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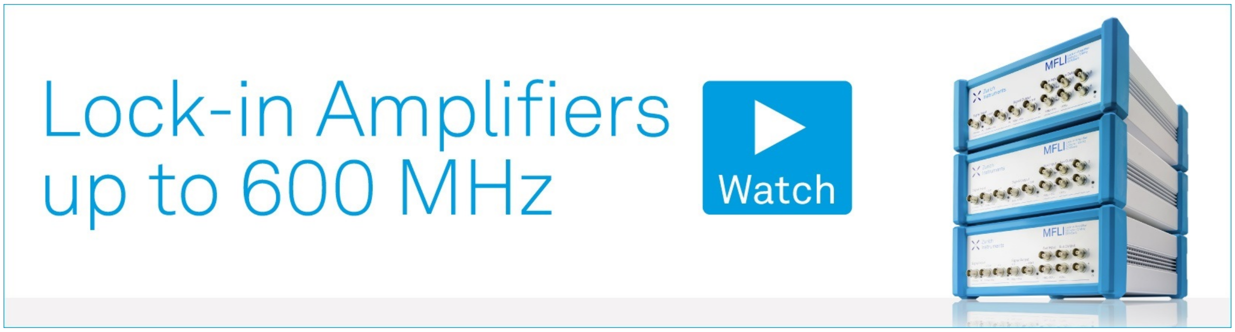

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On the nature of the Dipole Pygmy Resonance

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Abstract. The nature of the low-lying dipole states in neutron-rich nuclei, often associated to the Pygmy Dipole Resonance, has been investigated. This has been done by describing them within the Hartree-Fock plus RPA formalism. The analysis shows that they are not of collective nature although many particle-hole configurations participate to their formation. Taking advantage of their strong isospin mixing one can envisage combined reaction processes involving the Coulomb and different mixtures of isoscalar and isovector nuclear interactions in order to provide more hints to unveil the characteristic features of these states.

Keywords: Exotic nuclei, pygmy dipole resonance, nuclear excitation, RPA
PACS: 21.60.Ev; 21.60.Jz; 25.60.-t; 25.70.-z

INTRODUCTION

Exotic nuclei show a variety of new phenomena which have raised a lot of interest in recent years. In particular the collective behaviour of nuclei with neutron excess has been extensively studied. By increasing the neutron number, some strength, on the dipole strength distribution, appears at low energies well below the dipole giant resonance[1]. These strengths, with a small per cent of the isovector EWSR, are present in many isotopes of many nuclei and have been known as pygmy dipole resonances (PDR). Recently, measurements in high energy Coulomb excitation process with heavy ion collisions have been performed at GSI on ^{132}Sn[2] as well as on ^{68}Ni[3]. They have clearly shown the presence of these states. Another well-established method to study the PDR is by means of nuclear resonance fluorescence (or real photon-scattering experiments) performed on semimagic nuclei at Darmstadt[4]. Recently, the same nuclei have been investigated by means of the $(\alpha,\alpha'\gamma)$ coincidence method at KVI[5].

This dipole strength at low energies has been widely studied within several microscopic models, among which we quote the Hartree-Fock plus Random Phase Approximation (RPA) with Skyrme interactions, the Relativistic RPA (RRPA) and the Relativistic Hartree Bogoliubov (RHB) plus the Relativistic Quasi particle RPA (RQRPA). For a recent bibliography see ref. [6]. All these approaches predict similar strength for these states but whether or not such strength corresponds to a collective mode is still under discussion. One of the aim of this contribution is to shed some light on the nature of these low lying dipole states. A novel criterion is shown here in order to study the features and the collectivity degree of the PDR. Nevertheless, the precise nature of these

