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Polarized proton capture in the giant dipole resonance region

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Measurements of cross sections and analyzing powers are examined for polarized proton capture on ^{14}C, ^{30}Si, ^{54}Fe, ^{56}Fe, ^{58}Fe, ^{59}Co, and ^{88}Sr at energies which cover the giant dipole resonance region. These data are used to extract the relative amplitudes and phases of the contributing $E1$ T-matrix elements. A typical result exhibits two solutions. Calculations using the direct (or a direct-semidirect) capture model appear to provide a means for choosing the physical solution.

[NUCLEAR REACTIONS: $^{14}C(\vec{p},\gamma_0)$, $^{30}Si(\vec{p},\gamma_0)$, $^{54}Fe(\vec{p},\gamma_0)$, $^{56}Fe(\vec{p},\gamma_0)$, $^{58}Fe(\vec{p},\gamma_0)$, $^{59}Co(\vec{p},\gamma_0)$, $^{88}Sr(\vec{p},\gamma_0)$; measured $\sigma(\theta)$ and $A(\theta)$ over energy region of the giant dipole resonance. Deduced T-matrix amplitudes and phases. Compare results to direct-semidirect model calculations.]

Polarized proton capture measurements provide information regarding capture reactions which cannot be determined from unpolarized measurements alone. In particular, a pure $E1$ analysis of polarized and unpolarized angular distributions allows one to determine the relative amplitudes and the relative phase when two T-matrix elements are present.[1-3] Unfortunately, when deducing these quantities from the data, one finds two solutions. This paper will concern itself with the problem of choosing which of these two solutions is the physical one, along with the more general problem of describing the basic behavior of the relative amplitudes and phases found from these experiments.

We have examined angular distribution data for the (p,γ) reaction taken with unpolarized and polarized proton beams on a variety of target nuclei.[2-6] Proton energies were chosen to cover the giant dipole resonance (GDR) region of the nucleus under study. The unpolarized angular distributions were fitted to an expansion in terms of Legendre polynomials using a least squares criterion

$$\sigma(\theta) = A_0\left(1 + \sum_{k=1} a_k Q_k P_k(\cos\theta)\right),$$

where the coefficients Q_k correct for the effects of finite geometry. The asymmetry measurements consisted of determining the analyzing power[1,2]

$$A(\theta) = \left(\frac{N_+ - N_-}{N_+ + N_-}\right)\frac{1}{P},$$

where N_+ is the number of counts obtained for spin up measurements, N_- is the number in the spin down case, and P is the beam polarization. The product of the analyzing power and the cross section were fitted by an expansion in terms of associated Legendre polynomials

$$A(\theta)\sigma(\theta)/A_0 = \sum_k b_k Q_k P_k^1(\cos\theta),$$

where the geometrical effects due to the finite angular range, and the center of mass corrections, have been taken into account.

In order to reduce these data, it has been customary to rewrite the coefficients of the expansions (a_k and b_k) in terms of the various transition matrix elements. For example, in the case of $^{14}C(p,\gamma_0)^{15}N$, considering only $E1$ radiation, one can have a J^π state of $\frac{1}{2}^+$ or $\frac{3}{2}^+$ in ^{15}N which decays via $E1$ radiation to the $\frac{1}{2}^-$ ground state.[2] In the j-j coupling scheme, an incoming $s_{1/2}$ ($d_{3/2}$) proton leads to the formation of a $\frac{1}{2}^+$ ($\frac{3}{2}^+$) state. Therefore we must consider two transition matrix elements whose amplitudes are labeled as $s_{1/2}$ and $d_{3/2}$ and whose phases are labeled as ϕ_s and ϕ_d. The a_k and b_k coefficients can be written in terms of these quantities by evaluating the appropriate angular momentum coupling coefficients. For

pure $E1$ radiation only a_0, a_2, and b_2 are present and we have, assuming that the various matrix elements add coherently[1,7]:

$$a_0 = 1.0 = (s_{1/2})^2 + 2.0\,(d_{3/2})^2,$$
$$a_2 = -(d_{3/2})^2 - 2.0\,(s_{1/2})(d_{3/2})\cos(\phi_s - \phi_d), \quad (1)$$
$$b_2 = (s_{1/2})(d_{3/2})\sin(\phi_s - \phi_d).$$

It can be seen from Eqs. (1) that in this case a pure $E1$ analysis allows a determination of three numbers: the two $E1$ amplitudes and their relative phase. As a result of the quadratic nature of Eqs. (1), this analysis has the property of producing two solutions. In what is to follow we shall present the experimental results for a number of nuclei which have been studied in terms of the relative amplitudes and phases of the contributing $E1$ T-matrix elements. We shall then show that a model calculation, the so-called direct-semidirect model, appears to be capable of selecting one of the two solutions as the correct or physical solution.

