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Coupled-channels calculation for scattering and capture of alpha particles near the giant quadrupole resonance

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Coupled-channels calculations were performed for ^{54}Fe(α,α_0)^{54}Fe and ^{54}Fe(α,α_1)^{54}Fe* in the region of the giant quadrupole resonance. Reasonable agreement with the data was obtained. The wave functions were then employed to calculate the α capture cross section. This calculation suggests that the capture cross section is nonresonant. The implications for decay modes of the giant quadrupole resonance are discussed.

[NUCLEAR REACTIONS Coupled-channels calculation; alpha scattering on ^{54}Fe; alpha capture to ^{58}Ni; giant quadrupole resonance.]

I. INTRODUCTION

Since the prediction of a giant isoscalar quadrupole resonance (GQR) by Bohr and Mottelson,[1] several experiments have been performed in the ~58 $A^{-1/3}$ MeV excitation energy range in search of evidence for this phenomenon.[2-8] With a variety of projectiles on a variety of targets, broad peaks have been observed just below the giant dipole resonance. These peaks appear to have $J^\pi = 2^+$.

A systematic study of 27 nuclei from $A = 14$ to 208 has been performed with the (α, α') reaction at $E_\alpha = 96$ and 115 MeV.[9] The α particle is an appropriate probe of the GQR since it is $T = 0$, $J = 0$. This experiment located a distinct broak peak at ~63 $A^{-1/3}$ MeV for all targets with $A \geq 36$. This peak was assigned $J^\pi = 2^+$ on the basis of distorted wave calculations. The peak exhausted ~30–50% of the energy-weighted sum rule (EWSR) for the medium-light to medium mass nuclei. In particular, the peak exhausted 55 ± 15% of the EWSR in ^{58}Ni.

The observation of the GQR in the (α, α') experiment strongly warrants additional investigation of the 63 $A^{-1/3}$ energy region to determine the decay modes of the GQR. One such investigation[10] has been the reaction ^{54}Fe$(\alpha, \gamma)^{58}$Ni where a broad capture peak was observed at $E_\alpha = 10$ MeV. Two of the conclusions of this experiment were that (1) there are large nonstatistical components to the GQR and (2) the reaction ^{58}Ni$(\gamma, \alpha)^{54}$Fe exhausts only 4% of the EWSR. A recent ^{58}Ni$(e, e'x)$ experiment[11] has indicated that 56% of the EWSR is exhausted by α emission. This means that ~50% would be inelastic α emission. Because the decay-particle spectrum peaks at 8 MeV, the decay is expected to be primarily α_1. This is in disagreement with the ^{58}Ni$(\alpha, \alpha' x)$ results,[12] where protons are the primary decay mode of the GQR and α decay exhausts only 6% of the EWSR.

If the GQR does decay primarily by α_1 emission, then it must have a large inelastic α width, and the GQR could be observable in an (α, α_1) resonance reaction as the incident energy is varied between 8 and 18 MeV. The results of this experiment are now available.[13] However, the nature of the observed "peak" in the inelastic cross section and the resulting implications for the structure and decay mode of the GQR are not clear.

The purpose of this paper is to describe the predictions of a coupled-channels calculation for scattering and capture of alpha particles incident on ^{54}Fe, and then to discuss the resulting interpretation of the low energy inelastic α data of Ref. 13 and its relation to the GQR. The procedure for the coupled-channels calculation and comparison with experimental scattering data are presented in Sec. II. The capture calculation and results are presented in Sec. III. Section IV contains an analysis of both calculations which concludes that the GQR cannot be represented by an alpha cluster excitation.

II. COUPLED-CHANNELS CALCULATION

The present calculation employs the R-matrix technique of Lane and Robson[14] and Philpott.[15] This technique allows the most effecient solution of a coupled-channels potential model.[16] The solution can be expressed in terms of normal R-matrix parameters. This allows discussion of any resonant type behavior in terms of levels of the system. It is assumed that the system can be expressed in terms of an α particle and ^{54}Fe in its ground state or the 2^+ excited state.

