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ISOSPIN EFFECTS IN THE GIANT DIPOLE RESONANCE OF ^{42}Ca*

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The Giant Dipole Resonance (GDR) of ^{42}Ca was investigated through the $^{41}K(p,\gamma_o)^{42}Ca$ reaction. The gross structure indicates two peaks at 17.4±0.1 MeV (Γ = 3.3±0.5 MeV) and 20.4±0.1 MeV (Γ = 4.4±0.1 MeV) which contain 13% and 87% respectively, of the E1 strength in the (γ,P_o) channel. From a comparison of structure and excitation energies of the GDR in ^{40}Ca and ^{42}Ca, the two peaks can be identified with the T = 1 (at 17.4 MeV) and the T = 2 (at 20.4 MeV) isospin components of the GDR. This energy separation gives an effective symmetry potential of V = 63 MeV in agreement with the general predictions and observation in other nuclei. However, identification of the peaks with the K = 0 and K = 1 dipole oscillations in the deformed ^{42}Ca ground state is not ruled out. A shell model calculation of the dipole states in ^{42}Ca with good isospin was done by diagonalizing large matrices and using the Kuo-Brown G-matrix elements. This gives a concentration of T = 1 strength at 17.1 MeV and T = 2 strength at 19.6 MeV, in good agreement with the experimental results, and supports the isospin identification of the two components.

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I. Introduction

It has been demonstrated in several nuclei that the Giant Electric Dipole Resonances (GDR) built on ground states of nuclei with $T = T_z \neq 0$ is separated into two isospin components having $T_> = T + 1$, and $T_< = T$, respectively. This phenomenon, a consequence of isospin conservation and the isovector character of the electric dipole excitation, has been treated in a phenomenological description by Fallieros and Goulard.[1] Based on the general dependence of the GDR on A and T the prediction for the strength distribution is approximately given by

$$(1) \qquad |C_>|^2 = \frac{1}{T+1}\left(1 - \frac{3T}{2A^{2/3}}\right); \quad |C_<|^2 = \frac{T}{T+1}\left(1 + \frac{3T}{2A^{2/3}}\right)$$

and for the displacement energy between the two components[2]

$$(2) \qquad \Delta E = E_> - E_< = (\tilde{V}/A)(T+1) \text{ MeV}.$$

The validity of this relation and the value of $\tilde{V}$ = 60 MeV has recently been demonstrated in a series of nuclei throughout the periodic table.[3] We discuss here the isospin splitting of the GDR in ^{42}Ca based on data obtained in the $^{41}K(p,\gamma_0)^{42}Ca$ reaction. An isospin identification can be inferred from a comparison between the GDR of ^{40}Ca and ^{42}Ca, the first having been recently investigated in detail.

Experimentally ^{42}Ca is a favorable case because its ground state has T = 1 which, from eq. (1), leads to nearly equal dipole strength in each component. From the standpoint of theory, it is of interest since it has sufficiently simple structure so that shell model calculations for the collective states, using wave functions of good isospin, can be made directly. The results of such a calculation, which uses the same formalism and parameters which recently gave good agreement for the GDR in ^{40}Ca, are presented in the second part of the paper.

II. Experiment and Results

The $^{41}K(p,\gamma_o)^{42}Ca$ reaction was studied over an excitation energy region from 14 to 23 MeV. This covers the region where the GDR is observed[5] in ^{40}Ca. The proton beam was accelerated in the Stony Brook Tandem Accelerator to bombarding energies from 4 to 13 MeV. Isotopic ^{41}K targets were prepared by evaporation of 99% enriched KI, in situ, onto 50 μgr/cm^2 carbon foils for a target thickness of 50 keV to 10 MeV protons. Capture γ rays were detected in a large NaI detector system which has been described elsewhere.[5] A typical spectrum is given in the insert of Fig. 1. The γ_o transition originating from the $^{41}K(p,\gamma_o)^{42}Ca$ reaction (Q = 10.276 MeV) is the highest peak in the spectrum, and its strength was evaluated from a lineshape fitting procedure. No transitions to excited states in ^{42}Ca were analyzed because of the close spacing of final states and contaminating peaks from the $^{127}I(p,\gamma)^{128}Xe$ reaction (Q = 9.15 MeV). The cross section calibration scale was established both absolutely and relative to the $^{12}C(p,\gamma_o)^{13}N$ reaction as previously described.[6]

The excitation function for the γ_o transition from E_p = 4.0 to 12.7 MeV bombarding energy is given in Fig. 1. The step size is 100 keV except for the segment from 9.4 to 10.6 MeV where it is 50 keV. The general features of the curve are quite similar to those observed[4] in the GDR of ^{40}Ca, i.e. a giant resonance gross structure with superimposed intermediate and fine structure. At E_p = 11.0 MeV, or 21.11 MeV excitation, the curve reaches the maximum cross section of 5.7 μb/sr±40%. This amounts to only one half of the maximum cross section observed in ^{40}Ca.