In the direct-semidirect-(DSD) reaction model[8-10] the evaluation of the transition matrix elements involved here requires the evaluation of a radial matrix element having the form:

$$\left\langle \phi_{n,l,j}(r) \middle| r + \frac{V_1(r)}{E\gamma - E_d + \frac{1}{2}i\,\Gamma_d} \middle| \chi_{l',j'}(r) \right\rangle, \quad (2)$$

where $\chi_{l',j'}(r)$ is the initial proton continuum wave function, and $\phi_{n,l,j}$ is the wave function of the valence proton bound in the final state. The continuum wave function is calculated using the optical model potential. The bound state single particle wave function is obtained by integrating the Schrödinger equation and adjusting the Woods-Saxon potential, including a spin-orbit term, to reproduce the known bound state energy.

In the present work we are only interested in obtaining a reliable but simple method for extracting the proper *relative* transition amplitudes from Eq. (2). For this reason we choose to utilize the pure direct model [$V_1(r) = 0$ form factor] for our $E1$ capture calculations. However, because the Brown form factor[8] $V_1(r) \propto r$ gives the same relative amplitudes as the direct model (provided of course that the resonance parameters are independent of angular momentum quantum numbers) one can also regard our analysis as being direct-semidirect (DSD).[8-10] In fact, Likar *et al.*[10] have shown that in most cases different choices of real form factors do not significantly effect the results for the calculated angular distributions. Our particular DSD approach, a renormalized direct model, has the capability of producing correct cross-section magnitudes since there are now additional model parameters (e.g., E_d and Γ_d).

The transition matrix elements for the proton capture reaction were calculated for a variety of targets: ^{14}C,[54,56,58] ^{58}Fe, ^{59}Co, ^{88}Sr, and ^{30}Si. We shall discuss and interpret the results for each target separately.

A. $^{14}C(p,\gamma_0)^{15}N$

Reports of this experiment have been previously published[2,11] in an effort to account for the measured $a_1 - a_4$, $b_1 - b_4$ coefficients. The applicability of the DSD model was demonstrated for this reaction in Ref. 11. A pure $E1$ analysis of the data of Ref. 2 yields the solutions shown in Fig. 1. The error bars represent typical statistical errors obtained from this analysis.

Clearly, the solutions of Fig. 1 fall into two classes: in one (the dots) the cross section is predominantly $d_{3/2}$ proton capture, in the other (the x's) it is predominantly $s_{1/2}$. Furthermore, the relative phase $(\phi_d - \phi_s)$ between the two matrix elements has two distinctly different behaviors as a function of energy.

We began our calculation for this case by specifying the single particle state of the final nucleus. A $1p_{1/2}$ state (zero node wave function) was generated at a binding energy of -10.21 MeV using a Woods-Saxon well with a depth of 56.6 MeV. A spin-orbit well depth of 7.3 MeV was included. The geometrical parameters used here and in all cases to follow were $r_0 = 1.25$ fm and $a = 0.65$ fm. The optical model parameters used to generate the continuum proton wave function $\chi_{l',j'}(r)$ were taken from Ref. 13. Finally, the radial matrix elements of Eq. (2) were evaluated and, from these, the relative amplitudes and phases of the T-matrix elements were obtained.

