Microscopic background calculations for (p,n) reactions at intermediate energies

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The background of $^{40}Ca(p,n)$ and $^{48}Ca(p,n)$ spectra has been calculated in a microscopic model for an incident proton energy of 160 MeV. The continuous parts of the spectra are reproduced within a factor of 1.3. It is shown that most of the background subtracted in the experimental analysis of the $^{48}Ca(p,n)$-Gamow-Teller resonance is actually Gamow-Teller strength. The calculations predict a strong $\Delta L = 2$ (3^+) resonance in $^{48}Ca(p,n)$ at 25 MeV excitation energy, but none in ^{40}Ca.

[NUCLEAR REACTIONS (p,n) scattering: calculated background for $^{40}Ca(p,n)$ and $^{48}Ca(p,n)$.]

Recent (p,n) experiments[1–5] at intermediate energies have led to a major breakthrough in our understanding of spin-isospin correlations in nuclei. In particular the zero degree (p,n) spectra are dominated by the giant Gamow-Teller (GT) resonance, the spin-isospin $(\Delta S = 1, \Delta T = 1, \Delta L = 0)$ collective mode which was already predicted by Ikeda *et al.*[6] as early as 1963. The GT resonance appears energetically somewhat above the isobaric analogs of the target ground states (IAS) and is located on a continuum (background) the shape and magnitude of which is not known. Uncertainties in the decomposition of the spectra into resonance and background seriously limit the accuracy with which the amount of sum rule strength exhausted by the GT state can be determined. Since the "signal to background ratio" is very good for (p,n) reactions at intermediate energies the spectra still allow, in spite of the background problem, the conclusion that only around 50% of the theoretically[6] expected total GT strength is found in these experiments. Several authors[7] have suggested that this so-called quenching of the total GT strength is due to the admixture of $\Delta(1232)$ isobar-nucleon hole (ΔN^{-1}) excitations into the proton particle-neutron hole (pn^{-1}) GT state. For a quantitative understanding of this Δ isobar effect, however, it is of utmost importance to calculate the background in a most reliable way. Such a calculation is even more important for the $\Delta L = 1$ resonances[4,5] and resonances of higher multipolarities[5] where the signal to background ratio becomes rather bad. The $\Delta L = 1$ resonance (and resonances with $\Delta L \geq 2$) should provide information on the spin (J^π) dependence of the quenching.

In this Communication we present microscopic model calculations of the background below GT resonances. The model assumptions are as follows: (1) For (p,n) reactions at high incident energies $(E \geq 100$ MeV) the reaction mechanism is direct, i.e., the whole spectrum including peaks and continuum is a result of one step processes only. (2) The effective projectile-target nucleon interaction can be approximated by the free N-N t matrix, i.e., by the G3Y interaction of Love and Franey.[8] (3) The only nuclear states contributing to the (p,n) background at $E \geq 100$ MeV are spin-flip $(\Delta S = 1, \Delta T = 1)$ states. This argument is based on the fact that the $\sigma\sigma\tau\tau$ part of the G3Y interaction which excites spin-flip states is nearly energy independent while the $\tau\tau$ part which excites the non-spin-flip states gets strongly reduced at $E \geq 100$ MeV.[8] (4) The final nuclear states are assumed to be of simple proton particle-neutron hole doorway nature including bound, quasibound, and continuum states (see Fig. 1). The single particle wave functions of the bound states are generated from a Woods-Saxon potential which is chosen to reproduce the known experimental single particle energies. The continuum states are generated from the real part of the energy dependent Becchetti-Greenless potential.[9] The proton particle and neutron hole are coupled to states of spin parity J^π. This is advantageous since to 0° cross sections only states with low multipolarity can contribute. For the continuum wave functions we neglect the spin orbit potential, so that the transitions to all final nuclear states are completely incoherent. Then, the whole background is a simple superposition of cross sections of inelastic excitations to bound, quasibound, and continuum states. (5) The cross sections are calculated in the distorted-wave impulse approximation (DWIA) using the fast speed DWBA-code FROST-MARS[10] which includes knock-out exchange amplitudes exactly.

The particle-hole doorway model discussed above includes the nuclear continuum but does not include nuclear collectivity. The latter, however, may be included explicitly for certain selected collective states

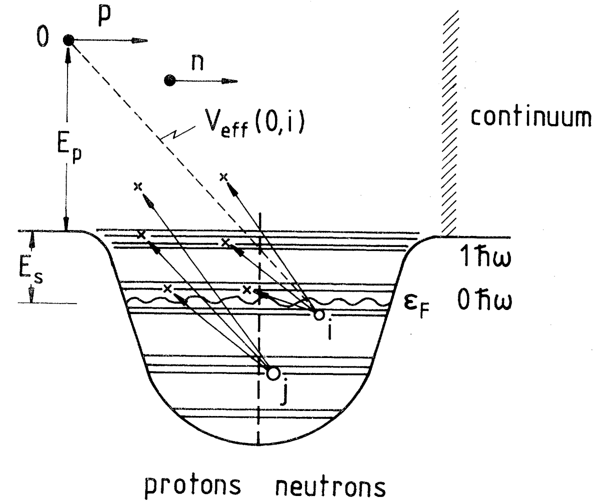

FIG. 1. Schematic representation of the microscopic model used for the background calculations. In the figure ϵ_F denotes the Fermi energy, E_S the nucleon separation energy, and E_p the incident projectile energy. For the effective projectile target nucleon interaction $V_{\rm eff}$ the G3Y interaction of Love and Franey (Ref. 8) is used.

