Comment on "Origin of the forward-backward asymmetry in the decay of the giant resonance structures of ^{24}Mg and ^{40}Ca"

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Recently Zwarts *et al.* presented data on the forward-backward asymmetry in the particle decay of giant resonances which they interpret as being due to interference with direct knockout processes. In discussing the interference problem we show that the presented features of an asymmetry beginning at the effective particle threshold and increasing with excitation energy are not characteristic for this interference but are expected to arise even in the absence of any resonance decay.

[NUCLEAR REACTIONS ^{28}Si$(\alpha, \alpha'\alpha_0)$, $E_\alpha = 155$ MeV; measured α-α_0 angular correlations; deduced giant resonance decay. Interference of sequential decay and knockout processes.]

In a recent Rapid Communication Zwarts *et al.*[1] attempted to explain the well-known forward-backward asymmetry (FBA) of angular correlations of decay products from giant resonances. They presented data obtained in $(\alpha, \alpha' c)$ coincidence experiments at $E_\alpha = 120$ MeV on ^{24}Mg and ^{40}Ca which show an asymmetry starting above the effective particle threshold $S_{\text{eff}}(c) = Q(c) + E_C(c)$ (in the notation of Ref. 1), and increasing smoothly with excitation energy E_x. This trend, which was observed in several charged particle decay channels $c = \alpha$, p, was presented as evidence for interfering quasifree scattering (QFS) processes. Simple considerations in this Comment show that, in general, a different energy dependence of the asymmetries will result from interference with QFS processes. ^{28}Si$(\alpha, \alpha'\alpha_0)$ data obtained[2] at $E_\alpha = 155$ MeV are in line with our considerations. So we are led to propose that the features described by Zwarts *et al.*[1] are probably of a different origin which is neither due to giant resonance decay nor to interference effects.

The interference of direct QFS processes and sequential decay amplitudes leading to identical final states has been recognized[3] and considered as a difficulty in all coincidence work devoted to giant resonance decay for many years.[2,4–10] The property of QFS amplitudes of being large at forward direction of the recoiling system, which roughly corresponds to "quasifree kinematics," and practically zero opposite to it ("anti-quasifree kinematics"[11]), trivially leads to a FBA if, as in Ref. 1, no background is subtracted underneath the resonances. The truly interesting question has been[2,6] the "residual" forward-backward asymmetry which survives the subtraction of a maximum of incoherent background in the coincidence spectra. Coherent interference of sequential with QFS amplitudes and/or overlapping resonances has been proposed[2,6,9,10] as an explanation. Zwarts *et al.*[1] claim to distinguish among these mechanisms. One should realize, however, that they are no real alternatives: QFS amplitudes which are most easily represented in a linear momentum basis may indeed also be expanded in an angular momentum basis.[11,12]

We first consider the interference in the inelastic excitation of a narrow resonance at an energy E_R and a broad resonance with respective parities of $(-1)^L$ and $(-1)^{L'}$, and their subsequent particle decays. The coincidence cross section σ_0 for decay into recoil direction $\theta_c = \theta_R$ is determined by the complex amplitudes $f_L(E)$ (rapidly energy dependent around the resonance energy E_R) and $g_{L'}$ (slowly energy dependent). Following Bohr's theorem[13] the FBA is then given by

$$\sigma_0/\sigma_\pi = |f_L(E) + g_{L'}|^2 / |(-1)^L f_L(E) + (-1)^{L'} g_{L'}|^2 \ . \tag{1}$$

Sufficiently far from E_R this ratio will be unity while strong variations occur in the resonance region. The former situation is expected to arise between isolated resonances, i.e., at low excitation energies.

Considering now the interference of $f_L(E)$ with a slowly energy dependent QFS amplitude $q = \sum_l g_l$ for knockout into recoil direction $\theta_c = \theta_R$, it is a good approximation to assume that $\sum_l (-1)^l g_l = 0$ for knockout with $\theta_c = \theta_R + \pi$. In plane wave impulse approximation this follows from the absence of sufficiently large momenta in the wave function of the struck particle. Hence the FBA is determined by

$$\sigma_0/\sigma_\pi = |f_L(E) + q|^2 / |f_L(E)|^2 \ . \tag{2}$$

In contrast to the situation discussed above, this ratio will be large far from the resonance energy E_R; in the resonance region the FBA will be reduced.

