PHYSICAL REVIEW C VOLUME 27, NUMBER 3 MARCH 1983

Continuum spectrum in the quasifree $(p, 2p)$ scattering

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(Received 25 October 1982)

It is assumed that the rescattering of the quasifree particles on the spectator part of the target nucleus constitutes the major source of the pre-equilibrium events situated beyond the four-body kinematic limit in the reaction phase space. A preliminary analysis suggests that the pre-equilibrium spectrum can be calculated in terms of the inelastic scattering of the quasifree particles on the spectator nucleus. Comparison with the ^{58}Ni$(p, 2p)^{57}$Co data at $E_0 = 198$ MeV supports the model prediction.

[NUCLEAR REACTIONS ^{58}Ni$(p, 2p)^{57}$Co, $E = 198$ MeV; measured $d^4\sigma/d\Omega_1 dE_1 d\Omega_2 dE_2$; discussion of continuum spectrum mechanism; DWIA calculations; connection with inelastic scattering analyzed.]

The quasifree (QF) scattering experiments $A(a,ab)B$ are among the few available probes of the inner nuclear shell structure. This is due to their distinctive feature of violent knockout by the projectile of a particle from a definite target shell model orbital ν while the rest of the target nucleus remains practically an inert spectator. Unfortunately, there exist perturbing factors[1] which tend to blur the basic physics underlying the QF scattering. One such factor is the particle flux attenuation due to the multiple scattering of both the projectile and the knocked out particle before and after the QF process. This effect adds to the difficulty of probing the inner nuclear shells, not only by reducing the corresponding observed particle yield, but also by creating a continuum background with the particles removed from the outer shells QF loci via multiple scattering.

Although the importance of particle rescattering for the interpretation of the QF events has been recognized,[2] so far there is no systematic study of the continuum spectrum in the QF reactions such as that conducted for the inclusive reactions. In this paper we report on preliminary results of an investigation[3] of the above question. Our main objective here is to account for the empirical observation[4] that the continuum $(p, 2p)$ spectrum is, to a certain extent, proportional to the (p,p') spectrum. The experimental data used for substantiating the theoretical arguments are provided by our recent coplanar coincidence measurements[3] of the ^{58}Ni$(p, 2p)^{57}$Co reaction using 198 MeV protons from the Indiana University Cyclotron Facility.

Figure 1 shows a sample of a measured two-dimensional energy spectrum associated with the emission of two coincident protons on the opposite sides of the beam. Clearly seen is the QF region corresponding to the knocking out of protons from the ^{58}Ni target outer shells $0f_{7/2}$ and $1s_{1/2}$, leaving the residual spectator (S) nucleus ^{57}Co in the $\frac{7}{2}^-$ ground state and the $\frac{1}{2}^+$ 2.981 MeV excited state. The respective proton binding energies[5] $E_\nu = -8.72$ and -11.16 MeV, together with the corresponding recoil energies E_R of the S nucleus, determine the three- and four-body reaction thresholds along the energy conservation kinematic loci $E_1 + E_2 = E_0 + E_\nu - E_R$, unresolved by our energy resolution of about 8 MeV.[6] Also shown in Fig. 1 is the pre-equilibrium (PEQ) region beyond the four-body threshold. Any QF kinematic loci appear here to be completely obscured by the continuous particle distribution.

The inset in Fig. 1 gives a geometrical illustration of our understanding of how the continuum coincidence particle PEQ spectrum arises. Thus we think that the PEQ spectrum results from a chain of nucleon-nucleon (NN) interactions, which is initiated by a QF collision. The entrance channel is then in the shell model terminology a one-particle (1p) state. Through a NN interaction this couples strongly with a two-particle—one-hole (2p-1h) doorway state having both particles unbound. Upon elevating above the Fermi level particles from different ν orbits, there are several such doorway states possible. The doorway states can decay via two routes: into the $p_1+p_2+\mathrm{S}$ open channel, thus feeding the QF particle loci, or into more complicated configurations involving a multiple scattering of the two particles on the S nucleus, thus feeding the continuum PEQ spectrum. For simplicity, the inset of Fig. 1 shows the rescattering of just one particle following the initial QF process.