Sample angular distributions were taken at the bombarding energies indicated in Fig. 1. Fits with a sum of Legendre Polynomials $W(\theta) = 1 + A_1P_1(\cos\theta) + A_2P_2(\cos\theta)$ gave the values for A_1 and A_2 plotted in Fig. 2. A_2 is universally negative and consistent with an average value $A_2 = -0.15$ which, again, is only half the value observed[4] in ^{40}Ca. Using the average angular distribution the integrated cross section for the ^{42}Ca(γ,p_o)^{41}K reaction between 14.2 and 22.7 MeV comes to 52 MeV·mb, or 8.4% of the classical electric dipole sum rule. This is 65% of the value obtained in the ^{40}Ca(γ,p_o)^{39}K reaction.

This paper is concerned with the gross structure of the GDR and in Fig. 3 the excitation function has been averaged over 1.5 MeV to take out intermediate-width fluctuations. This procedure has been explored in more detail in ^{40}Ca and justification in terms of a statistical analysis has been given there.[4] The gross structure of ^{42}Ca exhibits two broad peaks at 17.4 and 20.4 MeV, and an analysis with two Lorentzian curves gives the characteristics of these peaks listed in Table I. A comparison with the positions and strength distributions of the gross structure in ^{40}Ca included in Table I indicates that the major difference between the two nuclei is the observation of a sizeable amount of strength in ^{42}Ca shifted down with respect to the excitation energy of the main peak in ^{40}Ca. There are also two peaks present in ^{40}Ca, but the small upper component is predicted by almost all calculations[7] to contain most of the "spin-flip" contribution of the GDR. This peak should also be present in ^{42}Ca, but could not be verified because of the limitation of bombarding energy.

III. Comparison of the GDR of ^{40}Ca and ^{42}Ca

In a simple weak-coupling model the GDR of ^{42}Ca is build up from 1 particle-1 hole ($J = 1^-$, $T = 1$) excitations of the ^{40}Ca core, and two spectator neutrons coupled to $J^{\pi} = 0^{+}$, T = 1. The integrated dipole excitation strength observed in ^{42}Ca should then be about equal to that of ^{40}Ca. This requirement also follows from a collective picture since the mass difference between the two nuclei can be almost neglected. In fact, the experimentally obtained integrated (γ,p_o) cross section in ^{42}Ca is only ~65% of that observed in ^{40}Ca. However, this difference is largely accounted for by the different proton binding energies, i.e., 8.33 MeV in ^{40}Ca and 10.28 MeV in ^{42}Ca. The (square well) penetrabilities of f-wave protons emitted in the (γ,p_o) reaction at $E_\gamma \sim 19$ MeV are 0.26 and 0.42 in ^{42}Ca and ^{40}Ca, respectively, and are in the same ratio as the integrated (γ,p_o) cross sections. Similarly, the neutron binding energy is less in ^{42}Ca which results in a smaller portion of the dipole strength appearing in the proton channel than is the case in ^{40}Ca. Thus, qualitatively, the data bear out the assumption that the total dipole absorption strength is about equal in ^{42}Ca and ^{40}Ca. The difference in the observed A_2 coefficients of the angular distributions is very likely due to the different amounts of p and f wave proton arising from the change in Q values between the two nuclei.

The simple description of Akyüz and Fallieros[2] can now be used to obtain the effect of the two neutrons on the excitation energy of the collective dipole state. In ^{40}Ca the excitation energy is given by

$$E_o^{40} = \varepsilon + g^\circ S^\circ = 19.3 \text{ MeV}$$

where ε is the average particle-hole energy; the second term described the effect of the collectivity which is taken as proportional to the dipole strength S°. In ^{42}Ca the energy contains additional terms, i.e., for the T = 2 component it is

$$E_{>}^{42} = \varepsilon + V/A + g'S' \ (1 - 3/2 \ A^{-2/3})$$

where V/A is the symmetry energy for the single-particle single-hole states (V = 100 MeV) and the dipole strength is now modified in accordance with eq. (1). Thus the displacement energy is given by:

$$E_{>}^{42} - E_{0}^{40} = V/A + (g'S' - g°S°) - g'S' \ 3/2 \ A^{-2/3}$$

The first and third term can be lumped together[2] to produce $\tilde{V}/A = 1.43$ MeV ($\tilde{V} = 60$ MeV) and the second term amounts to -200 keV. This leads to $E_{>}^{42} = 19.3 + 1.23 = 20.5$ MeV, and the energy splitting between the T = 2 and T = 1 components is $E_{>}^{42} - E_{<}^{42} = 2 \cdot \tilde{V}/A = 2.86$ MeV.

On the basis of this model, a comparison of the gross structure of ^{40}Ca and ^{42}Ca in Table I suggests that the peaks at 20.4 MeV and 17.4 MeV in ^{42}Ca be identified with the $T_{>}$ and $T_{<}$ GD components, respectively. The observed centroid energy shift relative to ^{40}Ca is 400 keV rather than the 200 keV given by the simple estimate above, which means that the additional neutrons are coupled to the p-h excitations through more than just the symmetry potential. The energy separation of the two peaks implies, by use of eq. 2, $\tilde{V} = 3.0A/2$ MeV = 63 MeV, in very good agreement with the value deduced from the splitting of the GDR in other nuclei[3,6].

