pi^+\pi^-\gamma$, they postulate that $\eta \rightarrow 3\pi$ proceeds via $\eta \rightarrow \sigma + \pi^0$, followed by $\sigma \rightarrow \pi^+\pi^-$ or $\sigma \rightarrow \pi^0\pi^0$. Here σ represents an $I = 0$ dipion resonance with 0^{++} quantum numbers. Angular-momentum conservation forbids $\eta \rightarrow \sigma + \gamma$, so that the 3π mode is enhanced but the $\pi^+\pi^-\gamma$ mode is not. Following Brown and Singer,[10] we fit our spectrum to the expression

$$dN/dT_0 = C\,\phi(T_0)[(T_0 - A)^2 + B^2]^{-1},$$

where $\phi(T_0)$ is phase space, C normalizes the area to 97 counts,

$A = [(m_\eta - m_0)^2 - m_\sigma^2]/2m_\eta$ and $B = m_\sigma \Gamma_\sigma / 2m_\eta$.   We find $\chi^2_{min} = 2.7$,

where 4.0 is expected.   The best-fit parameters are

$$m_\sigma = 381 \pm 5 \text{ MeV},$$

and   (2)

$$\Gamma_\sigma = 48 \pm 8 \text{ MeV}. \quad [11,12]$$

The best-fit curve is shown in Fig. 2, labeled "Brown and Singer." From the

parameters m_σ and Γ_σ, Brown and Singer can predict the branching ratio R. [10]

We shall not write down their formula. [13]   Using our results (2) and their

formula, we obtain the prediction

$$R = 1.02 \pm 0.07.$$

The χ^2 probability for agreement with the measured value (1) is 57%.

In summary, our data are in poor agreement with the linear-matrix-element

theories, and in excellent agreement with the $I = 0$, $J = 0$ dipion-resonance

hypothesis of Brown and Singer. However, we can not rule out the possibility

that other hypotheses involving final-state interactions might also fit the data.

In particular we emphasize that it is only after we assume the existence of the

σ resonance that we can determine the parameters of Eq. (2).   Thus it is

not possible in our experiment to determine whether the resonance actually

does or does not exist. [12]

FOOTNOTES AND REFERENCES

† Work done under the auspices of the U. S. Atomic Energy Commission.

1. D. Berley, D. Colley, and J. Schultz, Phys. Rev. Letters $\underline{10}$, 114 (1963),
    have compiled 511 charged eta decays from eight different experiments.
    (For references see their Table I.) They estimate that not more than
    ~ 100 of the events are background. The $\pi^+ \pi^- \gamma$ decays were not separated
    out, and should constitute ~ 100 of the nonbackground events. Thus perhaps
    as many as 200 of the 500 events are spurious. The 69 events labeled
    "Berkeley-c in Table I were our preliminary results, obtained before
    we had eliminated a small background and separated out the $\pi^+ \pi^- \gamma$ decays.

2. This is demonstrated in Fig. 1 of Ref. 3, which contains 76 of our present
    97 events. First, the figure shows that essentially all events of the type
    $\pi^+ p \rightarrow \pi_1^+ p \pi_2^+ \pi^- \pi^0$ are due to η production, with $\eta \rightarrow \pi^+ \pi^- \pi^0$. Second, the
    figure (and our calculation) shows that about 16% of the events are
    ambiguous with respect to the π^+, when $\pi_1^+ \pi^- \pi^0$ and $\pi_2^+ \pi^- \pi^0$ both have the
    η mass. We always choose that combination yielding a mass closest to
    m_η = 548.0. Therefore we choose the wrong π^+ in 8% of the cases. We
    have examined our Dalitz/plot Fabri with the ambiguous events deleted and also
    with the ambiguous positive pions interchanged, and find no distinguishable
    change in the shape. Third, we discard events with "m $(e^+ e^-)$" < 100 MeV
    to eliminate $\pi^+ p \rightarrow \pi^+ p e^+ e^- \cdots$ from our sample. This cutoff also eliminates
    any event $\pi^+ p \rightarrow \pi^+ p \pi^+ \pi^- \pi^0$, where the π^- and one π^+ have the same direction
    in the laboratory. We have examined the cutoff events and find that about
    ten of them correspond to η production and decay into $\pi^+ \pi^- \pi^0$. Adding
    these events to the spectrum for T_0 produces no detectable effect on the
    shape of the spectrum. Finally, we have examined the events discarded

because they satisfy $\pi^+ p \to \pi^+ p \pi^+ \pi^-$, with a Coulomb scatter on one track (1-C fit. See Ref. 3). Six of these events are probably $\eta \to \pi^+ \pi^- \pi^0$. None satisfy the cutoff criterion on the error in m^2 (neutral) described in Ref. 4.

