Brief Reports

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Direct contributions to the decay of isoscalar giant resonances in ^{58}Ni

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Proton and α-particle emission from giant resonances in ^{58}Ni excited by inelastic α scattering at 129 MeV into 0° has been investigated. By this choice of kinematic conditions quasifree contributions to the coincidence cross sections were eliminated. The sequential decay processes show a population of low-lying states which exceed Hauser-Feshbach predictions substantially, indicating $>40\%$ direct contributions to the charged particle decay of the isoscalar giant resonances near $E_x=17$ MeV.

The damping of giant resonances (GR's) may proceed by direct particle emission or by coupling to complicated states and subsequent statistical decay. The former, if observed, provides insight into the microscopic structure of giant resonances. Coincidence studies of charged particle decay of the isoscalar giant quadrupole resonance (GQ_0R) so far have indicated a dominance of direct decay for light nuclei, and of statistical decay for medium-heavy nuclei ($A>40$).[1-3] More recently, studies of neutron decay in heavy nuclei[4,5] showed a 20% direct decay probability of the GQ_0R for ^{118}Sn (Ref. 4), $\approx 0\%$ and 15%, respectively, for the GQ_0R and the isoscalar giant monopole resonance (GM_0R) in ^{208}Pb (Ref. 5).

This prompted us to reinvestigate with improved techniques the giant resonance decay in ^{58}Ni, where previous experiments had reported results compatible with dominant statistical decay.[3,6] Progress was achieved by exciting the giant resonances by inelastic α scattering at 0°. This firstly reduces quasifree scattering (QFS) contributions to the coincidence cross section by minimizing the momentum transfer, and secondly yields, due to axial symmetry, in a model independent way 4π integrated cross sections from measurements in one plane only. Therefore we can rely on the integrated coincidence cross sections for the analysis of the decay modes without use of the singles spectrum, which is notorious for its background problems. In this paper we present evidence for a substantial direct decay probability of the isoscalar giant resonances near $E_x=17$ MeV in ^{58}Ni.

A 129 MeV α-particle beam from the Texas A&M cyclotron was focused on a ^{58}Ni target of ≈ 1 mg/cm^2 thickness. The α particles scattered into $0°\pm 2°$ were detected in the focal plane of the Enge-split-pole spectrograph by a resistive wire proportional counter backed by a plastic scintillator.[7]

An active slit system was used to reduce slit scattering from the solid angle defining collimators. An overall resolution of 300 keV was achieved. Eight threefold surface barrier detector telescopes[8]—four being placed in the forward hemisphere ($\theta=33°$, 48°, 63°, and 78°) and four in the backward hemisphere ($\theta=102°$, 117°, 132°, and 147°)—allowed for unambiguous particle identification of the charged decay products due to their specific energy loss and time-of-flight.

By measurement of the energies of the scattered α particles and the emitted charged particles the cross sections for the population of bound final states were determined in a kinematically complete way. Figure 1 shows