In the following discussion the data are examined for consistency with additional consequences following from the above T assignments to the two components at 17.4 and 20.4 MeV. In order to establish which decay channels are allowed for the two resonances, Q values and quantum numbers for pertinent decay modes are given in Fig. 4. The important fact to note with regard to states of good isospin is that both the $T_{>}$ and $T_{<}$ GD states (if properly identified) can decay by neutron emission to isospin-allowed final states in ^{41}Ca. In addition, from its structure and the angular momentum involved, the lowest T = 3/2 state in $^{41}Ca(J^{\pi} = 3/2^{-})$ is a favored final state for neutron decay from the GDR since it is the analog state of the ^{41}K ground state, whereas the ground state ($J^{\pi} = 7/2^{-}$) of ^{41}Ca is unfavorable. Thus the lowest final T = 1/2 states in ^{41}Ca which are available for neutron decay from the $T_<$ GDR are at least 2.5 MeV above the ground state and the effective energy available for neutron decay from the $T_>$ component is $\sim$2.3 MeV, quite comparable to the $\sim$3.4 MeV available for a decay from the $T_<$ GDR. On this basis the comparable total widths of the two resonances in ^{42}Ca are not in contradiction with their identification as two isospin components.

The simple model used above for the GDR predicts, from eq. 1, that the dipole strength be shared among the two components according to $|b_{T+1}|^2 : |b_T|^2 = 0.78$. The experiment indicates a distribution of the integrated (γ,p_0) strength in the ratio of $\sigma_>\Gamma_> : \sigma_<\Gamma_< = 6.6$. Penetration factors can account for only a factor of 3 (assuming f-wave capture). This is quite similar to the case of ^{26}Mg where the positions of the T = 1 and T = 2 GDR are correctly obtained[8] but the $T_>$ dipole strength exceeds prediction by a factor 2. The discrepancy might be removed by taking into account isospin mixing between the two components. In ^{40}Ca a mixing of 20% in amplitudes has been observed[9] in the GDR.

The identification proposed above is, of course, not the only possible one. It is well known that a dipole excitation based on a deformed ground state results in a splitting of the GDR into two components, e.g. the K = 0 and K = 1 component based on an ellipsoidal deformation. The energies of the dipole vibrations along the two half axis a and b can be calculated from the simple formula[10]

$$E_b/E_a = 0.911(a/b) + 0.089$$

The predictions for this effect can be checked in both ^{26}Mg and ^{42}Ca since the ground state deformations of both nuclei can be inferred from recently reported values for the static quadrupole moments of the lowest 2^+ states (assuming a rotational relationship between the 0^+ and 2^+ states). For ^{26}Mg the reported quadrupole moment[11] of $Q_2 = -0.14\pm0.05$ leads to $a/b = 1.39$ (using $r_o = 1.25$ f) and $E_b/E_a = 1.35$. Placing at 17.8 MeV puts E_b at 24.1 MeV, too high for the observed second peak[8] at 22 MeV. For ^{42}Ca, a preliminary value[12] is $Q_2 = 18.9\pm8.1$ eb, or $a/b = 1.19$. Assuming E_a at 17.4 MeV, this places E_b at 20.7 MeV, in agreement with the present data. This model distributes the dipole strength about 2:1 in favor of the upper peak and thus would remove the discrepancy discussed above.

However, even though the deformation effect cannot be rules out on the basis of systematics between ^{26}Mg and ^{42}Ca because of the large errors on Q_2, several contrary arguments come to mind. First, the same model does not work at all in ^{24}Mg which has a large deformation, and only one isospin component.[8] Second, the validity of the hydrodynamic model for these light nuclei is very questionable, since it is known[13] that the total dipole strength observed up to 30 MeV represents only between 60% and 80% of the classical sum rule.

There remains, of course, the well-known coupling of the GDR to low-lying dynamic quadrupole deformations.[14] ^{42}Ca has a low lying mode available not existent in ^{40}Ca, i.e., the recoupling of the two excess neutrons to 2^+ which requires only 1.5 MeV. For observations in other nuclei it is felt that this coupling is responsible for the intermediate structure observed in the GDR, but not the gross-structure splitting.

IV. Shell Model Calculation for ^{42}Ca

To investigate the role of isospin in the GDR further the 1^- states of ^{42}Ca are calculated in this section using a basis of good isospin, and the γ_o and γ_1 dipole spectra are obtained. The calculation is an appropriate extension of the particle-hole calculation done previously[7] for ^{40}Ca using the same model space potential parameters and single-particle energies.