The potentials used were Woods-Saxon potentials which reproduce double-folded potentials[17-19] in the region from a few fermis inside the Coulomb barrier out and also bind the $\alpha + {}^{54}$Fe system with the desired number of nodes[20] in the radial wave

TABLE I. Potential parameters.

V (MeV)	c_0 (fm)	a_0 (fm)	c_1 (fm)	a_1 (fm)	β
107.51	5.3295	0.5967	6.4180	0.2923	0.152

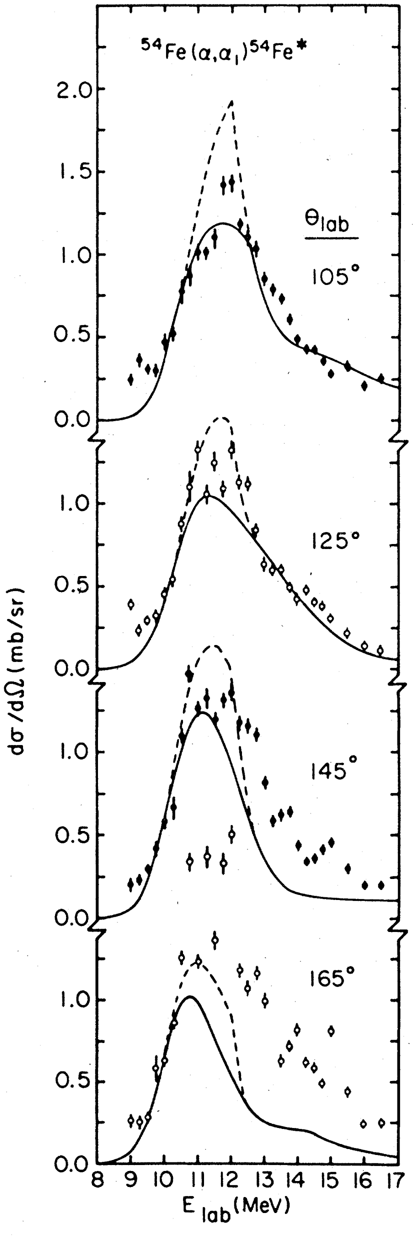

FIG. 1. Inelastic excitation functions for the reaction ^{54}Fe(α,α_1)^{54}Fe* (2^+; 1.408 MeV) from 8 to 17 MeV. The data are from Ref. 13. The two calculations given by the solid and dotted lines are discussed in the text.

function at the correct energy to approximate the ground state of ^{58}Ni. The double-folded potentials used were generated from elastic[21] and inelastic[22] electron scattering densities and a g-matrix interaction[23] corrected to approximately account for single-nucleon knockout exchange.[24] The potentials were evaluated using a momentum-space expansion.[18,25] This choice was made to give a realistic Coulomb barrier which is important for investigations of threshold phenomena and to ensure a reasonable strength of the potentials at short distances. The potentials used are given in Table I.

The 165° inelastic excitation function can be reasonably fitted with a constant absorption of depth $W=2$ MeV. However, at 105° and 125° the excitation function does not fall off at higher energies with this choice. Thus, a linearly increasing absorption was added starting at $E_{\rm lab}=12$ MeV with slope 1.5 MeV/MeV ($E_{\rm lab}$). This improved the agreement at the forward angles. To smooth the transition from constant absorption to increasing absorption, which accounts for the opening of

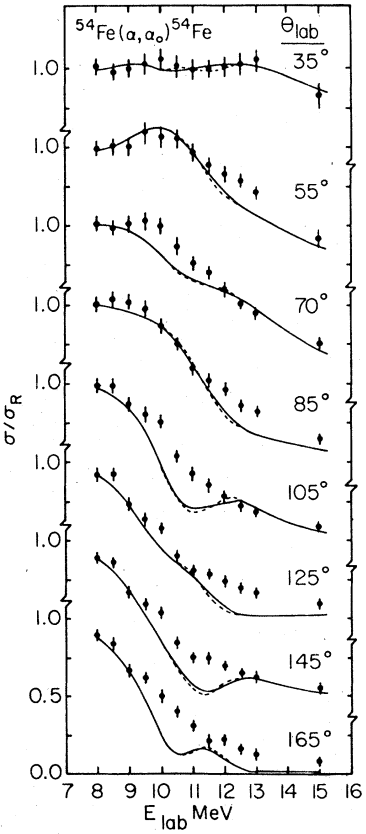

FIG. 2. Elastic excitation functions for the reaction ^{54}Fe(α,α_0)^{54}Fe (0^+; g.s.). The data are from Ref. 26.

