Neutron halos and $E1$ resonances in ^{208}Pb

J. P. Adams
Department of Physics, Queen's University, Kingston, Ontario, Canada K7L 3N6

B. Castel*
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

H. Sagawa
Center for Mathematical Science, University of Aizu, Ikki-machi, Aizu-Wakamatsu, Fukushima 965, Japan

(Received 1 November 1995)

Neutron halos and their relations to the structure of $E1$ resonances are examined in a microscopic random phase approximation continuum calculation of ^{208}Pb. Our results predict the occurrence of small but distinct $E1$ peaks located in the low energy tail of the giant dipole resonance and consisting of highly coherent neutron particle-hole excitations whose energy and strength are found to correspond well to photoneutron and electron scattering data. This work suggests that the high current interest in the appearance of neutron halos in light exotic nuclei could constructively be channeled to investigate similar occurrences in heavier systems where model calculations have already been thoroughly tested.

PACS number(s): 21.10.Gv, 21.60.Jz, 24.30.Cz, 27.80.+w

A great deal of attention is now being focused on the occurrence of neutron halo resonances in neutron rich nuclei and their relationship to neutron particle-hole (p-h) excitations. However, so far, the question has been nearly totally confined to exotic light nuclei such as ^{11}Li although there is now ample experimental evidence suggesting that similar manifestations indeed occur in heavier but stable nuclei with large neutron excess. There, nuclear structure calculations have already been particularly successful in predicting correctly other resonances such as the giant dipole resonance (GDR), the giant quadrupole resonance (GQR), etc. Our aim is thus to test whether neutron p-h excitations do indeed occur at low energy in heavy nuclei where $N>Z$, to determine their relationship to the so-called pygmy resonances observed experimentally [1–3], and to see if their structure can cast some useful information on the whole question of neutron halo occurrence. An earlier preliminary study of the Ca isotopes in the density functional theory has already shown clearly the link between the onset of pygmy resonances and the neutron excess [4]. The present work however is the first one using the random phase approximation (RPA) to focus on a heavy system like ^{208}Pb and for which an extensive body of experimental information [5–7] is available to test the validity and accuracy of our model predictions.

It is known that for an accurate and reliable microscopic description of collective excitations it is crucial to adopt a model well suited to excitation modes in which a large number of p-h states may contribute in a collective manner. The RPA has without question proven to be one of the most important of these techniques when it comes to the description of intermediate energy collective vibrations. Because of its proven reliability in characterizing the more dominant giant resonances like the GDR and GQR we were intrigued with the possibility of applying this technique to lower energies with the goal of locating any dipole strength that was collective enough in nature but decoupled from the usual giant dipole oscillation.

Our particular application of the RPA is a coordinate space solution of the RPA equation [8,9]

$$G^{\mathrm{RPA}}=G^0(1+(\delta V/\delta\rho)G^0)^{-1}, \tag{1}$$

where G^{RPA} is the RPA Green's function and $\delta V/\delta\rho$ is the effective p-h interaction. The single particle basis states were calculated in the Hartree-Fock approximation using a Skyrme-type interaction that was also used to calculate the effective p-h interaction. The parameters of the interaction—in this case the SGII interaction—are standard and thus leave our calculation with *no adjustable parameters*.

The spreading of the response function that results from scattering into the continuum—the escape width—is treated in our calculation using the method of continuum RPA [10]. The spreading that results from decays of RPA states through higher order modes of excitations—the spreading width—is outside the scope of that model, with the result that the calculated spectrum tends to contain more fine structure than could possibly be observed experimentally. As other investigators have noted [10] this effect is particularly noticeable in the case of isovector dipole excitations. To allow a more direct comparison with experiment we have included the effect of the spreading width by folding our results with a Lorentzian distribution with a 0.5 MeV width. It is important to note that this is done merely for display purposes and *in no way affects the conclusions to be drawn from our results.*

In Fig. 1 we display the calculated $E1$ spectrum corresponding to the low energy part of the GDR dominated, as we had hoped, by the occurrence of two distinct peaks situated at 8.7 MeV and 9.5 MeV with $B(E1;0^+\rightarrow1^-)$ values of 1.2 e^2 fm^2 and 0.9 e^2 fm^2, respectively. These two states, the lowest found with any $E1$ strength, together exhaust 2.4% of the total $B(E1;0^+\rightarrow1^-)$ strength (89.5 e^2 fm^2).

*Present address: Department of Physics, Queen's University, Kingston, ON, Canada K7L 3N6.

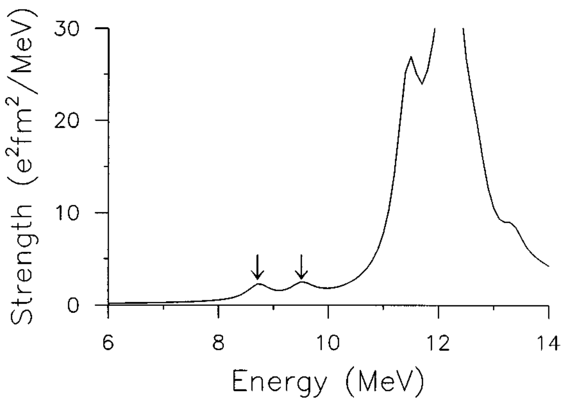

FIG. 1. The results of a continuum-RPA calculation of the isovector dipole strength in ^{208}Pb. The peaks of interest in our view are those seen at 8.7 and 9.5 MeV exhausting 2.4% of the $E1$ sum rule.

