Reply to "Comment on 'Continuum Tamm-Dancoff approximation calculations for the escape widths of the isobaric analog state and Gamow-Teller resonance in ^{208}Bi' "

D. P. Knobles and S. A. Stotts
Applied Research Laboratories, The University of Texas at Austin, Austin, Texas 78713-8029

T. Udagawa*
Department of Physics, The University of Texas at Austin, Austin, Texas 78712-8029

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A response is made to the Comment in Ref. [1]. The discussion centers on two approaches to evaluate the nuclear response in the continuum. Both approaches approximate the damping mechanism and can be considered complementary to each other since they can be used to study different aspects of the nuclear response. The issue of self-consistency between the mean field and residual interaction is addressed along with a discussion concerning the nature of the damping in the continuum. [S0556-2813(96)04409-3]

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The following is a response to the Comment [1] by Bortignon and Van Giai (BVG) on our paper entitled "Continuum TDA calculations for the escape widths of the isobaric analog state and Gamow-Teller resonance in ^{208}Bi" (see Ref. [2]). The main points of their Comment are the following: (1) "Our model is inconsistent as far as the relationship between the mean field and the effective residual interaction is concerned" and (2) "The conclusions drawn by us about the validity of other treatments of continuum effects are incorrect." In this response, we first present a brief discussion of our approach used in Ref. [2] and then give our answer to the above and other additional comments made by BVG.

The approach of Ref. [2] is centered on solving the continuum Tamm-Dancoff approximation (TDA) and random phase approximation (RPA) equations exactly for the purpose of evaluating the nuclear response in the continuum. The equations are constructed within a model Hamiltonian $H=H_{\mathrm{h}}+H_{\mathrm{p}}+V_{\mathrm{ph}}$, H_{h}, H_{p}, and V_{ph} being the hole-nucleus Hamiltonian, the particle Hamiltonian, and the residual particle-hole (ph) interaction, respectively. For H_{h}, we assume a pure shell-model Hamiltonian. The occupied (hole) single-particle states are generated by using a Woods-Saxon potential taken from the literature. H_{p} is a sum of a kinetic energy operator and a complex energy-dependent optical potential such as determined by Johnson *et al.* [3]. The potential discussed in Ref. [3] can accurately describe the single-particle states in both continuum and bound regions. For V_{ph}, we usually assume a delta force, whose strength is fixed such that the observed energy of the collective state in question is reproduced. The strength in the various spin-isospin channels of V_{ph} is the only free parameter in our theory. Our approach can thus take into account the continuum effect exactly and also the damping of the excited particle via the imaginary part of the optical potential. As is known, the optical model is the most successful model for describing, though phenomenologically, the scattering and damping of the single particle. Therefore, our description of the particle damping is on a sound basis. We remark here that essentially the same approach has also been used by other authors, e.g., by Ichimura *et al.* [4], for studies of (p,n) reactions at intermediate energies.

As is clear from what was described above, the approach does not take into account effects of the hole damping and also the interference effects between the particle and hole damping. We therefore expect that our approach may best be applicable to the description of highly excited ph states, where the neglected hole damping and interference effects will become relatively unimportant as compared with those of the particle damping. In fact, the approach has successfully been applied to analyze data of the Δ-hole (Δh) resonance seen in the 200–500 MeV excitation energy region [5]. In the Δh resonance case, there appear additional decay modes due to the decay of the Δ into a pion and a nucleon. One interesting decay mode coming from this is the coherent pion production, where the Δh resonance decays into a pion and the residual nucleus which is nothing but the ground state of the target. Our method turned out to be very successful in describing such a decay process. We note that Ichimura *et al.* [4] were also able to extract valuable information on the spin response of nuclei [6] in the quasielastic region from the analysis of the (p,n) reaction data using the same method.

There might be some question in applying the method to low-lying ph states such as the IAS and Gamow-Teller resonance (GTR). We tried, nevertheless, to apply the method to calculate the escape and damping width for these states [2] and also for the giant monopole, dipole, and quadrupole resonances [7]. In Ref. [2], we were particularly interested in the escape widths. For that purpose, the effects of the approximation introduced for the damping may not be serious. In fact, we have confirmed that in our approach the calculated particle emission widths obtained by including and excluding the damping effect are not much different. Therefore, the results of our calculations of the escape widths reported in Ref. [2] may not change significantly if a more careful treatment of the damping is made.

*Also with the Applied Research Laboratories, The University of Texas at Austin, Austin, TX 78713-8029.