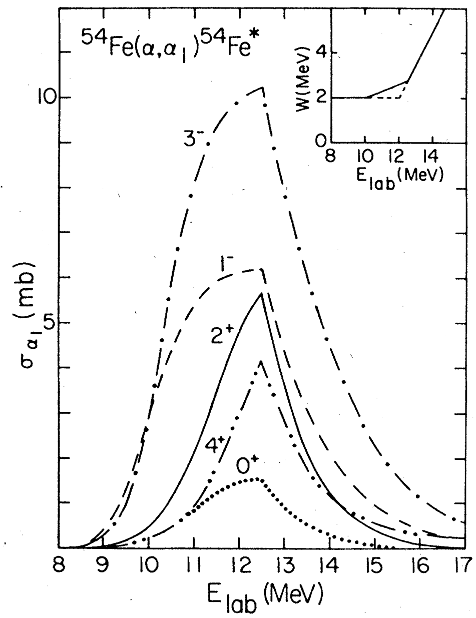

FIG. 3. Contributions to the total cross section from $J^\pi = 0^+, 1^-, 2^+, 3^-$, and 4^+ for the reaction ^{54}Fe(α,α_1) ^{54}Fe* (2^+, 1.408 MeV). The insert is the strength of the imaginary potentials used in the coupled-channels calculations as a function of energy.

channels not in the model, the region between $E_{\text{lab}} = 10$ MeV and 12.5 MeV was calculated with a linearly increasing absorption of slope 0.3 MeV/MeV (E_{lab}). The inelastic excitation functions[13] are shown in Fig. 1, the elastic excitation functions[26] are shown in Fig. 2, and W as a function of energy is shown in the insert of Fig. 3. In all three cases the dotted line is the result without the 0.3 MeV/MeV (E_{1ab}) term from 10–12.5 MeV. From Figs. 1 and 2 it can be seen that the inelastic result is very sensitive to W while the elastic is not so sensitive. Although the introduction of increasing W has caused the agreement between the calculations and data to deteriorate somewhat at the most backward angles, the trend of the results is in agreement. Introduction of J dependence[27] into the imaginary terms as employed in calculations of energy-dependent heavy-ion phenomena[28] would be expected to improve the agreement at far back angles.

III. CAPTURE

The coupled-channels calculation has treated the α particle–^{54}Fe system as two clusters. This model is also employed in the capture calculation. Therefore, the ground state of ^{58}Ni is represented as an α particle coupled to the 0^+ and 2^+ states of ^{54}Fe. The bound α particle wave function is obtained by solving the Hamiltonian with no imaginary potential. This produces a ^{58}Ni ground state with 57% $l=0$ and 43% $l=2$.

In the cluster model the $E1$ and $E2$ operators become[20]

$$Q_{1M} = (A_c Z_\alpha - Z_c A_\alpha)/(A_c + A_\alpha) e r (4\pi/3)^{1/2} Y_{1M} \quad (1)$$

and

$$Q_{2M} = (A_c^2 Z_\alpha + Z_c A_\alpha^2)/(A_c + A_\alpha)^2 e r^2 (4\pi/5)^{1/2} Y_{2M}. \quad (2)$$

The alpha particle is then treated as a single particle with these effective operators and the capture calculation can be performed by standard techniques.[29] If only $E1$ and $E2$ contributions are allowed then the angular distribution for capture can be written as

$$d\sigma/d\Omega = (1/4\pi)[A_1^2 + A_2^2 - (A_1^2 - (\tfrac{5}{7})A_2^2)P_2 - (\tfrac{12}{7})A_2^2 P_4 + (6/\sqrt{5})A_1 A_2 \cos(\phi_1 - \phi_2)(P_1 - P_3)], \quad (3)$$

where the $E1$ and $E2$ capture amplitudes are $A_1 e^{i\phi_1}$ and $A_2 e^{i\phi_2}$, respectively. This expression provides a means for extracting the $E1$ and $E2$ cross sections and relative phase from experiment. This extraction was performed from the α-capture data in Ref. 10, and the resulting $E2$ cross section is plotted in Fig. 4. Also in Fig. 4 are the results of the present capture calculations.