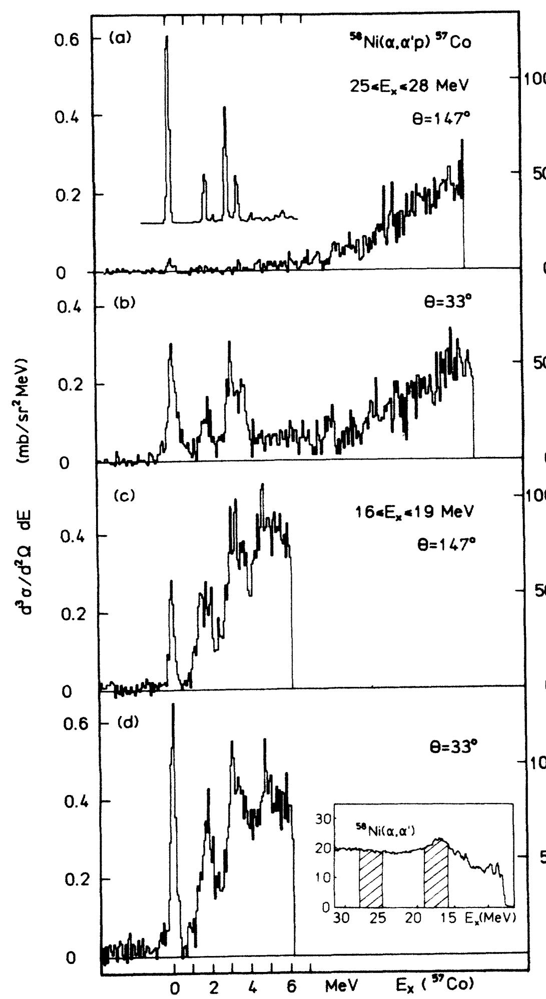

FIG. 1. The population of final states in ^{57}Co is shown for proton decay following excitation of ^{58}Ni to 25–28 MeV [(a) and (b)] and 16–19 MeV [(c)) and (d)], respectively, by inelastic scattering of 129 MeV α particles into 0°. The proton decay angles are 33° [(b) and (d)] and 147° [(a) and (c)], respectively. For comparison the inset in (a) shows (to scale) a ^{3}He spectrum of the ^{58}Ni(d,^{3}He)^{57}Co reaction of Ref. 13. The inset in (d) shows a single spectrum (cross section in mb/sr MeV) with regions of integration denoted by hatched areas.

^{58}Ni(α,α'p)^{57}Co coincidence cross sections (without any background subtraction) summed over 3 MeV of excitation in ^{58}Ni and projected onto excitation energies in ^{57}Co. Figures 1(a) and (b) contain spectra for an (apparent) excitation energy E_x(^{58}Ni) above the giant resonance region for the most forward and backward detector positions, respectively, located symmetrically about 90°; Figs. 1(c) and (d) contain the corresponding spectra with E_x(^{58}Ni) in the known GR region. In passing we note that our singles ^{58}Ni(α,α') spectrum [inset in Fig. 1(d)], which was taken simultaneously with the coincidence data, agrees with the findings of Ref. 9 in showing no evidence for compact isoscalar monopole strength. As no background was subtracted in our coincidence cross sections we cannot exclude possible monopole contributions. Unfortunately, the α_0 decay branch (feeding the ground state of ^{54}Fe) is too weak to allow a meaningful $E0/E2$ decomposition from the angular correlations as was possible for lighter nuclei.[10,11]

Figures 1(a) and (b) show on the right-hand side a yield from evaporation processes which exhibit the characteristic forward-backward symmetry. In contrast, fast protons feeding low-lying states in ^{57}Co appear in the forward direction only [Fig. 1(b)]. This striking asymmetry is interpreted as a signature of QFS processes.[12] Such processes as well as pickup reactions are known to feed one-nucleon hole states preferentially. In fact, a ^{58}Ni(d,^{3}He)^{57}Co spectrum[13] taken at $\theta=11°$ with 52 MeV deuterons shown to scale as an inset in Fig. 1(a) exhibits an amazing similarity with Fig. 1(b). To appreciate the selectivity of these reactions it is interesting to note the level density $\rho=30$ MeV^{-1} near 3.5 MeV. The vanishing coincidence cross section in Fig. 1(a) shows the negligible role of sequential processes for the population of low-lying states at high E_x(^{58}Ni).

In the decay from the giant resonance region [Figs. 1(c) and (d)] the same low-lying final states are populated both at forward and backward angles. The cut at E_x(^{57}Co)=6 MeV was chosen such that the corresponding proton energies even for E_x(^{58}Ni)=16 MeV exceeded the detection threshold of 1.0 MeV. The nonvanishing cross section at backward angles shows the presence of sequential processes be they of statistical or direct nature.

In order to disentangle these two mechanisms we compare the cross sections with Hauser-Feshbach (HF) predictions. To exclude QFS contributions the comparison (see Fig. 2) is made only for the backward hemisphere where