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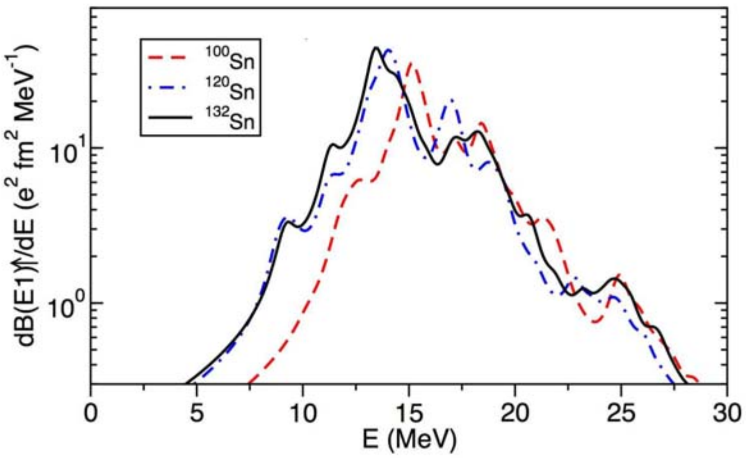

FIGURE 1. Isovector strength distributions for dipole states for tin isotopes calculated with the SGII interaction. The curves represent $dB(E1)/dE$ as obtained by adopting a smoothing procedure.

states should be inferred from experimental data.

Until now experimental evidence for these states comes from Coulomb excitation processes which provide information only on the multipole B(Eλ) transition rates. Further information on wave functions and transition densities are then in order. These can be obtained by resorting to reactions where the nuclear part of the interaction is involved[7].

In this contribution we show, with the help of a semiclassical model, the predictions for the excitation of the dipole states in the neutron-rich ^{132}Sn by different projectiles (α, ^{40}Ca, ^{48}Ca) at different bombarding energies. We will reveal how the excitation probabilities are sensitive to the details of the transition densities and how these can be probed by combination of different processes. Indeed, the relative role of the nuclear and Coulomb components, as well as of the isoscalar and isovector contributions, can be modified by choosing in an appropriate way the projectile mass, charge, bombarding energy and scattering angle of the reaction.

ARE THE PDR COLLECTIVE STATES?

Using the Hartree-Fock plus discrete RPA with Skyrme interactions we obtain the dipole states, their wave functions and the corresponding transition densities. The strength distributions for the three isotopes ^{100,120,132}Sn[8] are shown in Figure 1. The curves are generated by a smoothing procedure using a Lorentzian with a 1 MeV width. As known, the peak of the GDR is lowering with increasing mass number. As the neutron number increases we notice the appearance of some low-lying strength (carrying a fraction of the EWSR of the order of few per cent) below 10 MeV. These are precisely the states that are candidates to be interpreted as Pygmy Dipole Resonances. The small peak above 10 MeV is due to some states belonging to the tail of the GDR[8].

The question we want to address is how collective are these dipole states. The measure of the collectivity is usually associated to the number of particle-hole configurations entering in the RPA wavefunction with an appreciable weight[9, 10]. Such criteria do not take into account the other fundamental concept that underlies collectivity that is coherence. The final answer should be given by looking to the wave function of the state. Here we propose a novel criterion based on the reduced transition probability from the ground state to the excited state ν which can be written as

$$B(E\lambda) = |\sum_{ph} b_{ph}(E\lambda)|^2 = |\sum_{ph}(X^{\nu}_{ph} - Y^{\nu}_{ph})T^{\lambda}_{ph}|^2 \tag{1}$$

where T^{λ}_{ph} are the 2^{λ} multipole transition amplitudes associated with the elementary p-h configurations. The information given only by the RPA amplitudes may be misleading[8]. In Figure 2 we plot the partial contributions b_{ph}, in units of $e^2 fm^{2\lambda}$, versus the order number of the p-h configurations used in the RPA calculations for three states of the ^{132}Sn isotope. The bars corresponds to the individual values of the b_{ph} while the continuous thin line is the cumulative sum of the contributions. The dashed lines divide the protons from the neutron configurations. The order goes from the most bound configurations to the higher ones. The figure on the left is for the low-lying dipole state while the one on the right is for the GDR state. For further comparison we plot also the results for the low-lying 2^+ state. For the low-lying dipole states there are several p-h configurations participating to the formation of the $B(E1)$ but some of them have opposite sign giving rise to a final value which is small. For the other two states we have a different behaviour: one can clearly see how the $B(E\lambda)$ of the GDR and low-lying 2^+ states are built up by the small contributions of many p-h configurations which add coherently. From our novel analysis, it emerges that, although the low-lying dipole states cannot be considered as collective as the GDR states, they cannot be described as pure p-h configuration.