In the simplest picture the dipole states in ^{42}Ca can be obtained by coupling the low-lying states of $^{42}Ca(J_f)$ with the dipole states of $^{40}Ca(D_i)$. The resulting states $J_i = J_f \otimes D_i$ are not, of course, eigenstates of the total Hamiltonian, if the coupling between them cannot be neglected. (If this is so the above basis only provides a procedure for truncation of the real basis). In this scheme the GDR in ^{42}Ca is obtained by choosing J_f to be the ground state of ^{42}Ca and D_i to be the GDR of ^{40}Ca. The dipole states obtained in this way will be called "normal dipole states." If J_f is any other but the ground state they will be called "excited dipole states."

The above simple model predicts $BE1(J_i \to J_f) = BE;(D_i \to |0\rangle)$ and $E(J_i) - E(J_f) = E(D_i)$, i.e., it relates very simply the dipole strength of ^{40}Ca and ^{42}Ca. Of course, some differences are expected, because the states J_i are not characterized by unique isospin, while the states D_i have isospin T = 1. However, as described in the previous section the fragmentation of the total strength among the different isospins as well as the isospin splitting can easily be understood using a simple Lane potential and the isospin Clebsch-Gordan coefficients. Any further differences between the dipole spectra of ^{40}Ca and ^{42}Ca imply a mixing of the above states.

If such a mixing is important the above basis becomes more tedious to handle than a straightforward shell model calculation. It might be argued that such a basis is meaningful even if the coupling is not weak, because it can provide a physical understanding, which might be lost in the complexity of the shell model eigenstates. This is the reason why this basis is very useful in heavy nuclei. It is not as useful in light nuclei for two reasons. First, because a shell model calculation involving as many j-j configurations as the ones involved in the weak coupling basis is possible; second, because the Pauli principle, which is ignored in this simple approach, is important and must be taken into account. The weak coupling basis can be antisymmetrized in a tedious but straightforward fashion. However, if Pauli principle corrections are large, antisymmetrization changes completely the nature of the wave function and the simple physical picture is lost.

In the present calculation both the initial and final states involved in the dipole γ-emission have been obtained by diagonalizing large shell model matrices. The model space included the $0d^{-1}_{5/2}$, $1s^{-1}_{1/2}$, $0d^{-1}_{3/2}$, $0f_{7/2}$, $1p_{3/2}$, $0f_{5/2}$, $1p_{1/2}$ and $0g_{9/2}$ orbitals with unperturbed energies -13.56, -9.66, -7.26, 0., 2.10, 6.00, 4.10 and 4.98 MeV, respectively, for both protons and neutrons. The unperturbed energies were taken to be identical to the neutron[7] single particle energies used for ^{40}Ca. The final states were restricted to be 2-particle and 3-particle-1 hole components (3p-1h). In the case of the 3p-1h states the $0g_{9/2}$ orbit was omitted. The antisymmetry of the wavefunctions was guaranteed by applying the standard coefficient of fractional parentage (c.f.p) techniques[15] for mixed configurations. In the case of the T = 1 states one further approximation was necessary to keep the dimensions manageable. States of the form

$$|(j_1 j_2)J_{12}T_{12};(j_3 j_4^{-1})J_{34}T_{34};JT\rangle;\ j_3 \neq j_2 \text{ and } j_3 \neq j_1$$

with $T_{12} = 0$ or $T_{34} = 0$ were neglected. These states are not expected to contribute to the dipole γ-emission. The states with $T_{12} = 0$ will not contribute because the final nucleus is characterized by T = 1. The $T_{34} = 0$ components do not contribute because the isoscalar component of the dipole operator which is proportional to 1/2 (N-Z) is small (effective charges $e_p = -\frac{N}{A}e$ and $e_n = \frac{Z}{A}e$ have been used.) For transitions other than to the ground state the $T_{34} = 0$ states might contribute to the dipole matrix element through exchange terms, but their contribution is expected to be small, since only terms with $j_1 \neq j_2$ will contribute. With the above approximations the resulting 1^- matrices for T = 2 and T = 1 have dimensions of 182 and 216, respectively.

The Hamiltonian matrices were constructed using the bare Kuo-Brown[7,16] G-matrix elements. The isospin-mixing Coulomb interaction was completely neglected. The standard Racah and c.f.p algebra was applied in the calculation of the Hamiltonian as well as the dipole reduced matrix elements. The isospin formalism is relatively simple here because ^{40}Ca is a self-conjugate nucleus. The radial integrals were evaluated assuming harmonic oscillator wave functions with $\hbar\omega = 7$ MeV. The results are summarized in Tables II and III. In Fig. 5 the dipole γ_o transitions with widths $\Gamma_\gamma \geq .2$ keV are represented by vertical bars. States that are separated by less than 150 keV have been lumped together. Both isospin components are fragmented into a number of peaks. In the case of $T = T_< = 1$ most of the dipole strength is concentrated around 17 MeV with smaller peaks at 20 and 23 MeV. Appreciable dipole strength is found at 5.24 MeV resulting from state which is almost pure $f_{7/2}\, g_{9/2}$. This state is not shown in Fig. 5 since its width is small due to its small excitation energy.