3. Earle C. Fowler, Frank S. Crawford Jr., L. J. Lloyd, Ronald A. Grossman, and LeRoy R. Price, Phys. Rev. Letters 10, 110 (1963).

4. The technique is described in Ref. 3. See especially Fig. 3b. If we relax our cutoff on the error in m^2 (neutral) = m^2 (π^0 or γ), our 97 $\pi^+ \pi^- \pi^0$ events become 146 $\pi^+ \pi^- \pi^0$ events with a small (but not easily measured) contamination from $\pi^+ \pi^- \gamma$. The T_0 spectrum of these 146 $\pi^+ \pi^- \pi^0$ events is not distinguishable from that of our reduced sample of 97, which has nearly zero contamination. Thus the error cutoff does not distort the T_0 spectrum.

5. Our complete Dalitz-Fabri plot (not shown) only confirms the already well-established 0^{-+} quantum numbers for the eta. See for instance the review by G. Puppi in Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN, Geneva, 1962), p. 713; see also C. Alff, D. Berley, D. Colley, N. Gelfand, U. Nauenberg, D. Miller, J. Schultz, J. Steinberger, T. H. Tan, H. Brugger, P. Kramer, and R. Plano, Phys. Rev. Letters 9, 325 (1962); M. Chrétien, F. Bulos, H. R. Crouch Jr., R. E. Lanou Jr., J. T. Massimo, A. M. Shapiro, J. A. Averell, C. A. Bordner Jr., A. E. Brenner, D. R. Firth, M. E. Law, E. E. Ronat, K. Strauch, J. C. Street, J. J. Szymanski, A. Weinberg, B. Nelson, I. A. Pless, L. Rosenson, G. A. Salandin, R. K. Yamamoto, L. Guerriero, and F. Waldner, Phys. Rev. Letters 9, 127 (1962).

6. M. Gell-Mann and A. H. Rosenfeld, Ann. Rev. Nucl. Sci. 7, 407 (1957). [They discuss $K^+ \to 3\pi$.]; K. C. Wali, Phys. Letters 9, 120 (1962).

7. G. Barton and S. P. Rosen, Phys. Rev. Letters 8, 414 (1962); M. Beg, Phys. Rev. Letters 9, 67 (1962).
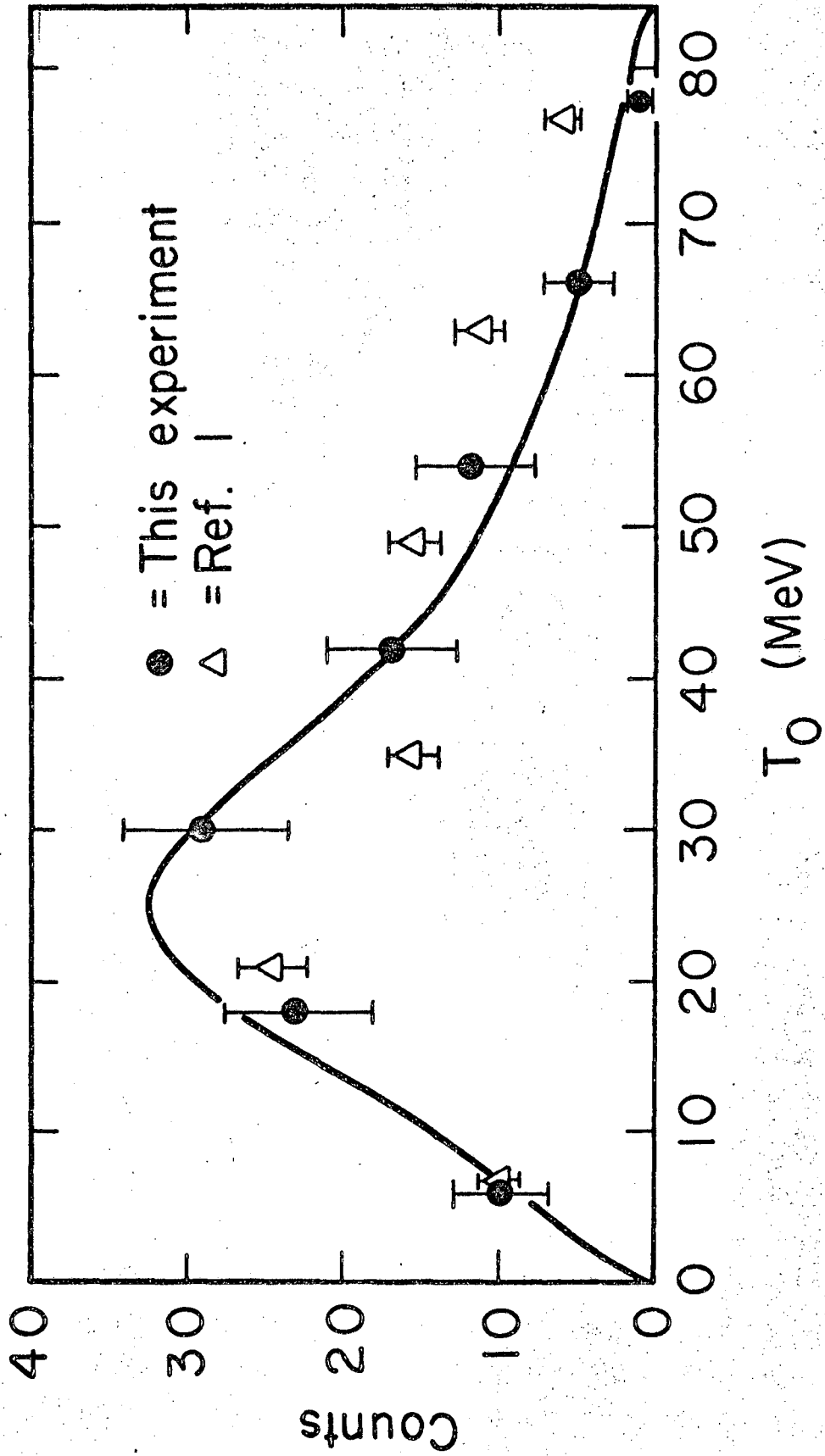
8.   Frank S. Crawford Jr., L. J. Lloyd, and Earle C. Fowler, Phys. Rev.