The nature of the two dipole states discussed above is qualitatively different. This is illustrated in Figure 3 where the RPA transition densities associated with the GDR (right frame) and with the PDR (left frame) in ^{132}Sn are shown. Neutron and proton components of the transition densities are separately shown, together with their isoscalar and isovector combinations. The one associated with the GDR shows a dominant isovector character together with the usual opposite-phase behaviour of the proton and neutron components. The situation is rather different in the case of the dipole state at lower energy. Here neutron and proton components oscillate in phase in the interior region, while in the external region only the neutrons give a contribution to both isoscalar and isovector transition densities which have the same magnitude. Such behaviour, which has been found also in all the other microscopic approaches, can be taken as a sort of definition of PDR. The strong isospin mixing at the surface open the possibility of exciting these dipole states also via an isoscalar probe.

We are indeed in presence of a new mode which in the literature is often macroscopically described as the oscillation of the neutron skin with respect to the proton+neutron cores. A simple macroscopic description of such a mode[7] produces transition densities similar to the microscopic ones, although a full interpretation of the state in the above macroscopic mode is not obvious. Furthermore, this macroscopic picture implies the re-

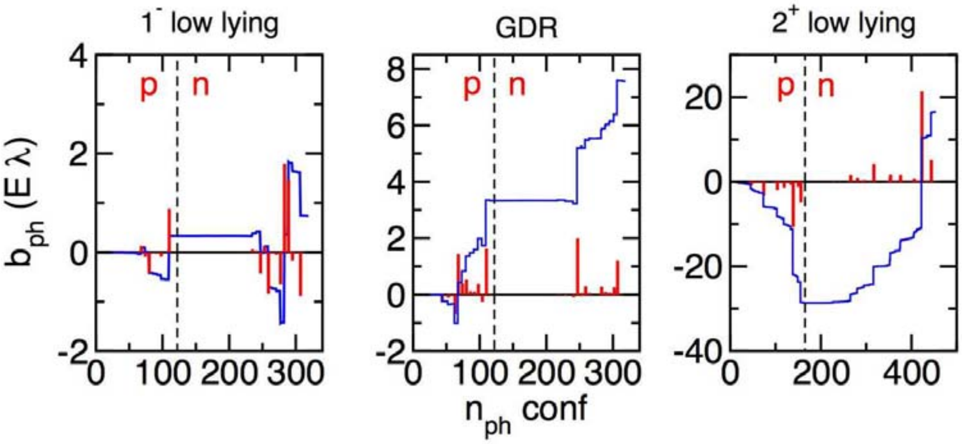

FIGURE 2. Partial contributions $b_{ph}(E\lambda)$, in units of $e^2 fm^{2\lambda}$, of the reduced transition probability vs. the order number of the p-h configurations used in the RPA calculations with the SGII interactions. The vertical dashed lines divide the protons from the neutron configurations. The order goes from the most to the less bound ones. The solid bars corresponds to the individual b_{ph} contributions while the unbroken thin line is the cumulative sum of the contributions.

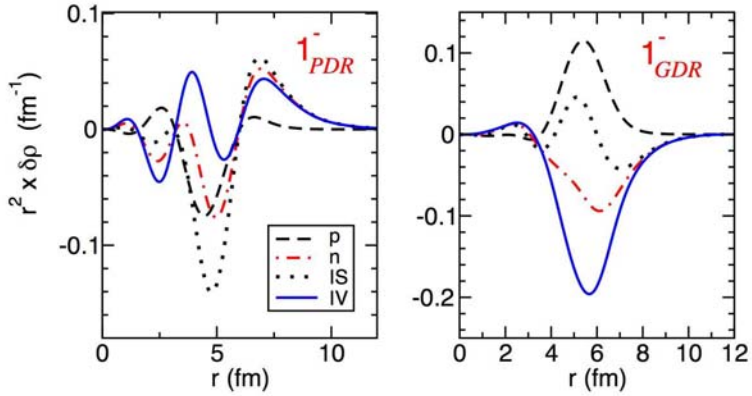

FIGURE 3. Transition densities for the low-lying dipole state (PDR) (left) and for the GDR (right) for the ^{132}Sn isotope calculated with the SLY4 interaction. We show the proton, neutron, isoscalar and isovector components (as indicated in the legend).

quirement of a collective nature of the state, which was not found to be fulfilled at least in our calculations.