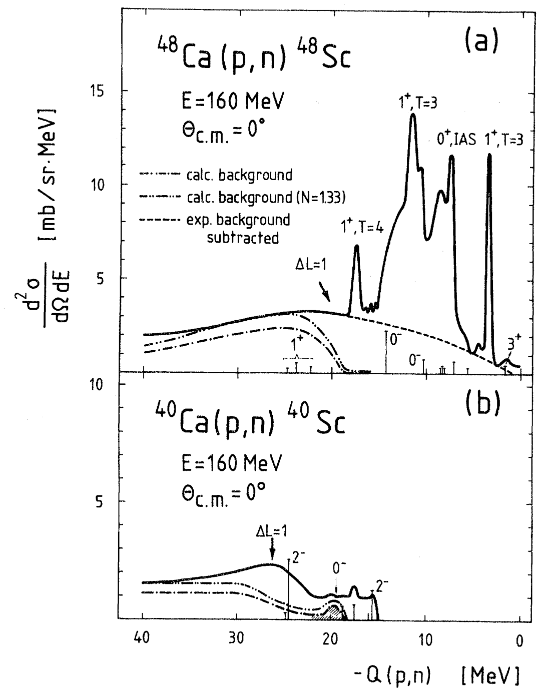

FIG. 2. Zero degree spectra for the reactions ^{48}Ca(p,n) (a) and ^{40}Ca(p,n) (b). The data (thick full line) are taken from Refs. 13 and 14 (see text). The discrete lines are calculated cross sections due to bound and quasibound states. The arrow labeled with $\Delta L=1$ indicates the location where the $\Delta L=1$ resonance $(0^-,1^-,2^-)$ would occur if nuclear collectivity were included for these states. The theoretical cross sections due to the GTR and IAS are *not* plotted. The optical parameters for the cross section calculations have been taken from Ref. 20.

like the GTR and IAS. For most of the other states nuclear collectivity is of minor importance. This argument is based on the work of Speth *et al.*[11] who have shown that for $\Delta S=1$, $\Delta T=1$ transitions collectivity plays only a role for low multipolarities, i.e., for 0^-, 1^+, 1^- $(\Delta S=1)$ and, maybe, 2^- states. This is simply an effect of the finite range residual particle-hole (ph) interaction in the $\Delta S=1, \Delta T=1$ channel[11] which is strongly repulsive for low spin states and weak for high spin states $(J^\pi \geq 2^-)$. Therefore, states with large J^π are nearly unaffected by the residual ph interaction (see also Ref. 12).

In Figs. 2(a) and 2(b) we show 0° spectra for the reactions ^{48}Ca(p,n) and ^{40}Ca(p,n), respectively. The experimental data (thick full line) have been taken from Ref. 13 in the case of ^{48}Ca (using the normalization of Ref. 14) and from Ref. 14 in case of ^{40}Ca. The data are compared to the calculated spectra which are the incoherent sum of all cross sections with multipolarities $\Delta L=0$ through 3 $(J^\pi=0^-,1^+,1^-,2^+,2^-,3^+,3^-,4^-)$. The calculations reproduce the spectra at large Q values within a factor of 1.33! This applies for both reactions, ^{40}Ca(p,n) and ^{48}Ca(p,n). The calculated continuum falls off sharply at $Q\sim-20$ MeV for ^{48}Ca and at $Q\sim-25$ MeV for ^{40}Ca. This falling off is a combined effect of the Coulomb and the centrifugal barrier which make the continuum wave function of the excited proton $|E_p,l_pj_p\rangle$ small in the nuclear surface region, especially for smaller energies $(E_p \leq 10$ MeV) and angular momenta $l_p \neq 0$. As a consequence the nuclear transition densities are small for these energies and therefore also the cross sections. The 0^- cross section at $Q=-20$ MeV in Fig. 2(b) is due to the $p_{3/2}$ proton single particle resonance which couples with the $d_{3/2}$ neutron hole to $J^\pi=0^-$. This 0^- resonance would be shifted to the energy region around $Q=-26$ MeV if our model would include nuclear collectivity. The same is true for part of the theoretical 2^- strength at lower Q values in ^{40}Ca.