     Letters <u>10</u>, 546 (1963).

9.   L. M. Brown and P. Singer, Phys. Rev. Letters <u>8</u>, 460 (1962).

10. L. M. Brown and P. Singer, Three-Pion-Decay Modes of Eta and K

     Mesons and a Possible New Resonance (submitted to Physical Review) compare

     their theory with the data on K and eta decay compiled in Ref. 1. We are grate-

     ful to these authors for several enlightening discussions of their preprint.

11. The off-diagonal error term is $\delta\Gamma_\sigma \, \delta m_\sigma = 12 \, (\text{MeV})^2$.

12. Our values for m_σ and Γ_σ, Eq. (2), may be compared with the values

     $m = 395 \pm 10$ MeV and $\Gamma = 50 \pm 20$ MeV for a $\pi^+\pi^-$ resonance observed

     by N. P. Samios, A. H. Bachman, R. M. Lea, T. E. Kalogeropoulos,

     and W. D. Shephard, Phys. Rev. Letters <u>9</u>, 139 (1963), and assigned

     I = 0 or 1 by them. The agreement is striking, but could be accidental.

     The existence of this resonance has not yet been directly confirmed,

     either in other experiments [see for instance C. Alff, D. Berley, D. Colley,

     N. Gelfand, U. Nauenberg, D. Miller, J. Schultz, J. Steinberger, T. H.

     Tan, H. Brugger, P. Kramer, and R. Piano, Phys. Rev. Letters <u>9</u>, 322

     (1962)] or in the present experiment. It is not possible to prove conclusively

     the existence of the σ resonance in the present experiment, mainly because

     the width $\Gamma_\sigma = 48$ MeV is not small compared with $T_0^{\text{max}} = 84$ MeV.

     Assuming the existence of the resonance, we determine the parameters of

     Eq. (2). Thus we do not regard our results as sufficient to confirm the

     observation of Samios et al.

13. If $\eta \rightarrow 3\pi$ went exclusively via $\eta \rightarrow \sigma + \pi_d^0$ (d for direct), and if the width

     Γ_σ were zero, then π_d^0 would not interfere with either of the neutral pions

     from $\sigma \rightarrow 2\pi^0$. The direct pion, π_d^0, would be distinguishable by its energy

     in the η frame. Then $R = (1/2)P \sim 0.55$ follows from the hypothesis $I_\sigma = 0$.