The above ideas can be implemented by extending the formalism of the Feshbach, Kerman, and Koonin (FKK)[7] statistical theory of the multistep direct reactions. Thus we assume that the energy averaged coincidence continuum cross section can be expressed as a convolution of the QF cross section with two chains of subsequent rescattering probabilities, one for each particle. We find it physically reasonable to further express the rescattering chains in terms of the probability that the two protons from the QF step, with energies E_1' and E_2' at angles Θ_1' and Θ_2', will inelastically scatter to the final angles Θ_1 and Θ_2 with energies E_1 and E_2. We assume that these probabilities are related to the cross section for inelastic (in) scattering on the S nucleus by the expression

$$\frac{d^2\sigma^{\text{in}}}{d(\Omega_i-\Omega_i')dE_i}(E_i';\theta_i,E_i)\Big/[2\pi\sigma_{\text{tot}}^{\text{in}}(E_i')] \ ,$$

where $\sigma_{\text{tot}}^{\text{in}}(E_i')$ is the θ_i- and E_i-integrated inelastic scattering cross section of particle i with incident energy E_i' and $\theta_i=|\Theta_i-\Theta_i'|$ is the inelastic scattering angle. Thus we have the expression

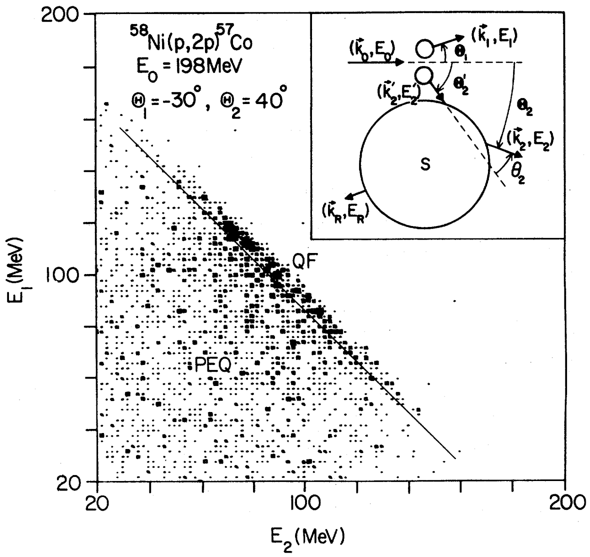

FIG. 1. Two-dimensional energy spectrum above the particle evaporation (equilibrium) region. The area of the points is proportional to the number of particles detected. The diagonal line marks approximately the separation between the three-body QF region and the PEQ region. The inset presents schematically the important steps toward forming the coincidence continuum. For simplicity, the rescattering of the p_1 proton is not shown.

$$\left\langle\frac{d^4\sigma}{d\Omega_1 dE_1 d\Omega_2 dE_2}(\Theta_1,E_1,\Theta_2,E_2)\right\rangle=\int dE_1'\,d\Theta_1'\,d\Theta_2'\sin\Theta_1'\sin\Theta_2' \times\sum_\nu\frac{d^3\sigma_\nu^{\text{QF}}}{d\Omega_1'dE_1'\,d\Omega_2'}(\Theta_1',E_1',\Theta_2',E_2')\,\sigma_{\text{tot}}^{\text{in}}(E_1')^{-1}\frac{d^2\sigma^{\text{in}}}{d(\Omega_1-\Omega_1')\,dE_1} \times(E_1';\theta_1,E_1)\,\sigma_{\text{tot}}^{\text{in}}(E_2')^{-1}\frac{d^2\sigma^{\text{in}}}{d(\Omega_2-\Omega_2')\,dE_2}(E_2';\theta_2,E_2)\ , \quad (1)$$

where the calculation of the QF cross section assumes a distorted wave for the incident proton and plane waves for the two QF emerging protons; E_1' and E_2' are related through the conservation of energy equation.

In order to provide a preliminary comparison of this expression with the measured coincidence continuum we consider here the average yields in two 40 MeV wide slices through the two-dimensional energy spectra, one centered at $\langle E_1\rangle=100$ MeV, and the other at 130 MeV, for two angles $\Theta_1=-12°$ and $-30°$ and several positive angles Θ_2. The reason for choosing these energy slices is that we want to use for the inelastic scattering cross sections the available experimental data for $E_2'=90$ MeV protons on ^{58}Ni (Ref. 8) and 62 MeV protons on ^{54}Fe (Ref. 9); the fact that these targets differ somewhat from ^{57}Co is not expected to change the results significantly.