EXCITATION CROSS SECTION OF DIPOLE STATES

The presence of an isoscalar components in the transition densities opens the possibility for these states to be excited also by an isoscalar probe. This has been exploited in the past[12] in the case of very-neutron rich nuclei. Here, we want to explore the fact that the relative population of the different states can be altered by changing the relative role

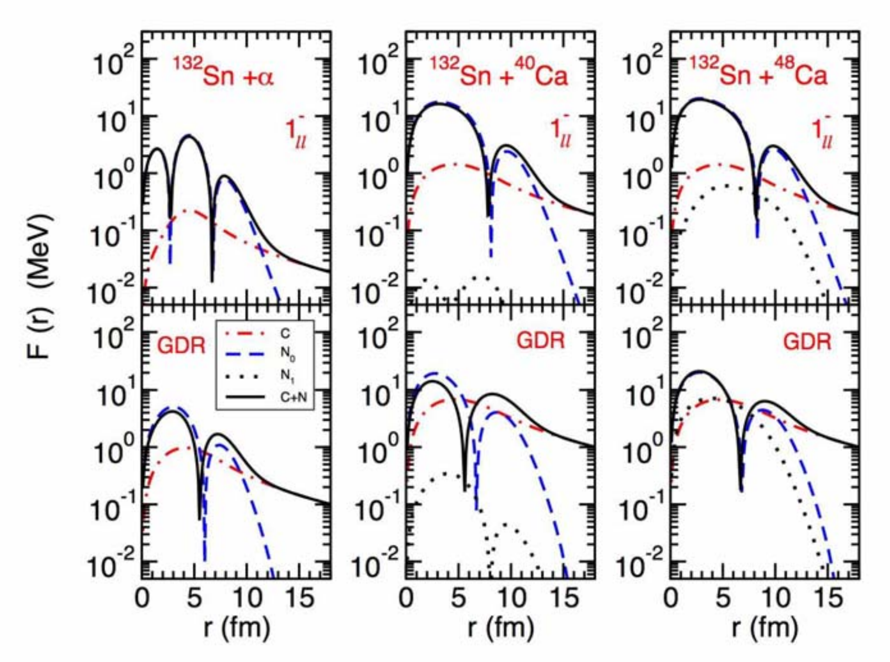

FIGURE 4. Formfactors for three different systems ^{132}Sn + α, ^{40}Ca, ^{48}Ca. The upper parts refer to the PDR states while the lower ones are for the GDR. The different component are shown together with the total one (solid black line).

of nuclear and Coulomb components. This can be achieved by modifying the partners of the reaction and/or the bombarding energy as well as the scattering angle.

In order to describe the excitation processes we make use of a semiclassical model valid for grazing collisions. As a consequence, we assume that nuclei move on classical trajectories, while the internal degrees of freedom are treated quantum mechanically[13]. The Schrödinger equation is cast in a set of coupled equations for the probability amplitude of the states taken into consideration. Then the cross section for the excitation of each of the states is obtained by integrating the excitation probabilities over the impact parameter. The dipole states for which we calculated the cross section are taken as the one with a strong EWSR percentage among the RPA states. More details are given in ref. [13].

The real part of the nuclear optical potential, which together with the Coulomb interaction determines the classical trajectory, is constructed with the double folding procedure[14]. If we take into account also the isospin dependent part of the nucleon-nucleon interaction then the folding potential will be formed by two parts, one of them depending of the isospin degree of freedom. This part will go to zero when one of the two reaction partner has $N = Z$[14].

The formfactors are obtained by the same procedure where the transition densities from the ground states to the state in consideration is taken instead of one of the charge density. Both isoscalar and isovector nucleon nucleon interaction have been used generating then two components for the nuclear form factors. Calculations have been done for the excitation of dipole states in ^{132}Sn by different partners: α, ^{40}Ca and