By comparison of the experimental spectra for ^{40}Ca and ^{48}Ca (see Fig. 2) one immediately sees that for ^{40}Ca there is no cross section in the Q value region from 0 to 15 MeV while for ^{48}Ca we have in this region the large cross sections due to the GT states, due to the "background" and, to a small fraction, due to the IAS. Also our microscopic model gives zero cross section for ^{40}Ca(p,n) at $0 \geq Q \geq -15$ MeV. For ^{48}Ca(p,n) the background cross section below the GTR and IAS has then to be produced from all the transitions which promote a neutron from the $2s$-$1d$ and $1f_{7/2}$ shell via charge exchange into the proton $2p$-$1f$ shell (see Fig. 1) or into the continuum (the neutron separation energy is ~ 10 MeV). The cross sections produced by these states are shown in Fig. 2(a) (the discrete states, the cross sections to the GTR and IAS are not plotted). Most of this background cross section is due to $\Delta L = 1$ ($0^-, 1^-, 2^-$) and $\Delta L = 2$ (3^+) excitations. The sum of all cross sections in the Q interval from 2 to 15 MeV amounts to 5.4 mb from which 2.5 mb are due to 0^-, 1.4 mb due to 2^-, and 1.0 mb due to 3^+ excitations. Note that most of the $\Delta L = 1$ ($0^-, 1^-, 2^-$) strength is shifted into the energy region around $Q = -22$ MeV (as indicated in the figure) when the residual ph interaction is switched on. We emphasize that there exists a sum rule for $\Delta L = 1$ charge exchange modes.[6] This sum rule tells us that when we consider a residual ph interaction the strength is only redistributed, i.e., the strength is moved from the low to the high excitation energy region. Therefore, the 5 mb calculated in our unperturbed ph-doorway model represent an upper limit for the background below the GTR in ^{48}Ca. In the experimental analysis, however, a background of roughly 17 mb is subtracted [see Fig. 2(a)]. Our calculations show that at least 12 mb of this background are actually GT strength. By adding this cross section of 12 mb to that of the 1^+, $T = 3$, 11 MeV state the GT cross section at 0° is changed from 48 to 60 mb which makes an effect of 25%. This also means that the amount of GT strength seen in ^{48}Ca is now increased from 43% to 51% of the total GT strength.

In Fig. 3 we show calculated spectra for a scattering angle of 12°. The striking point in this figure is that there appears a strong $\Delta L = 2$ (3^+) resonance in ^{48}Ca(p,n) (centered around $Q = -26$ MeV) while there is none in ^{40}Ca. The 3^+ resonance is a $2\hbar\omega$ excitation and is mainly built up by the $[\pi g_{9/2} \nu 1d_{3/2}^{-1}]_{3^+}$ and the $[\pi g_{7/2} \nu 2s_{1/2}^{-1}]_{3^+}$ configurations. The appearance of the resonance in ^{48}Ca is associated with an additional attraction from the isovector part of the single particle potential (~ 4 MeV) which produces a potential pocket for the $g_{9/2}$ and $g_{7/2}$ orbits. This does not happen for ^{40}Ca. We remark that the width of the 3^+ resonance in ^{48}Ca is ~ 4.5 MeV at half maximum. Since our model includes only the escape width one would expect an additional broadening of the resonance due to 2p-2h admixtures (spreading width). The $\Delta L = 2$ resonance has been observed in the ^{90}Zr(p,n) and ^{208}Pb(p,n) reactions,[5] while not in ^{40}Ca(p,n) (Ref. 15) agreeing with our prediction.

In summary we have presented microscopic back-

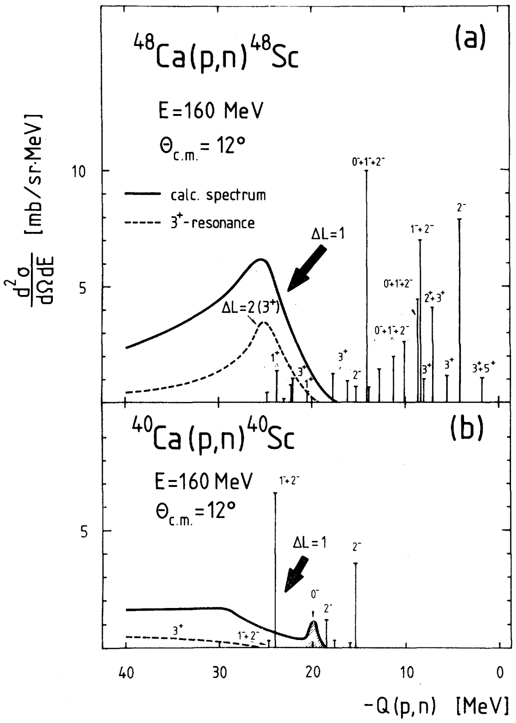

FIG. 3. (a), (b) Same as in Fig. 2 but for $\theta_{c.m.} = 12°$. No data are published yet for this scattering angle.

ground calculations for (p,n) reactions at intermediate energies which reproduce the ^{48}Ca(p,n) continuum at 0° within an accuracy of 30%. The calculations show that the shape of the background below the GTR in ^{48}Ca(p,n) is quite different from that drawn by the experimentalists. We find a strong $\Delta L = 2$, 3^+ resonance in ^{48}Ca(p,n), but *not* in ^{40}Ca(p,n). The concentration of $\Delta L = 2$ strength depends on the neutron excess. Finally, to our knowledge there exists no background calculation[16–19] up to now which calculates background and peaks of a spectrum with the same footing as we do and which comes so close to experiment.

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