They agree nicely with experiment as we shall discuss below and appear likely candidates to be identified as pygmy resonances. As anticipated, neither of these states can be ascribed as having dominant one-proton–one-proton-hole or one-neutron–one-neutron-hole character but rather appear to have a *highly coherent structure* of small amplitudes of all neutron p-h configurations. The best evidence for this collective nature stems from an examination of our calculated transition densities and energies which differ markedly from pure Hartree-Fock results. To connect the present work to that being done in light nuclei like ^{11}Li where the neutron character of the excitations is so important, we expanded our calculations to allow for the simultaneous projection of the proton and neutron responses from the total Green's function. At the energy of these lowest pygmy states *the neutron response indeed was found to be a factor of 10 larger* than the proton response whereas at energies corresponding to the GDR this ratio was about 1.6 or roughly N/Z.

The first investigations, performed more than 20 years ago, into the possible existence of low-lying dipole states were not in agreement on the degree of collectivity of the decoupled states. Lane [11] viewed the low energy state as a single doorway state whereas in Harvey and Khanna's schematic model calculations [12] *the pygmy resonance had a truly collective nature involving eight major p-h states with no single p-h configuration contributing more than 15% to the sum rule value*. Our results, based on a much more sophisticated calculation than the schematic model employed by Harvey and Khanna, do indeed support their contention that the low-energy strength is concentrated in states that are collective in nature and can therefore be considered as ''soft giant resonances.''

Turning now to experiment, it is interesting to note that three separate experimental investigations of the low lying ^{208}Pb spectrum by elastic photon scattering [5], photoneutron [6], and electron scattering [7] all detected sizable ''fine structure'' peaks representing between 3 and 6 % of the $E1$ sum rule and located in the 9 to 11 MeV region without being able to offer a theoretical context for such a finding at the time. The experimental peaks are characteristically seen about 1 MeV above their predicted position, while the energy of our calculated GDR peak is also underestimated by the same amount. This then must be traced to a slight dependence of the energy levels on the interaction chosen. More interestingly, Bell *et al.* [6], analyzing the photoneutron data, concluded that *eight neutron p-h amplitudes were predominant in the fit to the* $^{208}Pb(\gamma,n)^{207}Pb$ *branching ratios*, adding thus an experimental validation to our conclusion regarding the collective character of the two pygmy resonances in question.

To conclude, we have presented here, in the context of our investigations into the structure of ''soft'' dipole resonances, a microscopic calculation of the $E1$ ^{208}Pb spectrum in the region below the GDR. Our results demonstrate conclusively the existence around 9 MeV of a concentration of dipole excitations exhausting 2.4% of the $E1$ sum rule. The position and strength of calculated resonances agree broadly with the $E1$ fine structure detected in that region through several scattering experiments. In one of them a precise analysis in terms of neutron particle-hole was needed to fit the branching ratio data and was consistent with the nature of collective states assumed for these ''soft'' $E1$ resonances. These states represent by their predominant neutron p-h character the analog of the halo excitation currently investigated in light nuclei. In our opinion the high current interest in neutron halo excitations should thus elicit a renewal of experimental investigations in the low energy shoulders of GDR states especially now that higher energy and more precise electron scattering facilities are coming on line.

This work was supported in part by the Natural Sciences and Engineering Research Council of Canada and the U.S. Department of Energy.

[1] G. A. Bartholomew *et al.*, Adv. Nucl. Phys. **7**, 229 (1973).
[2] J. W. Knowles, A. M. Khan, and W. F. Mills, Can. J. Phys. **56**, 1021 (1978).
[3] R. E. Pywell, B. L. Berman, J. G. Woodworth, J. W. Jury, K. G. McNeil, and M. N. Thompson, Phys. Rev. C **32**, 384 (1985); M. Igashira, H. Kitazawa, J. Shimizu, H. Komano, and N. Yamamuro, Nucl. Phys. **A457**, 301 (1986).
[4] J. Chambers, E. Zaremba, J. P. Adams, and B. Castel, Phys. Rev. C **50**, 2671 (1994).
[5] R. D. Starr, P. Axel, and L. S. Cardman, Phys. Rev. C **25**, 780 (1982).
[6] Z. W. Bell, L. S. Cardman, and P. Axel, Phys. Rev. C **25**, 791 (1982).
[7] G. Kühner, D. Meuer, S. Müller, A. Richter, E. Spamer, O. Titze, and W. Knüpfer, Phys. Lett. B **104**, 187 (1981).
[8] G. F. Bertsch and S. F. Tsai, Phys. Rep. **18**, 126 (1975).
[9] P. M. Boucher, B. Castel, Y. Okuhara, and H. Sagawa, Ann. Phys. **196**, 150 (1989).
[10] S. Shlomo and G. F. Bertsch, Nucl. Phys. **A243**, 507 (1975).
[11] A. M. Lane, Ann. Phys. **63**, 171 (1971).
[12] M. Harvey and F. C. Khanna, Nucl. Phys. **A221**, 77 (1974).