For the case of interest, $f_L(E)$ does not represent a single resonance but a giant resonance with considerable fine structure. Such a fine structure is apparent in our sample case [see Figs. 1(a) and 1(b)]. One consequence of the interference between resonant and background amplitudes are angle dependent shifts of the fine structure peaks whose existence has been shown previously.[9,10,14] Zwarts *et al.*[1] have preferred to average over those fine structures, thus eliminating largely the interference properties. Within our simple picture the FBA resulting from the energy averaged cross sections $\langle\sigma\rangle$ is given by

$$\langle\sigma_0\rangle/\langle\sigma_\pi\rangle = 1 + |q|^2/|f|^2 \quad . \tag{3}$$

It is obvious that this quantity generally will not exhibit the features presented in Ref. 1 as indicative for interference between resonant and QFS amplitudes: The FBA will be strongly correlated with the strength distribution $|f(E)|^2$ in the channel under consideration, being large whenever $|f(E)|^2$ is small and vice versa. These features are manifest in Fig. 1 realizing that the spectrum taken in the antirecoil direction [Fig. 1(b)] represents the resonant strength distribution $|f(E)|^2$ in the channel $c=\alpha_0$. Figure 1(c) also shows that the FBA averaged over the fine structures exceeds unity [see Eq. (2)] while the fluctuating part due to the interference terms in Eq. (1) leads to local minima in σ_0/σ_π below unity, demonstrating unambiguously the coherence of the two amplitudes, and, in consequence,[2,10] the "direct" decay mode of the isoscalar giant quadrupole resonance (GQ_0R) in ^{28}Si. Except for the $^{24}Mg(\alpha,\alpha'\alpha_0)$ reaction, the lack of spectra in Ref. 1 does not allow a test of Eq. (3); for this channel the observed features are consistent with our Eq. (3).

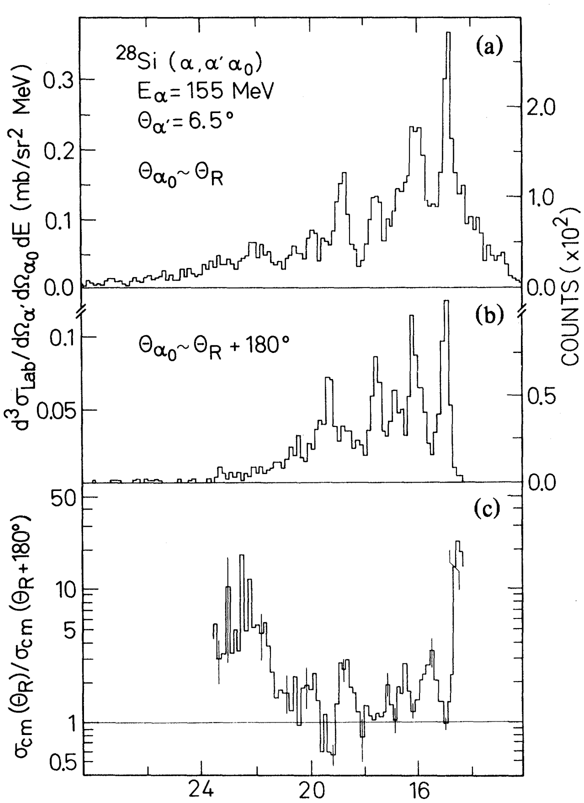

FIG. 1. The $^{28}Si(\alpha,\alpha'\alpha_0)$ spectra measured (Ref. 2) at $\theta_{\alpha'}=6.5°$ in coincidence with α_0 decay particles detected at about (a) the direction θ_R of the recoiling ^{28}Si nucleus, and (b) opposite to it. (c) The forward-backward asymmetry of the α_0 angular correlation. It is the ratio of the above $(\alpha,\alpha'\alpha_0)$ coincidence cross sections transformed into the center-of-mass system of the recoiling ^{28}Si nucleus as a function of excitation energy E_x. Representative statistical errors are indicated.