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Keeping what was discussed above in mind, we now turn to respond to comments made by BVG. For the first of the two major comments already described at the beginning of the paper, our response is simply that our approach does not satisfy such a self-consistency between H_h+H_p and V_{ph} as discussed in Ref. [1]. There are two types of consistencies involved: One is associated with the Hartree-Fock field in H_h+H_p and the residual interaction, and the other is the consistency between the imaginary (+ some small real) part of H_p and a residual interaction term that originates from the truncation of the model space (channel elimination). The neglect of the consistency of the first type has been made in almost all of the TDA and RPA calculations in the past 35 years, and thus BVG's comment applies not only to our work of Ref. [2] but also to all these other works as well. For the second consistency, it is simply ignored, because it is too difficult to take into account in a rigorous manner at this moment; i.e. an exact solution to the continuum n-particle–n-hole RPA equations is an unsolved problem in nuclear theory. These remarks of course do not necessarily justify the neglect of self-consistency. The key question that still remains is how good or how bad is a calculation that ignores these two types of self-consistencies. This, in our opinion, is still an open question.

The second major comment concerns our remark made on the relative magnitude of the escape widths of $\Gamma^{\uparrow}_{p_{3/2}}$ and $\Gamma^{\uparrow}_{p_{1/2}}$ of the $p_{3/2}$ and $p_{1/2}$ states, respectively. We were curious with the result $\Gamma^{\uparrow}_{p_{3/2}}<\Gamma^{\uparrow}_{p_{1/2}}$ obtained in earlier calculations made by BVG and their collaborators [8,9] while our prediction is opposite, i.e., $\Gamma^{\uparrow}_{p_{3/2}}>\Gamma^{\uparrow}_{p_{1/2}}$. In an attempt to understand the difference between the two results, we repeated our calculations by neglecting the diagonal terms of the residual interaction, finding that the resultant relative magnitude is reversed. We then remarked that it is important to treat the continuum coupling exactly in reproducing such a subtle feature as the relative magnitude between $\Gamma^{\uparrow}_{p_{3/2}}$ and $\Gamma^{\uparrow}_{p_{1/2}}$. The second comment by BVG is made against the above and other additional remarks. Our response is that we had no intention to doubt the overall validity of their approach as implied in their Comment. Rather, we wished to point out that the escape widths depend sensitively on such details as the diagonal coupling in the continuum. A similar opinion is also expressed by BVG, saying that the escape widths depend sensitively on the mean field and the residual interaction.

Another issue raised by BVG is the validity of neglecting the imaginary part of the optical potential in calculating the escape widths of the IAS, while it is included in the calculations of the GTR. As is known, the IAS is a special state, and the damping of the state is largely prohibited because of the isospin conservation. Namely, the particle and hole can hardly damp in the IAS. This means that the imaginary potential is extremely small for the particle in the IAS.

Finally, we give a few comments on the approach used by BVG. The approach emphasizes the self-consistency between the residual particle-hole (ph) interaction, the average nuclear potential, and self-energy insertions. A Skyrme-like force is used to construct the ph interaction and the real part of the average nuclear field via the Hartree-Fock approach. The damping is approximated by including three 2p-2h self-energy insertions: particle, hole, and the ph interference terms in a manner consistent with the residual interaction. In order to make the calculation feasible, it is also necessary to approximate the effects of the nuclear continuum. The approach will thus find some difficulty in applying it to highly excited continuum states. The BVG theory, however, exhibits the desirable feature of self-consistency between the residual ph interaction and the real part of the average nuclear field.

In our opinion, the BVG approach is complementary to ours: The approach can describe, though approximately, the damping mechanism microscopically. One can study the role of the hole and interference effects in some detail. We have, however, to keep in mind that the treatment is still approximate; the damping is treated through the coupling with the pure 2p-2h or two-phonon states. It has recently been demonstrated [10,11] that the strength distribution of the nuclear response changes rather dramatically if the residual interaction between 2p-2h states is introduced; the residual interaction, particularly the interaction between a particle and a hole in the 2p-2h states, makes the resultant 2p-2h states chaotic [10,11]. It might be possible that this chaotic character of the damping will further be enhanced if mixings of many-particle–many-hole states are included in the calculations. In the calculations made so far by BVG and their collaborators [8,9,12], however, the residual interactions in the 2p-2h states are ignored. The strong fluctuations observed in some of the results of their calculations may reflect this approximation. In our approach, on the other hand, the mixings with the many-particle–many-hole states are effectively included, although the treatment is phenomenological and we include only the particle damping. One case where the two approaches lead to quite different physical consequences is the width of the isoscalar giant monopole resonance (GMR); our approach predicts that the width comes almost entirely from damping, while the BVG approach predicts that it comes from the Landau damping and the particle escape. Hopefully, more detailed data on the damping will become available, which may tell us which prediction is correct. In conclusion, the two approaches, BVG's and ours, have both merits and dismerits, and can be used to study different aspects of the nuclear response.

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