The results of this calculation for $^{14}C(p,\gamma_0)^{15}N$, shown in Fig. 1, provide a good description of the experimental situation, reproducing the general behavior of both the relative amplitudes and the phase. The two experimental points which show poor agreement with this result clearly require further experimental and/or theoretical investigation. A second calculation (not shown) using a slightly different optical model potential[12] was also performed. The results indicated that the relative phase appeared to be the quantity most sensitive to the choice of the potential parameters, decreasing at all energies by 30°-40° for the latter choice. However, the dominant $d_{3/2}$ solution is clearly favored by both calculations, accounting for 90-95% of the cross section at 10 MeV, for example. Attempts to significantly vary this result by changing the parameters of the optical model and/or the bound state well in any reasonable manner were unsuccessful. Hence we con-

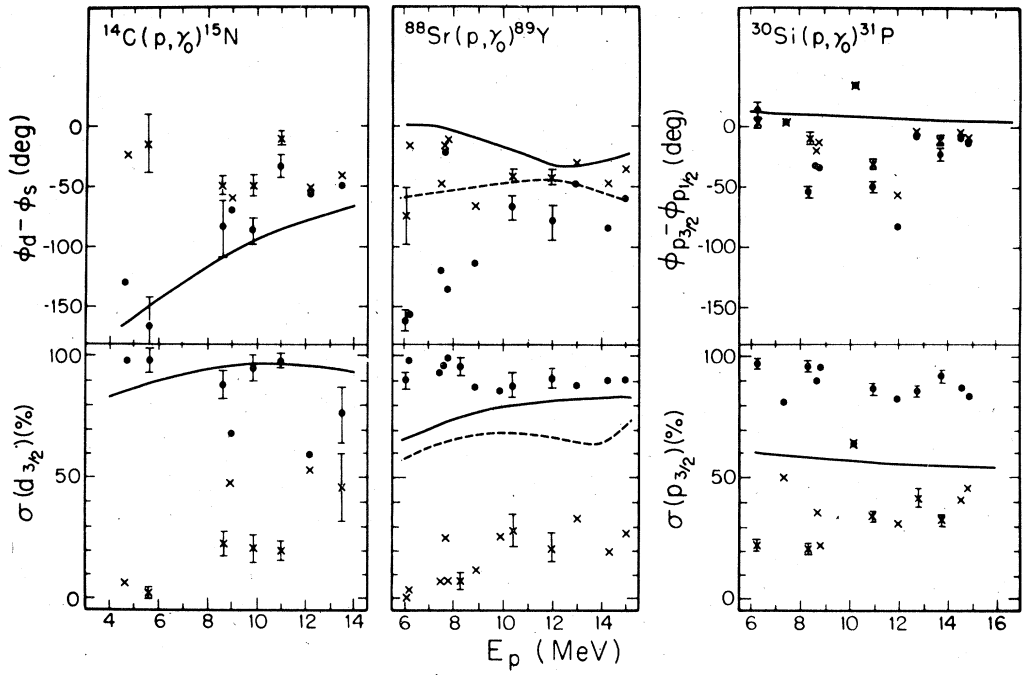

FIG. 1. The two solutions (dots and x's) resulting from a pure $E1$ analysis of the data are shown along with the results of the calculation for target nuclei of ^{14}C, ^{88}Sr, and ^{30}Si. The remaining cross section in the case of ^{14}C and ^{88}Sr is due to the $s_{1/2}$ matrix element. In the case of ^{30}Si it arises from the $p_{1/2}$ matrix element. The error bars represent typical statistical errors associated with the data points. The amplitudes are presented in terms of the percentage of the total cross section for which they are responsible. The curves represent DSD calculations as described in the text. The dashed curves in the case of ^{88}Sr were obtained using the optical model parameters of Ref. 16 while the solid lines were obtained from the parameters of Ref. 18.