For the purpose of this paper, in which $E_1>E_0/2$, we will neglect the contribution to the continuum at positive angles Θ_2 coming from the QF protons initially emitted at negative angles Θ_1'. Equation (1) is now replaced by

$$\left\langle\frac{d^4\sigma}{d\Omega_1 dE_1 d\Omega_2 dE_2}(\Theta_1,\langle E_1\rangle,\Theta_2,E_2)\right\rangle=\int d\Theta_2'\sin\Theta_2'\sum_\nu\frac{d^3\sigma_\nu^{\text{QF}}}{d\Omega_1 dE_1 d\Omega_2'}(\Theta_1,\langle E_1\rangle,\Theta_2',E_2')\,\sigma_{\text{tot}}^{\text{in}}(E_2')^{-1} \times\frac{d^2\sigma^{\text{in}}}{d(\Omega_2-\Omega_2')\,dE_2}(E_2';\theta_2,E_2)\ , \quad (2)$$

where the QF cross sections assume distorted waves for the p_0 and p_1 protons and plane waves for the p_2 protons.

As no QF kinematic loci are seen in the PEQ region, we assume that the major contribution to this region is due to the further interaction of the particles resulting from the initial QF scattering on the $0f_{7/2}$ and $1s_{1/2}$ orbits. Figure 2 shows these QF cross sections, which are required in Eq. (2), calculated in the distorted-wave impulse approximation (DWIA) formalism.[10] Their products with $\sin\Theta_2'$ act like weighting functions in the Θ_2'-averaging integrals (2), and we could eventually replace them with the χ^2-fitted Lorentz shapes $N(W/\pi)\{1/[(\Theta_2'-\overline{\Theta}_2)^2+W^2]\}$ shown in Fig. 2. It appears evident now that in the $W\rightarrow 0$ limit, when the Lorentz shapes become $N\delta(\Theta_2'-\overline{\Theta}_2)$, the continuum spectrum is proportional with the inelastic scattering cross section as

$$\left\langle \frac{d^4\sigma}{d\Omega_1 dE_1 d\Omega_2 dE_2}(\Theta_1, \langle E_1\rangle, \Theta_2, E_2)\right\rangle \sim N\sigma_{\rm tot}^{\rm in}(E_2')^{-1}\frac{d^2\sigma^{\rm in}}{d(\Omega_2-\Omega_2')dE_2}(E_2';\Theta_2-\overline{\Theta}_2,E_2) \quad . \tag{3}$$

Although this proportionality obviously represents an oversimplification, the previous empirical 100 MeV ^{58}Ni$(p,2p)^{57}$Co study[4] showed that it is, however, noticeable at many observation angles Θ_2. We now understand that this happens when the inelastic scattering cross sections are not too different from their angle averages of Eq. (2). The comparison made in Fig. 3 by using the (p,p') spectra[8,9] at several available angles θ_2 shows that, in general, the best shape agreement with our continuum data is obtained when θ_2 is close to $\Theta_2-\overline{\Theta}_2$ using the χ^2-fit $\overline{\Theta}_2$ values from Fig. 2. As expected, discrepancies occur mostly in the region of small and large angles Θ_2 where the inelastic cross sections may differ considerably in magnitude and/or shape from their angle averages. Although at this stage we do not place much emphasis on the comparison in magnitude we note, however, that this looks reasonable. Thus the ratios between the numbers needed to multiply the singles to fit the coincidence spectra in Fig. 3 and $N\sigma_{\rm tot}^{\rm in}(E_2')^{-1}$ are 0.8 and 2.1 (for $\langle E_1\rangle = 100$ MeV with $\Theta_1 = -12°$ and $-30°$, respectively), 0.5 and 1.5

