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Resonant Octupole Strength at 13 MeV in ^{58}Ni and ^{60}Ni and the Character of the $53A^{-1/3}$ State in Heavy Nuclei*

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ABSTRACT

Inelastic electron scattering reveals a concentration of resonant E3 strength at (13.3 ± 0.2) MeV in ^{58}Ni and (12.8 ± 0.2) MeV in ^{60}Ni. The energy agrees closely with the 52 $A^{-1/3}$ MeV predicted by Hamamoto for the isovector ($1\hbar w$) E3 mode on the basis of the Bohr-Mottelson self-consistent shell model, but the strength, (13 ± 1)% and (8 ± 2)% of the energy weighted sum rule, respectively, is a factor of 5 too large. This result weakens recent arguments in favor of a monopole assignment for the 53 $A^{-1/3}$ MeV resonance found by (e,e') in heavy nuclei.

A distinct resonant excitation at 13 MeV in ^{58}Ni, ^{60}Ni and ^{64}Ni has first been reported by Gulkarov et al.[1], who searched for the surface quadrupole oscillations coupled to the volume dipole oscillations, predicted by the collective dynamic model.[2] The structure found was explained in the framework of this model. After the discovery that a giant quadrupole resonance existed as a genuine property of the nuclear continuum, a re-evaluation of the data in Born Approximation identified the 13 MeV resonance in all three isotopes as E2.[3] Later experiments which find structure at this energy [~(50-53) $A^{-1/3}$ MeV] in nuclei with $56 \le A \le 60$ are contradictory to this result and contradictory to each other.

Torizuka, et al.[4] finds two E2 (or E0) states with a rather small width (<0.6 MeV) at 13.2 MeV and 14.0 MeV in ^{58}Ni, which exhaust 7.4 ± 0.7 and 4.8 ± 0.7% of the isoscalar energy weighted quadrupole sum rule [(E2, $\Delta T = 0$) EWSR]. Similarly, polarized proton measurements favor E2 (or E0), while ruling out E3.[5] Inelastic ^{3}He scattering on ^{48}Ti, ^{56}Fe, ^{59}Co and ^{60}Ni by Arvieux, et al.[6] finds consistently a peak with width $\Gamma \approx 1.2$ MeV at 51 $A^{-1/3}$ MeV (13 MeV in ^{60}Ni) for which an E2 assignment was the most probable, but an E4 could not be ruled out. However, in 155 MeV proton scattering[7] and 250 MeV electron scattering[8] on ^{56}Fe a peak around 13.5 MeV has (tentatively) been assigned E3. The report on inelastic scattering of deuterons[9] finally, while not giving an assignment, shows that the angular behavior of the cross section of a state at 13 MeV is different from the E2 ($\Delta T = 0$) giant resonance at 16 MeV.

While the existence of a resonance 13 MeV up in the continuum with a width of only (1-2) MeV is exciting enough, even more importance comes to this state at 51 $A^{-1/3}$ from the observation in (e,e') of a state at the same energy (in $A^{-1/3}$) in many nuclei between $139 < A < 208$[10-15] which, consistent in all experiments, has been assigned to be either E2 or E0. (See, e.g., Ref. 16 for the difficulties in discriminating E2 and E0 in (e,e').)

Since the existence of a second giant quadrupole resonance in the continuum below the 63 $A^{-1/3}$MeV mode seems unlikely[15] (but not impossible), the 53 $A^{-1/3}$ MeV state <u>is</u> a serious candidate for the giant monopole (breathing mode) resonance. On the other hand, 52 $A^{-1/3}$ MeV is the energy predicted by Hamamoto[17] for the isovector E3 (1 $\hbar\omega_0$) state, based on the Bohr-Mottelson self-consistent shell model.

In general, the various continuum modes discovered since 1971 have exhibited a very smooth dependence on nuclear mass A, and resonances at the same energy (again in $A^{-1/3}$ MeV) in different nuclei have been found to be of the same multipolarity. We thought it therefore of the utmost importance to investigate the 53 $A^{-1/3}$ MeV mode in nuclei with $A < 139$. However, a first experiment on ^{89}Y surprisingly did not show any resonant cross section around 53 $A^{-1/3}$ MeV which would be compatible to the strength found in heavy nuclei.[18]

The measurements reported here were undertaken with 102 MeV electrons from the 120 MeV Electron Linear Accelerator of the Naval Postgraduate School. Experimental set-up and evaluation procedures have been described recently.[18] Since the state in question is a weak resonance close to the GDR and GQR ($\Delta T = 0$), great care was taken to select the correct line shape and its momentum transfer dependence.[19]