So far we have disregarded the different energy dependence and the different relative magnitude of the QFS amplitudes q and the resonant amplitudes f in various channels. For example, the ratio of QFS α_0 to α_1 yields[15] are about 5 and 20 in ^{24}Mg and ^{40}Ca, respectively; moreover, the resonant strengths in the p_1 and α_0 decay channels in ^{40}Ca are known[5] to differ by more than a factor of 5. This shows that the importance of a mechanism for a FBA based on interference between q and f will strongly depend on the channel under consideration and the kinematical conditions of the experiment. In fact, the FBA is not a general feature since, in a previous $^{40}Ca(\alpha,\alpha'c)$ coincidence experiment[5] ($E_\alpha=115$ MeV, $\theta_{\alpha'}=20°$), FBA's close to unity have been found in the p_0 and p_1 channels throughout the GQ_0R region. Also, the observation that in $(\alpha,\alpha'c)$ experiments on ^{16}O and ^{28}Si at $E_\alpha=155$ MeV (Refs. 2 and 6) and FBA in the α_1 channel is smaller than in the α_0 channel is in line with these considerations.

Therefore, to explain all of or part of the FBA's shown in Ref. 1 we propose an alternative mechanism which works even in the absence of resonant strength in the respective decay channel c. It is based on the presence (*not interference*) of both QFS processes and statistical decays from background states. The crucial point in the arguments by Zwarts *et al.*[1] is that in each decay channel c the FBA starts just above the effective particle threshold $S_{eff}(c)$ and increases smoothly with excitation energy E_x, since QFS processes "will become important as soon as E_x becomes greater than S_{eff}."[1] While the latter statement is far from being obvious and definitely not evidenced by the quoted $(\alpha,2\alpha)$ work,[15] it is, in fact, just around $S_{eff}(c)$ where the channel c is most strongly populated by evaporation particles. A very abundant source of evaporation products is presented by the large continuous background in the giant resonance region: In inelastic α scattering this background is largely due to multistep processes, hence of complex nature, and thus decays to a large extent statistically.[16] Therefore it is just around $E_x = S_{\text{eff}}(c)$ where channel c will be populated by an intense component of decay particles which have symmetric angular correlations with respect to 90°. In consequence, it is around this excitation energy where the FBA in channel c will exhibit a local minimum, the value of which might be well close to unity, since the QFS cross section generally is still small there and no interference will take place with statistical decays due to phase averaging. With increasing excitation energy the major flux of the evaporation products will gradually move to other decay channels so that the fast, coherent, and forward-backward asymmetric QFS processes gain in relative importance due to their much less pronounced E_x dependence. Since the discussed mechanism will take place in any decay channel, we have arrived at a simple yet consistent description of the features presented in the work of Zwarts *et al.*[1] without evoking any interference between QFS and giant resonance decay. [Of course, this does not exclude the occasional occurrence of interference phenomena as, e.g., the 17.5-MeV minimum in the $^{24}\text{Mg}(\alpha, \alpha'\alpha_0)$ channel in Ref. 1].

In conclusion, we have seen that a forward-backward asymmetry increasing with excitation energy is not typical for the *interference* of giant resonance decay with quasifree scattering processes. We have presented a discussion of the interference problem that leads to a qualitative understanding of our data which were obtained at an incident energy of 155 MeV where the giant resonance excitation is stronger than at 120 MeV. Our discussion predicts different energy dependences of the forward-backward asymmetry in different decay channels, a feature which is not substantiated by the 120-MeV data of Zwarts *et al.*[1] Thus we proposed an additional source for FBA's which is totally independent of giant resonance decays or interference phenomena. This shows that the conclusions of Ref. 1 are not justified but that several processes might be relevant for understanding the various experimental results. An improved understanding is expected to come only from a detailed analysis of angular correlation functions.

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