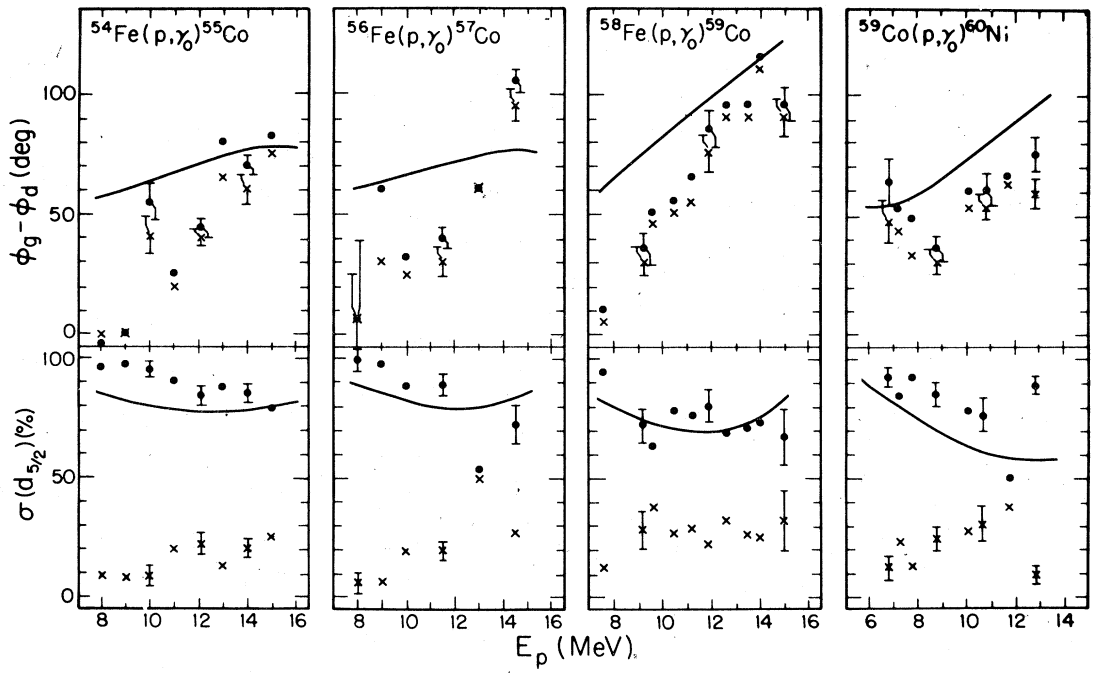

FIG. 2. Same as Fig. 1 for the target nuclei of ^{54}Fe, ^{56}Fe, ^{58}Fe, and ^{59}Co. The remaining cross section is due to the $g_{9/2}$ matrix element.

clude that the "correct" or "physical" solution for this problem is the solution which corresponds to predominantly $d_{3/2}$ proton capture. It is of interest to note that it is the $d_{3/2}$ partial wave which appears to exhibit a resonance-like behavior in the elastic scattering experiment.[13]

B. ^{54,56,58}Fe$(p,\gamma_0)^{55,57,59}$Co

A previous publication presented the data and the results of a pure $E1$ analysis for these reactions.[3] In these cases the $E1$ T-matrix elements, labeled according to the incoming proton's angular momentum, are $g_{7/2}$, $g_{9/2}$, and $d_{5/2}$.

The results of the analysis of Ref. 3 indicated that the $g_{7/2}$ ($E1$) T-matrix element was small over the energy region of the GDR. The results of the $E1$ analysis when this amplitude (essentially spin-flip) is set equal to zero are shown in Fig. 2, where we have plotted the percentage of the cross section which is due to the $d_{5/2}$ matrix element; the remainder being due to the $g_{9/2}$ matrix element. Neglecting the $g_{7/2}$ ($E1$) contribution is consistent with the results obtained in a recent microscopic calculation utilizing the shell model formalism of Mahaux and Weidenmuller[14] for the case of ^{54}Fe$(p,\gamma)^{55}$Co.

The bound single particle state is taken to be $1f_{7/2}$ for the three Co nuclei. Well depths of 53.2, 53.5, and 54.4 MeV were used to achieve the observed binding energies of -5.06, -6.02, and -7.38 MeV for ^{55}Co, ^{57}Co, and ^{59}Co, respectively. The spin-orbit well depths were all taken to be 6.9 MeV. The optical model parameters used for ^{54}Fe and ^{56}Fe were those obtained from an analysis in which elastic scattering cross section and analyzing power data for the case of ^{56}Fe$(p,p)^{56}$Fe were fitted.[15] Calculations using the optical model parameters of Becchetti and Greenlees[16] were also performed. For comparison, the results for ^{58}Fe were obtained using these latter parameters. Again, it was found that the use of different optical model parameters showed up most strongly in the calculated relative phases, the relative amplitudes being quite insensitive to these parameters.