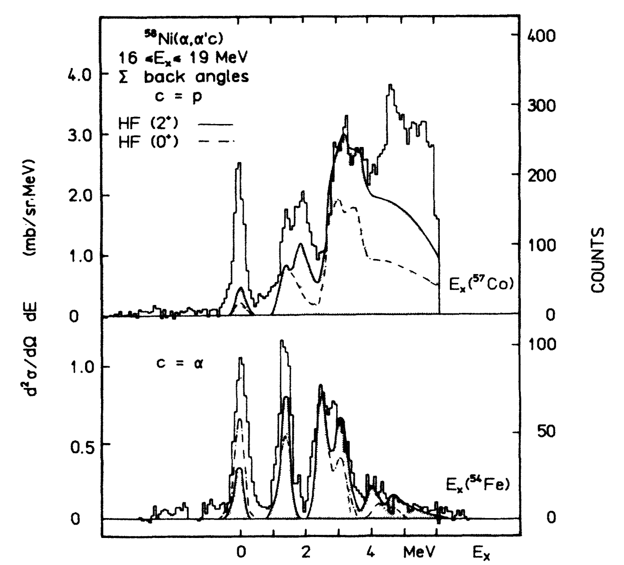

FIG. 2. Sum of experimental cross sections (with a $\sin\theta$ weighing) for the population of final states in ^{57}Co and ^{54}Fe, respectively, by proton (top) and α-particle (bottom) emission into the backward hemisphere from ^{58}Ni states with $16 \le E_x \le 19$ MeV (histogram). The solid (dash-dotted) curve represents upper bounds for contributions from statistical decay assuming a pure $E2$ ($E0$) excitation in ^{58}Ni.

the angular correlations are nearly isotropic in all decay channels. Incidentally, the results of the integration over the forward hemisphere were very similar showing the relative unimportance of quasifree processes for the 4π integrated cross section due to the $\sin\theta$ weighing. The smooth curves in Fig. 2 give results from statistical model calculations performed with the code STAPRE (Ref. 14) with parameters carefully adjusted by a fit to a large body of data. Up to 50 known levels[16] were used for $E_x(^{57}\mathrm{Co}) < 4$ MeV, $E_x(^{57}\mathrm{Ni}) < 6$ MeV, and $E_x(^{54}\mathrm{Fe}) < 5$ MeV, respectively. At higher energies, level densities were calculated in the framework of the backshifted Fermigas model[15] with parameters reproducing the number of known levels.[16] Evaporation spectra were calculated with 50 keV resolution for seven equidistant excitation energies in ^{58}Ni between 16 and 19 MeV assuming a resonance with $J^\pi = 2^+$ (full line) and 0^+ (dash-dotted line), respectively. They were summed with equal weight and folded with the experimental resolution. The assumption of constant strength is justified by the large widths of the GQ_0R and of the noncompact GM_0R. In fact, a quadrupole strength distribution of Gaussian shape with $E_x = 16.4 \pm 0.3$ MeV and $\Gamma = 4.9 \pm 0.2$ MeV (Ref. 17) leads to evaporation spectra differing at most by 5%.

Usually HF calculations are normalized to the singles spectra after background subtraction. In order to avoid such background problems the HF cross sections in Fig. 2 were normalized such as not to overshoot the coincidence cross sections anywhere in either the proton or α-decay channel. This way we obtained an upper limit to the fraction of the singles cross section undergoing statistical decay. Assuming a pure GM_0R this fraction is 60% lower than for a pure GQ_0R. As may be seen from Fig. 2 this results from the strong population of the 0^+ state at 2.5 MeV in ^{54}Fe by evaporation of α particles from a GM_0R. Random phase approximation (RPA) calculations[18] predict additional $E4$ strength and $E6$ strength in this region exhausting 20% and 5% of the energy-weighted sum rules, respectively. Calculated spectra including this strength distribution differ at most by 10% in the population of individual final states from those for a pure $E2$ spectrum.

We base the following estimates on a pure GQ_0R (shaded area) which results in a maximum statistical decay fraction. Yet Fig. 2 shows an excess of the experimental cross sections of up to a factor 4 over the calculations notably for low-lying states both for proton and α decay. This is interpreted as direct contribution to the decay of the GR's. The smooth behavior of the cross section for proton decay to $E_x(^{57}\mathrm{Co}) > 4$ MeV is due to the use of level density formulas: again the experimental excess cross section is interpreted to be the result of direct decay which is likely to feed $1d_{3/2}$ hole states known[13] to be located near $E_x(^{57}\mathrm{Co}) \sim 4.5$ MeV. The integrated cross sections for charged particle decay are comprised in Table I. From the difference of the HF calculation and the experimental data an overall (last line of Table I) direct contribution to the giant resonance decay is deduced which exceeds 40%. We would like to emphasize that these numbers represent lower limits as (i) the evaporation part was maximized by construction of the normalization and by choice of the multipolarity, and (ii) more complicated background states excited, e.g., by multistep processes, are more likely to decay statistically than giant resonances. We mention in passing that for $14 < E_x(^{58}\mathrm{Ni}) < 16$ MeV a very similar percentage for direct coincidence cross sections was obtained; however, experimental and theoretical uncertainties are increased due to the proximity of particle thresholds.