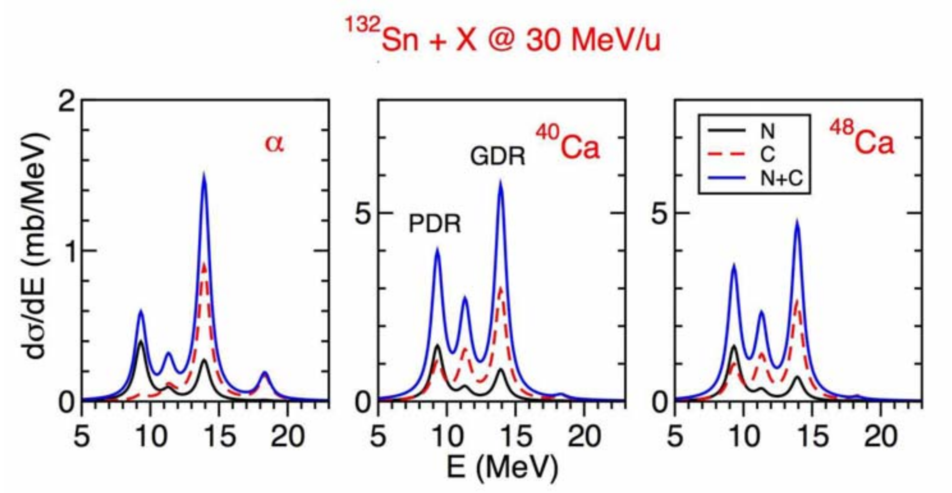

FIGURE 5. Differential cross sections as function of the excitation energy for the systems ^{132}Sn + α, ^{40}Ca, ^{48}Ca at 30 MeV per nucleon. Coulomb (dashed), nuclear (lower solid line) and total contributions are separately shown.

^{48}Ca. The formfactors for the PDR and GDR states are shown in Figure. 4. The nuclear components are indicated with dashed line (N_0, the isoscalar part) and dotted line (N_1, isovectorial part). We get strong contribution from the isovector part only for the ^{48}Ca case while in the other cases the contribution is inhibited because we have N=Z for one of the reaction's partner. We note that the nuclear and Coulomb part interfere destructively at small radii and constructively at large radii. This is more evident for the GDR state and it is a direct consequence of the fact that the isoscalar dipole transition density has different sign at small and large radii[1, 15]. The interference is less pronounced in the ^{48}Ca case because of the presence of the isospin dependent part of the nuclear form factor. As a result, we expect that the GDR state will be less excited when the ^{48}Ca is used as a target rather that ^{40}Ca. Conversely, one is not expecting any change for the PDR state. We already see at this level how different reactions may alter the relative intensities of the PDR and GDR states due to the different interplay of their isoscalar and isovector contributions.

This behaviour is confirmed when the dynamics of the process is taking into account. Indeed, in Figure 5 it is shown the inelastic cross section for three different systems ^{132}Sn + (α, ^{40}Ca, ^{48}Ca) at the same incident energy (30 MeV/u). The Coulomb and the nuclear contributions are separately drawn as well as the total cross section. We observe that the relative strength between the PDR and the GDR may change drastically in different reactions. An alternative possibility to balance the PDR and GDR excitations is to consider different incident energies in order to alter the relative role of nuclear and Coulomb contributions. In Figure 6 it is shown the evolution (as function of the bombarding energy) of the inelastic cross section of the system ^{132}Sn + ^{48}Ca. As the incident energy is decreased, the variation rate of the cross section for the two states (PDR and GDR) is different, making the two dipole states excitations comparable. Indeed, the ratio between the two cross section goes from 5 (at 100 MeV/u) to 1.3 (at 30 MeV/u). However, we should note that at low energies the dipole cross section might

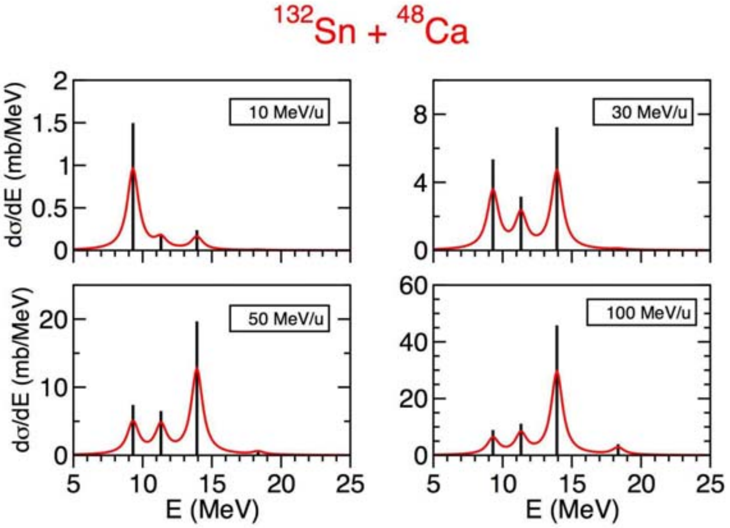

FIGURE 6. Differential cross sections as function of the excitation energy for the system ^{132}Sn + ^{48}Ca at different incident energies.