Self-supporting targets of ^{58}Ni and ^{60}Ni, with mass densities between 45 and 135 mg/cm^2, isotopically enriched to 99% of the respective isotope were used at scattering angles of 45°, 60°, 75°, 90° and 105°. A typical spectrum is shown in Figure 1. While at low ($q \lesssim 0.6$ fm^{-1}) momentum transfer the radiation tail is the dominant part of the cross section, contributing 90% or more to it, this is no longer the case at higher momentum transfer. The structure of the spectra itself turned out to be more complex than those for any previous (e,e') experiment in heavier nuclei. Numerous resonances of E1, M1, E2, E3 and E4 character were found between 6 and 45 MeV which will be reported elsewhere in a comprehensive article. Here, due to its special importance for the monopole question, and with that the problem of nuclear compressibility, we will concentrate on the (51-53) $A^{-1/3}$ MeV resonance. Figure 1 thus shows only the disentangling into the resonant cross sections for the resonances found at 13.3 and 16.3 MeV in ^{58}Ni. The momentum transfer dependence for resonances at this energy in both isotopes is shown in Figure 2, which compares the experimental values to DWBA calculations on the basis of the Goldhaber-Teller model. These calculations have been discussed in more detail in Ref. 18 which also contains the definitions of the sum rules and single particle units used. Figure 2 shows that E3 is the preferred assignment for the 13 MeV resonances in both nuclei, while the 16 MeV states follow an E2 momentum transfer dependence. The quantitative details like excitation energy, width and strength, are accummulated in Table 1.

We are reasonably sure of the assignment. Electro-excitation of giant resonant states has given very reliable results since the initial discovery of modes other than the dipole state. Table 1 shows that the E3 states do not only exhaust a sizeable fraction of the sum rule, they are also quite strong in single particle units. Generally, one has found that collective transitions are described very well with the Goldhaber-Teller or Tassie model, where the transition charge density is simply the derivative of the ground state charge density. For an E2 state the rms radius for the excited state would have to be approximately 30% smaller than that of the ground state in order to mimic the momentum transfer behavior of an E3.

There are several problems to solve. First, one has to explain the different assignment for this resonance in medium-heavy contrasted to heavy nuclei. Secondly, the different assignments for the Nickel region (E0, E2, E3 and E4) discussed earlier have to be explained. Concerning the

latter, one makes the astonishing discovery that none of the references quoted in the beginning makes a definite statement, nearly all assignments are called tentative. Critical analysis of the data also shows that the statistical uncertainties are quite large[6,7], that the assignment rests mainly on two low points in the spectrum at the highest momentum transfer[4], or that other problems have been encountered (see, e.g., remark in Ref. 4 of Ref. 9). Although the excitation energy agrees closely with the $52\ A^{-1/3}$ MeV predicted by Hamamoto,[17] this state cannot be isovector due to its appearance in (d,d') spectra,[9] and its strength is a factor of 5 too large. We conclude that in medium-heavy nuclei the E3 strength is even more fragmented than anticipated.

This leaves us with the first problem, to decide whether the $53\ A^{-1/3}$ MeV state is E0 or E2. Analysis of the published data[10-15,18] shows that the strength is approximately proportional to the ground state isospin, i.e., the neutron excess. This property is difficult to explain if one does not want to assume the resonance to be an isovector E2 oscillation of the excess neutrons.[20] This assumption would explain why hadron scattering does not show this resonance, because isovector excitations are suppressed by a factor of ten compared to isoscalar ones.[15] Both macroscopic and microscopic calculations have predicted isovector E2 strength at the excitation energy of the isoscalar resonance.[21] If this state is the monopole (breathing mode) state, no immediate reason is obvious why it should be proportional to the neutron excess.

In summary, electro-excitation of the giant resonance region in ^{58}Ni and ^{60}Ni shows a relatively strong part of the E3 strength at 13 MeV. The results make a decision between E0 and E2 for a resonance at 53 $A^{-1/3}$ MeV in heavy nuclei even more difficult, since it weakens our recent argument in favor of a monopole assignment.[15]

Table 1. Results for the Giant Quadrupole and Octupole Resonances at 16 and 13 MeV, respectively, in ^{58}Ni and ^{60}Ni.