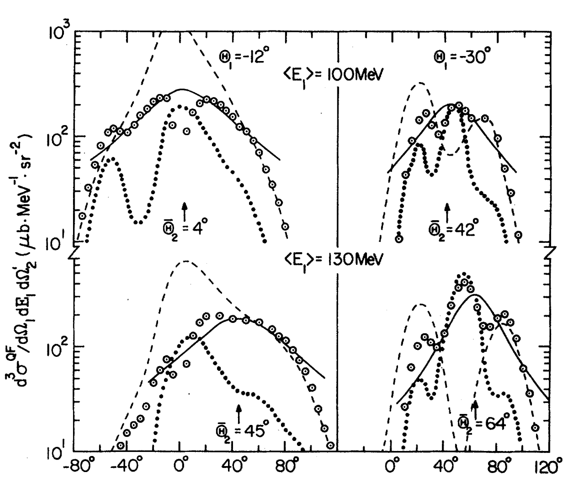

FIG. 2. QF cross section impulse approximation calculations assuming distorted waves for the p_0 and p_1 protons and plane wave for the p_2 proton. The curves $\cdots\cdot$ and $---$ represent proton knockout from the orbitals $1s_{1/2}$ and $0f_{7/2}$, respectively, using maximum spectroscopic factors. The curve ⊙⊙⊙ represents the sum of these two contributions times $\sin\Theta_2'$ and —— is a χ^2 fit of this with the Lorentz function from text using the parameters $\overline{\Theta}_2$ indicated.

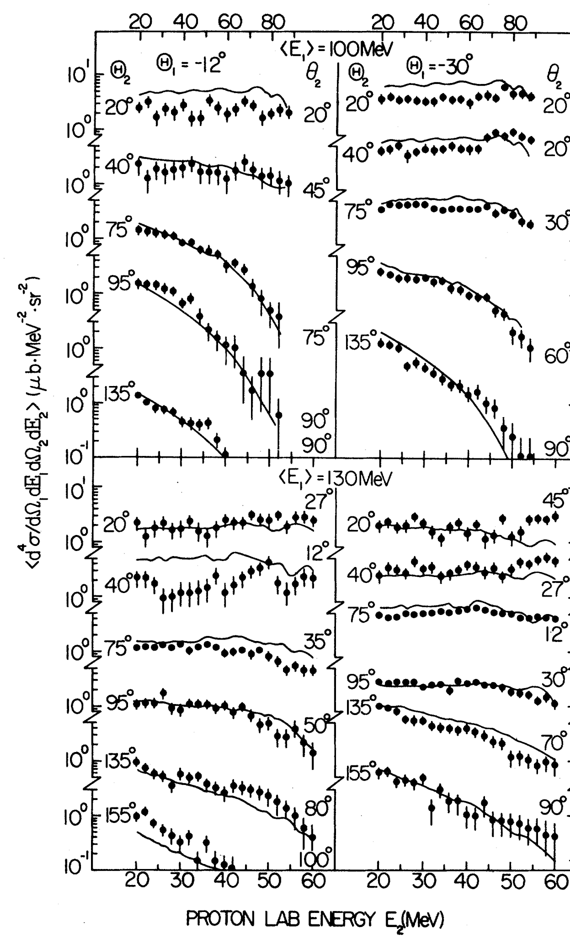

FIG. 3. Comparison between the data (full circles) from the two-dimensional energy spectra corresponding to fixed values for $\langle E_1\rangle$ and Θ_1 and (p,p') spectra (——) at various detection angles θ_2 reported in the literature (Refs. 8 and 9). The incident energy E_2' of the inclusive spectra is related to $\langle E_1\rangle$ by the energy conservation equation. A unique normalization (see text) of the singles to the coincidence data is used for the same $\langle E_1\rangle$ and Θ_1.

(for $\langle E_1 \rangle = 130$ MeV with $\Theta_1 = -12°$ and $-30°$, respectively). To a certain extent these numbers may be fortuitous but they nevertheless seem to reflect the uncertainties of our QF calculation which was not normalized to the data.

In summary, in order to explain the coincidence continuum in the $(p,2p)$ reaction, and in other QF reactions as well, we propose here a method which treats the QF scattering as a doorway stage followed by the inelastic scattering of the two protons on the rest of the nucleus. This method allows us to provide a reasonable explanation for the previously[4] observed proportionality of the continuum with the inelastic scattering spectrum. In another publication[3] we will show that complete calculation of Eq. (3), which implements this idea, provides a very good fit, both in shape and magnitude, with the continuum data.

The authors express their gratitude to Professor N. S. Chant for making available his cluster knockout DWIA code. Fruitful discussions of the above ideas with Professor J. J. Griffin and Professor E. F. Redish are kindly acknowledged. One of us (G.C.) also benefited from a discussion with Dr. J. M. Moss. The calculations were carried out on a grant from the University of Maryland Computer Science Center. This work was supported in part by the National Science Foundation.

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