     In the limit $\Gamma_\sigma \rightarrow \infty$, any-one of the three neutral pions could be regarded

as direct, so that the $|\text{amplitude}|^2$ for $\eta \to 3\pi^0$ would be enhanced over the case $\Gamma_\sigma = 0$ by a factor $|(1+1+1)/\sqrt{3}|^2 = 3$, because of the three possible assignments for π_d^0. In that limit, one has $R = (3/2)P = 1.7$. The $3\pi^0$ are then in the totally symmetric $I = 1$ state.
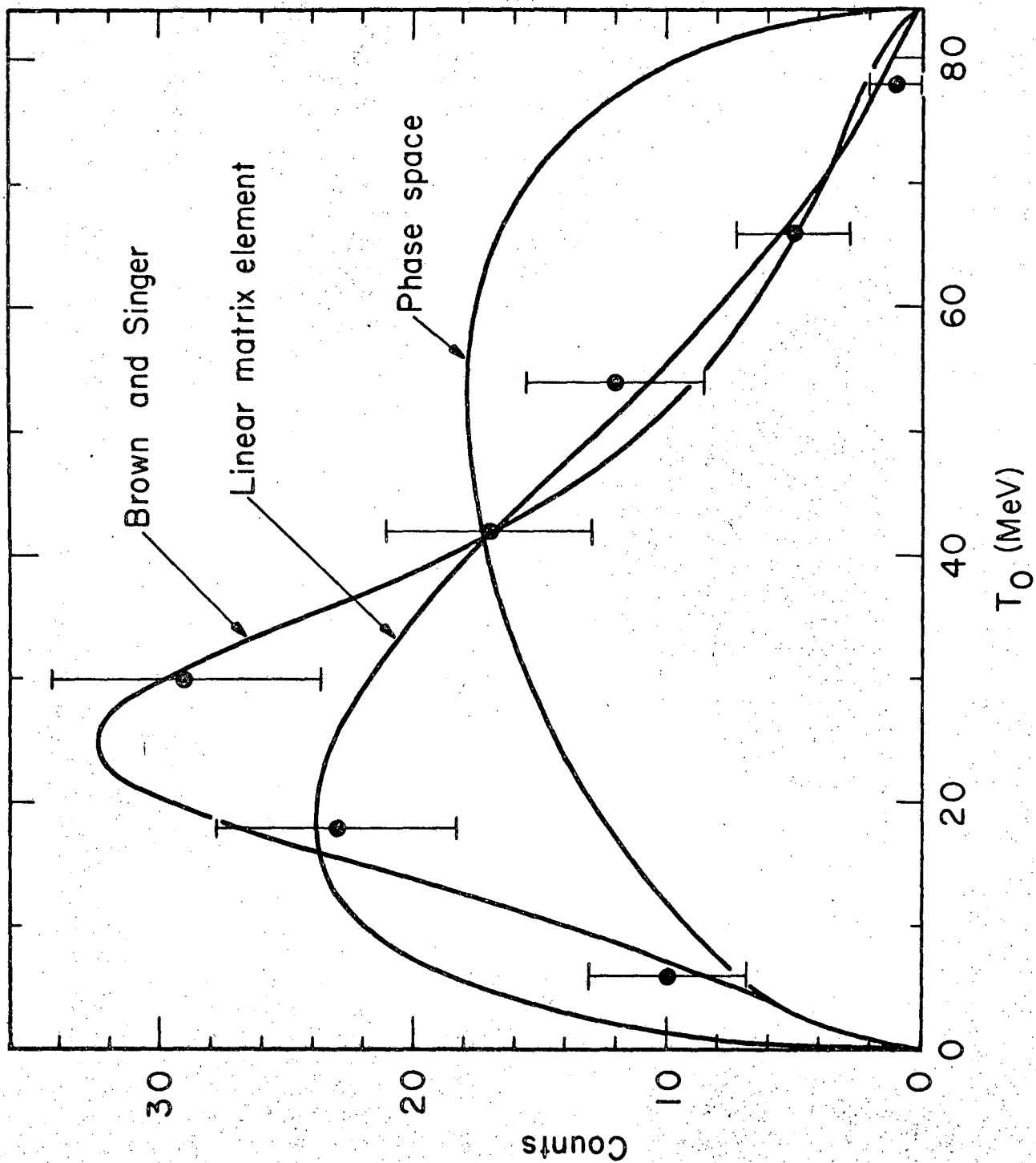
FIGURE LEGENDS

Fig. 1. Spectrum of kinetic energy of π^0 from $\eta \to \pi^+\pi^-\pi^0$. Solid circles
represent the present experiment; open triangles represent the compilation
of Ref. 1, renormalized so as to give the same area. The smooth curve
is a best fit of our data to the theory of Brown and Singer, and is
included in this figure only to aid comparison of the present experiment
with the previous compilation. (The same smooth curve appears in
Fig. 2.)

Fig. 2. Spectrum of the π^0 kinetic energy from $\eta \to \pi^+\pi^-\pi^0$. The experimental
points are from the present experiment. The three smooth curves
correspond to phase space, the linear-matrix-element theories,[6,7] and
the $I = 0$, $J = 0$ dipion-resonance theory of Brown and Singer.[9,10]

Fig. 1

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Fig. 2

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