There are two striking features of the calcula-

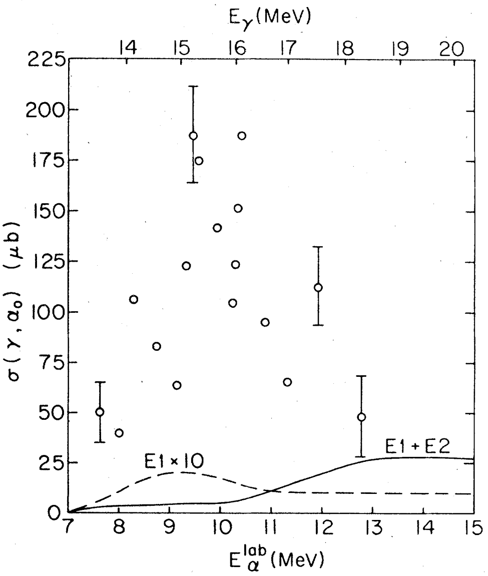

FIG. 4. Cross section for α_0 emission. Open circles are $E2$ cross section extracted from the α capture from experiment. Solid curve is calculated $E1 + E2$ cross section. Dashed curve is ten times the calculated $E1$ cross section.

tion. First, the $E1$ cross section is two orders in magnitude smaller than experiment. The small cross section is due to the small $E1$ effective charge,

$$e(A_c Z_\alpha - Z_c A_\alpha)/(A_c + A_\alpha) = 0.07e\,.$$

Second, the $E2$ cross section is clearly nonresonant. Therefore, the α cluster capture process contributes only to the background for the GQR and $T_<$ GDR as would a direct capture process.

IV. ANALYSIS

The 8–15 MeV energy region contains several R-matrix levels. Therefore, the apparent resonance shape of the inelastic cross section is somewhat misleading since there are many levels of many spins contributing. The peak cannot be associated with just one level which would then have been called a resonance. The resonance-shaped envelope is a result of the α_1 channel opening, letting the cross section rise, and then other channels opening, taking flux away and dropping the cross section at higher energies. If the R-matrix levels are to be associated with any structure in the experimental cross section, it would only be with the oscillations with widths ~1–2 MeV. The use of an appropriate J-dependent absorption might make some of this structure visible.

Figure 3 shows a breakdown of the total inelastic cross section into contributions from individual spins and parities. The 2^+ peak is only 17% of the total cross section peak. Due to parameter sensitivity, this value could vary plus or minus several percent, but the value demonstrates that there is no selective excitation of 2^+ strength in the low energy (α, α_1) resonance reaction as would be expected if the GQR had a large inelastic α width. Also, the capture calculation demonstrates that the 2^+ component of the nuclear wave function provides no resonant $E2$ strength.

The conclusion must be that the GQR is outside the model space and that it does not overlap with an α cluster excitation. The GQR must correspond to another mode of excitation which does not look like $|{}^{54}\mathrm{Fe}(2^+) \otimes \alpha(l)\rangle$. This model is therefore not consistent with the GQR having as large an α_1 width as that extracted from the $(e, e'x)$ experiment.

V. CONCLUSION

This paper has presented the prediction of a coupled-channels calculation for α scattering and capture in the region of the GQR. The calculation indicates that there is no selective excitation of 2^+ strength and that there are large contributions to the inelastic cross section from other spins and parities. The 2^+ component in the GQR region does not carry appreciable $E2$ strength in the α cluster excitation model. These calculations are consistent with a small α width for the GQR in agreement with the $(\alpha, \alpha' x)$ experiment.

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