Nucleus	Eλ	E_x (MeV)	$E_x (A^{-1/3}$MeV)	Γ (MeV)	B(Eλ) ($fm^{2\lambda}$)	$R^{a)}$	$SPU^{b)}$
^{58}Ni	E3	13.3 ± 0.2	51.5	1.5 ± 0.2	$9.5 \cdot 10^3$	0.13 ± 0.02	7
	E2	16.3 ± 0.2	63.1	4.5 ± 0.4	$4.8 \cdot 10^2$	0.48 ± 0.06	7
^{60}Ni	E3	12.8 ± 0.2	50.1	1.5 ± 0.2	$5.9 \cdot 10^3$	0.08 ± 0.02	4
	E2	16.2 ± 0.2	63.4	4.7 ± 0.3	$4.1 \cdot 10^2$	0.42 ± 0.05	6

[a] $R = E_x \cdot B(E\lambda)/EWSR\ (E\lambda,\ \Delta T = 0)$.

[b] The single particle units used are those of S.J. Skorka et al., Nucl. Data A2, 347 (1966).

Figure 1.

Spectrum of 120 MeV electrons scattered inelastically from ^{58}Ni at 105°. The spectrum shows very pronounced the transition from the sharp bound states to the broad continuum states. Note that the zero is not suppressed; the giant resonance cross section is a sizeable fraction of the total cross section, i.e., with inclusion of the radiative and experimental background. The cross section has not been corrected for the constant magnetic dispersion of the spectrometer. For graphical purposes, the number of points shown (measured were 10/MeV) has been reduced by a factor of 2 below 10 MeV, and by a factor of 4 above. The decomposition of the spectrum into the resonant cross sections for the E3 state at 13.3 and the E2 state at 16.2 MeV are shown, a giant E3 state in the bound state region at 7 MeV, the M1 giant states at 10 MeV and the isovector E3 and E2 resonances at 27 and 32 MeV, respectively, are also apparent. The statistical error is of the size of the circles representing the data.

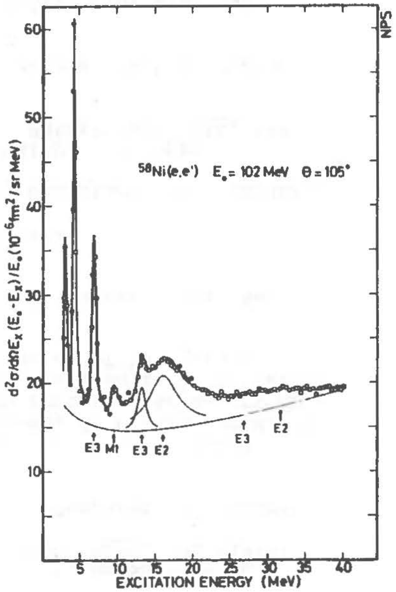
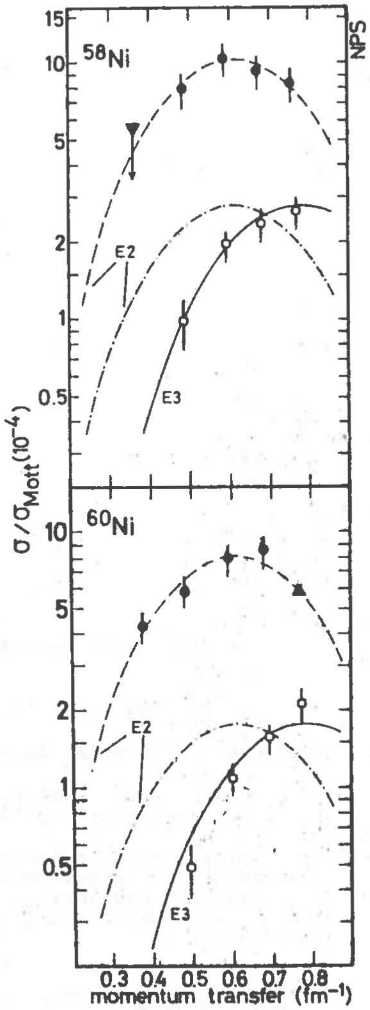


Figure 2.

Comparison of the experimental resonant cross section at 13 and 16 MeV in ^{58}Ni and ^{60}Ni with DWBA calculations for E2 and E3 transitions using the hydrodynamical model. The open circles (O) represent the experimental results for the resonances around 13 MeV, the closed circles (●) for the 16 MeV resonance. It is evident that the former are better described by an E3 assignment, while the latter follow the E2 DWBA curve. The closed triangle (▼) with arrow indicates an upper limit for the 16.3 MeV resonance in ^{58}Ni, while the closed triangle (▲) indicates that the cross section for the 16.2 MeV resonance in ^{60}Ni was held constant to the value extrapolated from lower momentum transfer.



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