The $T = T_> = 2$ dipole strength is shared by the two states at 19.33 (width $\Gamma_\gamma = 3.24$ keV) and 19.88 MeV ($\Gamma_\gamma = 2.48$ keV). Appreciable strength is found around 25 MeV.

Since both the $T_>$ and $T_<$ strength is somewhat fragmented it is necessary to compute average quantities and investigate their trends. One such quantity is the "effective" symmetry energy which characterizes the splitting of the G.D.R. in its isospin components. If we define

$$\overline{E} = \sum_i \Gamma_i E_i / \sum_i \Gamma_i$$

we get $\overline{E}_> = 21.23$ MeV and $E_< = 18.70$ MeV. In the above summation we restricted ourselves only to states with $\Gamma_i \geqslant .3$ keV. Using formula (2) we get $\tilde{V} = 53.1$ MeV which is in very good agreement both with the present experimental results and the predictions of the Akyüz and Fallieros[2] model. Similar values of $\tilde{V}$ have also been obtained by detailed calculations in Sr region.[17]

The present calculation predicts for the total $T_>$ dipole strength to the ground state $BE1(T_> \rightarrow T_f) = 2.18 e^2 fm^2$, and for the $T_<$ strength $BE1(T_< \rightarrow T_f) = 2.75 e^2 fm^2$. Thus the ratio is $BE1(T_> \rightarrow T_f):BE1(T_< \rightarrow T_f) = .793$. Since $T = 1$ this is equal to the ratio of the "reduced dipole strengths" $|b_{T+1}|^2 : |b_T|^2$ of Ref. 1 and the corresponding phenomenological estimate from eq. 1 gives $|b_{T+1}|^2 : |b_T|^2 = .78$ in good agreement with our detailed calculation.

An energy weighted[18] sum rule, including Majorana exchange forces, is given as follows:

$$\sum_i (E_i - E_f)\ BE1(i \rightarrow f) = \frac{(\hbar ce)^2}{2mc^2}\ \frac{9}{4\Pi}\ \frac{NZ}{A}\ (1+.8\chi)$$

where χ is the ratio of the Majorana force to the direct force. (The index i runs over states of all states that can couple with the state f). In the present case taking f to be the ground state and assuming $\chi \simeq .5$ we get

$$\sum_i (E_i - E_f)\ BE1(i \rightarrow f) \simeq 218\ \text{MeV}\ \text{-}e^2\text{fm}^2.$$

Our calculation predicts a summed oscillator strength of 260 MeV-e^2fm^2 (128.7 MeV-e^2fm^2 comes from states with $T = T_>$, and 130.8 MeV-e^2fm^2 from states with $T = T_<$). Hence our calculation exceeds the sum rule even if exchange forces are included.

An expansion of the strong dipole states obtained in the present calculation in terms of the normal and excited dipole states mentioned earlier in which D_i is the GDR in ^{40}Ca is not very meaningful, because Pauli principle corrections are important, e. g., one gets the following overlaps:

$$<(f^3_{7/2})J_i=7/2,T_i=3/2;d^{-1}_{3/2};T=1|(f^2_{7/2})J_1=0,T_1=1;[f_{7/2}d^{-1}_{5/2}]J_2=1,T_2=1>= \frac{1}{2\sqrt{3}}$$

$$<(f^3_{7/2})J_i=7/2,T_i=3/2;d^{-1}_{5/2};T=2|(f^2_{7/2})J_1=0,T_1=1;(f_{7/2}d^{-1}_{5/2})J_2=1,T_2=1>= \frac{1}{2};$$

where the ket is not antisymmetrized. Hence Pauli principle corrections are important, since the ground state of ^{42}Ca contains the $(f^2_{7/2})$ configuration with amplitude .9543 while the amplitude of $[f_{7/2}d^{-1}_{5/2}]J=1\ T=1$ in the GDR of ^{40}Ca is -.7078. Furthermore the dipole strength is fragmented among many shell model states. This explains why the overlaps of the proper eigenstates with the "normal" giant dipole state listed in Tables II and III are rather small. No attempt has been made to compute the overlaps with the antisymmetrized normal dipole state.

Dipole transitions from 1^- states to the first excited 2^+ state (γ_1)

have also been calculated although the corresponding transition has not been studied experimentally. The strong γ_1 transitions are plotted in Fig. 6 and listed in Tables IV and V. Both the T> and T< strengths are fragmented into a number of peaks. The strongest T< state is found at 21 MeV, with width 1.04 keV although most of the dipole strength is found around 19 MeV. The strongest T> state is at 21.92 MeV with width 3.7 keV. A number of strong peaks are predicted at 20.31, 21.05 and 22.72 MeV with widths 1.49, 2.13 and 1.03 keV. As in the γ_0 case we obtain $\bar{E}_> = 22.28$ MeV $\bar{E}_< = 19.87$ MeV. This yields $\tilde{V} = 50.6$, somewhat less than the corresponding value for the γ_0 case, but still in good agreement with the simple model of Ref. 2. The energy shift of the γ_1 average peak relative to the corresponding γ_0 peaks is 1.17 MeV and 1.05 MeV for the $T_<$ and $T_>$ states respectively. If there was no coupling between the normal and excited dipole states one would expect a shift of 1.55 MeV which corresponds to the calculated excitation energy of the first excited 2^+ state. It seems that the weak coupling scheme works well for the $T=T_>=2$ states, but not so well for the $T=T_<=1$ states. Unfortunately no experimental information is available regarding the γ_1 dipole spectrum.