Finally, it is interesting to estimate the various contributions to the inclusive (α,α') cross section of 58 mb/sr for $16 \le E_x(^{58}\mathrm{Ni}) \le 19$ MeV at $\theta = 0°$. From the observed forward-backward asymmetry of the proton decay and assuming an equal contribution from the unobserved neutrons we obtain 2–4 mb/sr for quasifree scattering. The HF calculations described above yield 21 mb/sr for the fraction of (α,α') cross section leading to p, n, or α evaporation. The observed coincidence cross section for direct, α-particle and proton decay contribute ~ 10 mb/sr. Losses due to experimental thresholds are estimated to < 3 mb/sr. Hence about two-thirds of the singles cross section can be accounted for. The missing third may be due to direct neutron decay and/or physical background in the singles spectrum, mainly resulting from slit scattering.

If we neglect a possible experimental background we obtain lower limits for the global branching ratios of $\Gamma_p/\Gamma > 41\%$ and $\Gamma\alpha/\Gamma > 7\%$ which are consistent with the corresponding quantities for GQ_0R decay from Refs. 3 and 6. There, a compatibility of the *global* branching

TABLE I. Integrated cross sections for excitation of ^{58}Ni with $16 \le E_x(^{58}\mathrm{Ni}) \le 19$ MeV and subsequent p and α decay into various energy bins of the final nuclei ^{57}Co and ^{54}Fe. As experimental values we give twice the result of the integration over the backward hemisphere. The Hauser-Feshbach calculations assume decay from $J^\pi = 2^+$ resonances.

Channel Final nucleus	E_x (MeV)	Integrated cross section (mb/sr) Expt.	HF[a]	Excess[b]	Excess percentage[b]
α	0–4	3.5	2.1	1.4	40
	4–6	0.4	0.4	0	0
p	0–4	12.7	8.2	4.5	35
	4–6	11.0	6.0	5.0	45
$\sum \alpha,p$	0–6	26.6	16.7	10.9	41

[a]Upper limit.
[b]Lower limit.

ratios with statistical decay had been concluded. It is due to the analysis of final state spectra that we were able to recognize the $>40\%$ direct decay contribution to the GR decay. Also in the present 0° experiment the monopole contributions to the GR will be enhanced relative to the previous ones. Results of a ^{54}Fe(α,γ) study[19] have revealed direct contributions consistent with the factor of 3 enhancement in the population of the ^{54}Fe ground state over HF predictions visible in Fig. 2.

For the first time it was possible to suppress QFS contributions considerably and perform an integration of the coincidence data over 4π in a model independent way due to axial symmetry. This allowed us to unravel the decay modes of giant resonances in ^{58}Ni independent of the singles data with their notorious background problems. The $>40\%$ probability for direct decay shows that the escape and spreading widths of the giant resonances studied are about equal in this medium weight nucleus. Thus the escape widths are large enough to make detailed studies of giant resonances decay as a test of microscopic models for medium-heavy nuclei as well as light nuclei.

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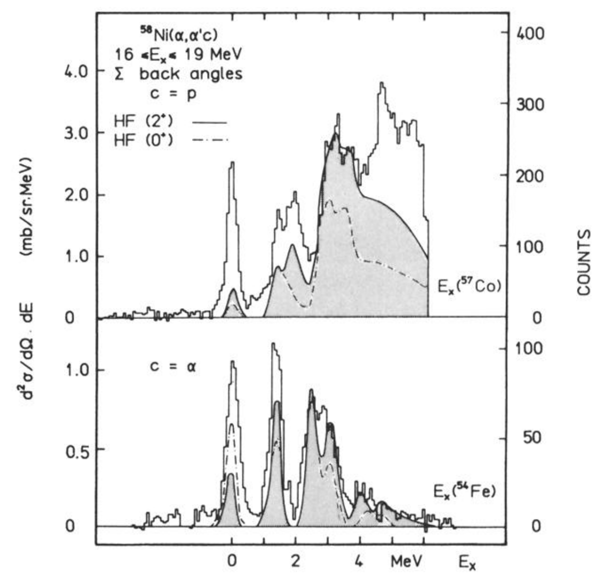

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