Since the $g_{7/2}$ strength was set equal to zero in the analysis of the data, the calculated results were normalized using this assumption for plotting purposes. In fact, the calculation predicts that the $g_{7/2}$ amplitude typically accounts for $\lesssim 10\%$ of the cross section. Of course, the relative $d_{5/2}$ to $g_{9/2}$ strength is not effected by this normalization procedure, and it is clear from Fig. 2 that the calculation selects the primarily $d_{5/2}$ solution as the correct solution. The relative phase seems to have the correct trend, although the disagreement at the lower energies is especially large. It is interesting to note that the model does predict that this phase increases towards or through 90° as the energy increases. This changes the sign of a_2 as a function of energy, an effect which was once suggested as possibly being related to isospin splitting.[17] This effect, according to the present calculation, is primarily the result of the energy dependence of the optical model phase shifts which, we have found, are the dominant factors in determining the relative phase of the matrix elements. Since a pure direct model predicts this result, we conclude that the effect can be explained independently of the details of the giant dipole resonance.

C. ^{59}Co$(p,\gamma_0)^{60}$Ni

The situation here[6] is similar to that of the Fe isotopes in that there are three $E1$ T-matrix elements which, in jj coupling, we label as $g_{7/2}$, $g_{9/2}$, and $d_{5/2}$. Since the $g_{7/2}$ amplitude is essentially the spin-flip amplitude, we neglect it and perform a pure $E1$ analysis. We have

$$a_0 = 1 = (g_{9/2})^2 + (d_{5/2})^2,$$

$$a_2 = 0.143(d_{5/2})^2 - 0.333(g_{9/2})^2 + 1.464\, d_{5/2}\, g_{9/2} \cos(\phi_d - \phi_g),$$

$$b_2 = 0.488\, d_{5/2}\, g_{9/2} \sin(\phi_d - \phi_g).$$

The results of this analysis are shown in Fig. 2. Typical statistical errors are indicated. The results of the calculation, which were plotted with the $g_{7/2}$ strength set equal to zero, are also shown. In this case a Woods-Saxon well depth of 57.25 MeV and a spin-orbit well depth of 6.2 MeV gave the $1f_{7/2}$ single particle binding energy of -9.537 MeV in ^{60}Ni. The optical model parameters were taken from Ref. 16. The calculation obviously selects the predominantly $d_{5/2}$ solution here, and accounts for the general character of the relative $g_{9/2}$-$d_{5/2}$ phase.

D. ^{88}Sr$(p,\gamma_0)^{89}$Y

This example[5] is similar to ^{14}C$(p,\gamma)^{15}$N in terms of the angular momenta involved. Since the ground state of ^{89}Y is $\frac{1}{2}^-$, the T-matrix elements to be considered in an $E1$ analysis are $s_{1/2}$ and $d_{3/2}$. The results of a model independent pure $E1$ analysis are shown in Fig. 1. They are suprisingly similar to the results obtained for the case of ^{14}C$(p,\gamma_0)^{15}$N.

The results of the calculation are also shown in Fig. 1. A Woods-Saxon well depth of 56.7 MeV was found to give a $2p_{1/2}$ single particle state bound by -7.29 MeV. A spin-orbit well depth of 7.0 MeV was used. The optical model parameters were taken from the work of Genz.[18] The calculation

clearly favors the primarily $d_{3/2}$ solution. However, the phase is poorly reproduced, especially at lower energies. This is expecially interesting since the experimental values of the phase behave as they did in the case of $^{14}C(p,\gamma_0)^{15}N$. Several parameters were varied in an attempt to improve this situation. The bound state binding energy was varied by several MeV, the optical potential parameters of Becchetti and Greenlees[16] were tried (see Fig. 1), the Genz parameters[18] (V_0 and W_s) were varied, but no significant improvement was obtained. However, it was found that the $d_{3/2}$ amplitude dominated for all reasonable calculations. Since the results for the amplitudes and phases are in fair agreement at the higher energies where we expect a predominantly direct mechanism, it seems reasonable to conclude that the predominantly $d_{3/2}$ solution is the physical one.