The present calculation automatically takes into account the Pauli Principle and effects like the mixing between the normal and excited dipole states (dipole-quadrupole coupling), if present. The existence of the latter effects, in addition to the energy shifts mentioned above, can be demonstrated by finding states which have both γ_0 and γ_1 widths. In Table VI we show states which leave either $\Gamma_{\gamma_0} \geq .4$ keV and $\Gamma_{\gamma_1} \geq .1$ keV or $\Gamma_{\gamma_0} \geq .1$ keV and $\Gamma_{\gamma_1} \geq .4$ keV. From this table it is clear that the quadrupole-dipole coupling is small. But one cannot be certain of this until the effects of deformation are included into the calculation, which is a difficult problem. Such effects could alter the results if the 0^+ and 2^+ states are not equally deformed.[19] So from the theoretical point of view the effects of deformation on the dipole states should be investigated. It is also clearly important, albeit difficult, to study the γ_1 excitation function.

V. Summary

Both a general model as well as the microscopic description of the GDR in ^{42}Ca yields a splitting of the collective state into T = 1 and T = 2 components. The ^{41}K(p,γ_o)^{42}Ca yield function up to an excitation energy of ~22 MeV has been obtained and indicates two main peaks at 17.4 and 20.4 MeV. The energies of these peaks agree quantitatively with the predictions of the isospin model. Qualitatively, the distribution of dipole strength among both components appears to favor the upper peak in contradiction to the predictions. However, since the symmetry energy is not strong enough in ^{42}Ca to separate the peaks beyond their widths, isospin mixing could be important. This not only changes the dipole strength ratio but also the proton widths of both states and thus may have a strong effect on $\sigma(p,\gamma_o)$.

The above interpretation brings ^{42}Ca in line with many other reported cases of isospin-splitting of collective dipole states[3,6,8], and, in turn, the systematics support the individual case. However, both in ^{26}Mg and ^{42}Ca the observed GDR gross structure can also (qualtitatively) be explained by considering a deformed ground state. Both effects may coexist, and probably do in heavy nuclei. The example of ^{24}Mg bears evidence against a simple hydrodynamical description of the coupling between deformation and dipole excitation in this region of nuclear masses.

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TABLE CAPTIONS

Table I: Comparison of the GDR gross structure observed in ^{40}Ca[a] and ^{42}Ca in radiative proton capture.

Table II: Calculated dipole γ_o transitions in ^{42}Ca (1^-,T=2 → 0^+, T=1) only transitions with $\Gamma_\gamma \geq .1$ keV are listed. The overlaps listed are the overlaps of the eigenstates with the "normal" giant dipole state (see text).

Table III: Calculated dipole γ_o transitions in ^{42}Ca (1^-, T=1 → 0^+, T=1). The notation is the same as in Table II.

Table IV: Calculated γ_1 dipole transitions in ^{42}Ca (1^-, T=2 → 2^+, T=1). The overlaps listed are the overlaps of the eigenstates with the "excited" giant dipole state.

Table V: Calculated γ_1 dipole transitions in ^{42}Ca (1^- T=1 → 2^+, T=1). The notation is the same as in Table IV.

Table VI: States which have either $\Gamma_{\gamma_o} \geq .4$ keV and $\Gamma_{\gamma_1} \geq .1$ keV or vice versa.

Table I

Comparison of the GDR gross structure observed in ^{40}Ca[a)] and ^{42}Ca in radiative proton capture

E_x(MeV)	$\sigma_o(\gamma,p_o)$ (mb/sr)	% of (γ,p_o) Strength	Γ(MeV)	
17.4±0.1	0.13±0.1	13±2	3.3±0.5	^{42}Ca
20.4±0.1	0.64±0.1	87±4	4.4±0.1	
19.3±0.1	1.95±0.1	84±13	3.1±0.2	^{40}Ca
22.0±0.5	0.35±0.25	16±12	3.2±0.5	

[a]From Ref. 4.

Table II

Calculated dipole γ_0 transitions in ^{42}Ca (1^-, T=2 → 0^+, T=1) only transitions with $\Gamma_\gamma \geq .1$ keV are listed. The overlaps listed are the overlaps of the eigenstate with the "normal" giant dipole state (see text).