be embedded into a large background coming from other multipolarities or multistep excitations.

The ratios can be also modified by looking at different scattering angles. In the semi-classical picture, the differential angular distributions are related to different range of impact parameters. In Figure 7 we show the "partial wave cross section" for three systems ^{132}Sn + (α, ^{40}Ca, ^{48}Ca) at 30 MeV/u incident energies and for the two considered dipole states (PDR and GDR). In each graph we draw separately the Coulomb and nuclear contributions as well as the total one. In the upper frames we notice that, independently of the system, the nuclear contribution is always bigger that the Coulomb one. Conversely, for the GDR the Coulomb field produce a stronger excitation in most of the cases. We mention also that the nuclear contribution is generated by a small range of impact parameters which should correspond to a small range of scattering angles. Indeed, nuclear contributions are known to be enhanced at grazing angles, corresponding to "surface" impact parameters.

SUMMARY

Are the low-lying dipole states, known as PDR, collective states? In order to answer this question we have investigated the nature of the PDR states within the H-F plus RPA formalism. Our conclusion is that although they are formed by many particle hole configurations their collective nature may be questioned if one takes into account also the coherence properties. The typical profiles of their transition densities reveals their strong isospin mixing allowing therefore the possibility to be excited also by an isoscalar probe even though their primary nature is isovector-like. We explore how this possibility can be used to get valuable information on the nature of these states. We resort then to reactions

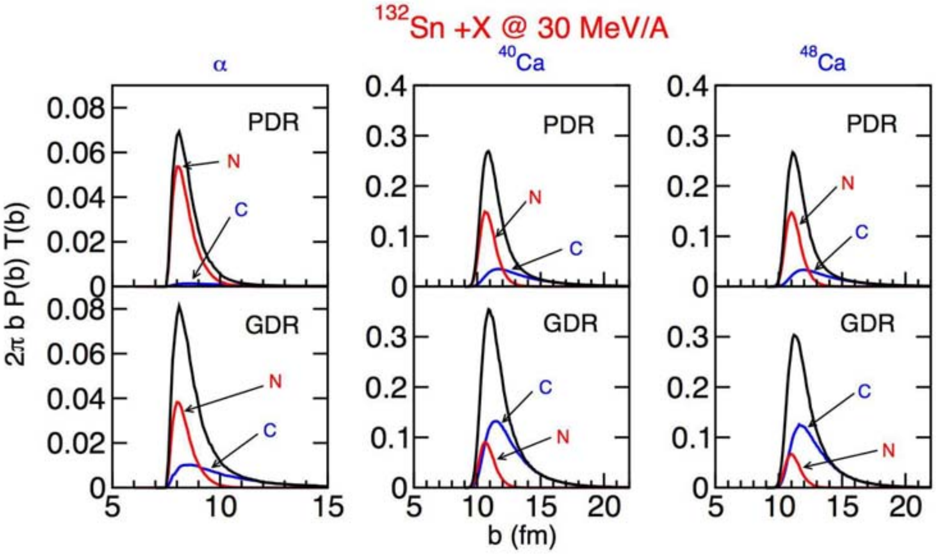

FIGURE 7. "Partial wave cross sections" vs. impact parameter b for three systems ^{132}Sn + (α, ^{40}Ca, ^{48}Ca) for the two dipole states, PDR (upper frames) and GDR (lower frames). The results for the Coulomb (C), nuclear (N) and total are drawn separately.

where the nuclear interaction is involved. Modulating in a proper way the projectile, mass, charge, incident energy as well as the scattering angles one can alter the relative importance of the Coulomb and nuclear components in order to disclose new features of these states.

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