The low energy discrepancy here is somewhat puzzling. It was seen to some extent in the case of the Fe isotopes. It is worth noting that since the (p,γ) cross section for $^{88}Sr(p,\gamma_0)$ does not follow the GDR shape as seen in the (γ,n) reaction,[19] where most of the sum rule is found, it would appear that other strength is affecting the present data. This strength, which could have more to do with the proton channel than the γ_0 channel, may partially account for this discrepancy. Indeed, this result may indicate the breakdown of the DSD reaction mechanism assumption at lower energies, a plausible possibility since this is where statistical compound nucleus effects would be expected to be relatively more important. One might also wonder if the form factor of the DSD calculation could be varied to improve the situation. However, a preliminary study using a complex form factor also fails to reproduce the experimental results below $E_p \sim 10$ MeV.[10,20] Nevertheless, it seems clear that the DSD model favors the primarily $d_{3/2}$ solution as the physical one and, above 10 MeV, gives a reasonably good description of the behavior of the relative amplitudes and phase involved here.

E. $^{30}Si(p,\gamma_0)^{31}P$

This case[4] is distinctly different from the others we have studied since the two T-matrix elements have the same incoming l value. Since the ground state spin of ^{31}P is $\frac{1}{2}^+$, we have, for $E1$ radiative capture, $p_{1/2}$ and $p_{3/2}$ capture amplitudes. Considering only the dominant $E1$ radiation we can write

$$a_0 = 1 = p_{1/2}^2 + 2p_{3/2}^2,$$

$$a_2 = -p_{3/2}^2 - p_{1/2}p_{3/2}\cos(\phi_{p_{1/2}} - \phi_{p_{3/2}}),$$

$$b_2 = -p_{1/2}p_{3/2}\sin(\phi_{p_{1/2}} - \phi_{p_{3/2}}).$$

Since the phase angle difference will be small compared to the case where the two T-matrix elements have different l values (arising here from spin orbit interactions), b_2 is expected to be relatively small in this case. Therefore, it can be expected that this analysis will be more sensitive to the presence of non-$E1$ T-matrix elements than the other cases which we have examined. In Fig. 1 we show the results obtained from a pure $E1$ analysis. The results of the calculation are also shown. The bound state wave function was generated from a Woods-Saxon potential having a depth of $V_0 = 55.8$ MeV (a $2s_{1/2}$ single particle state with a binding energy of -7.287 MeV was used). The spin-orbit well depth was taken to be 6.5 MeV. The optical model potential was taken from Ref. 21. In this case we see that the model predicts a solution which is 50–60% $p_{3/2}$, while the pure $E1$ analysis gives two solutions, neither one of which agrees very well with this calculation.

In order to investigate this case further a preliminary analysis which included the two possible $E2$ amplitudes was performed on the data. The angular distributions consisted of measurements at nine angles for $\sigma(\theta)$ and seven angles for $A(\theta)$. The experimental data were fitted directly to deduce the amplitudes and phases in this case. The $E1$ results for the best χ^2 solutions obtained in this analysis are in good agreement with the model calculation. That is, we find one set of solutions for which the $p_{3/2}(E1)$ amplitude accounts for about 60–70% of the cross section, as predicted by the calculation. Although the $E2$ strength in this analysis only accounts for a few percent of the cross section, its effect on the $E1$ solutions is quite dramatic. This case demonstrates the importance of considering non-$E1$ radiation under some circumstances. A detailed description of these data and the $E1$-$E2$ analysis will be published in the near future.

The most outstanding result of these studies is the rather surprising success of the direct-semidirect model using the Brown form factor in predicting the observed angular distributions (equivalently the relative amplitudes and phases of the T-matrix elements). The angular distributions calculated with this model are the same as for a pure direct capture process. So, although the GDR is essential in order to account for the magnitude of the cross section, its presence does not show up very dramatically in the angular distributions. Presumably some of the discrepancy between our calculated and experimental results are due to particular effects of the GDR. Departures from the assumption that the resonance parameters are the same for all contributing T-matrix elements could certainly occur.

A pure $E1$ analysis produces two solutions when cross-section and analyzing power data are considered and spin-flip terms, when present, are ignored. It has been previously demonstrated[22] that, for the case of $^{15}N(p,\gamma_0)^{16}O$, a calculation based on the doorway state ideas of Feshbach, Kerman, and Lemmer[23] selects one of the two possible solutions as the "correct" one. Our rather simple calculations are seen to predict a result which is close to one of the two possible solutions for a number of target nuclei. Although discrepancies between the calculated and experimentally determined phase differences at lower energies remain to be explained, it does appear that one can safely choose the physical solution on the basis of this calculation, especially if data at the high energy side of the GDR, where fewer extraneous effects are expected to be present, are available.

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