State	Ex (MeV)	BE1 (e^2fm^2)	Γ_γ keV	Overlap
6	13.93	0.04558	129	-0.06614
11	15.03	0.04142	147	0.03648
13	15.72	0.04581	186	-0.06551
15	16.06	0.05241	227	0.02272
20	17.04	0.04454	231	0.03916
21	17.41	0.04497	249	-0.07359
22	17.42	0.03106	172	0.04964
23	17.68	0.02091	121	-0.05224
29	18.44	0.07178	471	-0.10023
30	18.48	0.08851	585	0.12516
31	18.61	0.01831	124	0.04173
33	18.93	0.10664	758	0.03876
37	19.33	0.42882	3244	0.23330
41	19.88	0.30188	2483	-0.20304
43	20.05	0.10700	903	-0.09736
44	20.14	0.03130	268	0.04793
48	20.53	0.03346	304	0.00454
49	20.59	0.01890	173	0.22778
71	22.72	0.00898	110	0.06887
76	23.19	0.01330	174	-0.00250
79	23.53	0.00821	112	0.02353
80	23.53	0.01239	169	-0.02240
81	23.61	0.01443	199	-0.06971
85	23.89	0.00872	125	0.02348
87	24.14	0.02950	435	0.01781
88	24.23	0.01505	224	0.05140
89	24.39	0.01723	262	0.11590
93	24.72	0.01042	165	0.03670
94	24.84	0.02232	359	-0.01117

(continued)

$1^- \; T=2 \rightarrow 0^+ \; T=1$ (continued)

State	Ex (MeV)	BE1 (e^2fm^2)	Γ_γ keV	Overlap
95	24.98	0.00980	160	0.03985
97	25.08	0.03646	603	-0.12925
101	25.60	0.00661	116	-0.05236
102	25.67	0.00874	155	0.03266
108	26.08	0.00583	108	-0.03218
109	26.18	0.00742	139	0.04763
111	26.40	0.01324	255	-0.03790
122	27.52	0.01338	292	0.05225
123	27.66	0.00705	156	0.03857
150	30.85	0.01893	341	-0.04857
175	35.40	0.00809	376	0.07244

Table III

Calculated dipole γ_o transitions in ^{42}Ca (1^-, T=1 → 0^+ T=1). The notation is the same as in Table II.

State	Ex (MeV)	BE1 (e^2fm^2)	Γ_γ (eV)	Overlap
1	5.24	0.45072	68	0.01940
24	14.447	0.03292	104	-0.07952
30	15.00	0.08336	295	0.07371
41	16.40	0.04254	197	-0.05571
43	16.70	0.09776	477	-0.05702
44	16.72	0.02113	103	-0.07214
45	16.80	0.15752	782	0.12651
47	16.95	0.20791	1061	-0.11687
48	17.07	0.20188	1053	0.14526
49	17.23	0.03197	171	-0.03092
52	17.39	0.18268	1007	0.16615
55	17.73	0.02778	133	0.00905
56	17.77	0.02996	176	0.13925
60	18.06	0.04386	271	-0.03156
61	18.12	0.05162	322	-0.08808
70	18.84	0.01438	101	-0.30402
71	18.89	0.01517	107	0.17912
75	19.56	0.07150	561	0.17181
78	19.75	0.04649	375	-0.11575
79	19.83	0.01342	110	0.17095
84	20.19	0.06872	593	0.05666
85	20.23	0.02140	186	0.08982
86	20.35	0.02581	228	-0.10509
88	20.55	0.07216	656	0.00308
101	21.33	0.01420	144	0.03078
103	21.53	0.01472	154	-0.08845
109	22.08	0.01016	114	0.04243
113	22.35	0.00971	113	-0.03264
118	22.88	0.02945	369	-0.09330

(continued)

1^- T=1 → 0^+ T=1 (continued)

State	Ex (MeV)	BE1 (e^2fm^2)	Γ_γ (eV)	Overlap
119	22.99	0.02262	288	-0.10313
120	23.01	0.01874	239	-0.11234
122	23.11	0.01617	209	-0.06357
123	23.21	0.02548	334	-0.07506
126	23.39	0.00970	130	0.04320
128	23.49	0.00938	127	-0.03335
129	23.53	0.02294	313	0.06725
131	23.64	0.01823	252	0.03921

Table IV

Calculated γ_1 dipole transitions in ^{42}Ca (1^-, T=2 → 2^+ T=1). The overlaps listed are the overlaps of the eigenstates with the "excited giant dipole state.

State	Ex (MeV)	BE1 (e^2fm^2)	Γ_γ (eV)	Overlap
11	15.03	0.11378	292	-0.03065
13	15.72	0.05931	177	0.01568
16	16.17	0.03432	112	0.01273
26	18.13	0.06506	311	-0.06936
38	19.42	0.02182	130	0.04449
40	19.68	0.08456	528	-0.07373
44	20.14	0.04382	295	-0.01140
47	20.31	0.20891	1492	0.05304
48	20.35	0.04580	328	-0.02904
49	20.59	0.08316	602	-0.00440
52	20.91	0.08109	617	-0.00024
53	21.05	0.27423	2130	0.01485
57	21.31	0.01403	113	0.11747
59	21.44	0.01321	109	0.02560
60	21.56	0.02937	247	-0.17045
63	21.92	0.41720	3698	-0.36946
65	22.15	0.09242	846	-0.29343
66	22.20	0.05227	483	0.04785
67	22.32	0.04734	444	-0.08889
70	22.58	0.37572	459	0.11961
71	22.72	0.10392	1033	-0.16141
73	22.77	0.09792	980	0.13781
74	22.89	0.04346	443	-0.02946
97	25.08	0.01820	249	-0.10680
99	25.23	0.00996	139	-0.07033
101	25.60	0.00786	115	0.05560
102	25.67	0.02097	309	0.06668
104	25.85	0.01451	218	0.07259

(continued)

1^- T=2 → 2^+ T=1 (continued)

State	Ex (MeV)	BE1 (e^2fm^2)	Γ_γ (eV)	Overlap
122	27.52	0.01081	199	-0.06082
123	27.66	0.00850	159	-0.04630
126	27.94	0.00991	191	0.05489
132	28.61	0.00708	147	0.04097
147	30.25	0.00450	112	0.01407

Table V

Calculated γ_1 dipole transitions in ^{42}Ca (1^- T=1 → 2^+ T=1). The notation is the same as in Table IV.

State	Ex (MeV)	BE1 (e^2fm^2)	Γ_γ (eV)	Overlap
47	16.95	0.10187	390	-0.08456
51	17.31	0.02694	111	0.04932
52	17.39	0.02690	112	0.09324
65	18.31	0.02098	104	0.01573
66	18.35	0.09858	490	-0.03463
68	18.57	0.03616	187	-0.00740
70	18.84	0.08968	486	0.03104
72	18.97	0.33273	844	-0.08802
73	19.20	0.10502	606	0.00809
77	19.64	0.01876	116	-0.07147
78	19.75	0.02227	141	0.11024
79	19.83	0.09826	630	-0.23789
82	19.99	0.02327	153	-0.10416
86	20.36	0.01614	112	0.19210
87	20.47	0.02341	166	-0.10298
91	20.70	0.08305	611	-0.19579
92	20.78	0.01443	108	-0.07833
93	20.85	0.02064	155	0.12344
95	20.94	0.06588	503	0.16441
96	21.04	0.13432	1041	-0.27357
98	21.20	0.02304	183	-0.11677
99	21.23	0.02474	198	-0.16059
101	21.33	0.02223	180	0.12515
103	21.53	0.01455	122	-0.10152
110	22.16	0.02234	205	0.07892
112	22.28	0.02406	225	0.08696
113	22.35	0.01649	155	0.06732
114	22.50	0.03506	338	0.11315
116	22.62	0.03041	298	-0.08303

(continued)

1^- T=1 → 2^+ T=1 (continued)

State	Ex (MeV)	BE1 (e^2fm^2)	Γ_γ (eV)	Overlap
120	23.01	0.03881	402	0.10090
122	23.11	0.01476	155	0.07631
123	23.21	0.01675	178	0.05154
124	23.22	0.01091	116	-0.07011
128	23.49	0.01675	185	-0.05871
131	23.64	0.01560	176	-0.07699

Table VI

States which either $\Gamma_{\gamma_o} \geq .4$ keV and $\Gamma_{\gamma_1} \geq .1$ keV or vice versa.

T = T<				T = T>			
E_x	Γ_{γ_o}	Γ_{γ_1}	$\frac{\Gamma(\text{weak})}{\Gamma(\text{strong})}$	E_x MeV	Γ_{γ_o} (keV)	Γ_γ keV	$\frac{\Gamma(\text{weak})}{\Gamma(\text{strong})}$
16.95	1.061	.390	.368	20.59	.173	.602	.287
17.39	1.007	.112	.111	22.72	.110	1.033	.106
18.84	.101	.486	.208	24.14	.435	.249	.572
19.83	110	.630	.175				
23.01	.239	.402	.843				

Figure Captions

Fig. 1. Excitation function of the $^{41}K(p,\gamma_o)^{42}Ca$ reaction taken over the Giant Dipole region of ^{42}Ca, at $\theta = 90°$. Complete angular distribution were taken at the indicated bombarding energies. The insert shows the high-energy portion of the γ spectrum obtained at $E_p = 10.5$ MeV. The arrow labels the γ_o transiton.

Fig. 2. Plot of Legendre Polynomials coefficients A_1 and A_2 obtained from angular distributions at various energies in the GDR of ^{42}Ca.

Fig. 3. Comparison of the energy-averaged excitation functions for the γ_o transitions in ^{40}Ca and ^{42}Ca. The data were averaged by a 1.5 MeV sliding interval.

Fig. 4. Energetics and quantum numbers for neutron and proton decay from the T = 1 and T = 2 components of the GDR in ^{42}Ca. The final states are labelled by (J^{π}, T).

Fig. 5. Calculated γ_o dipole transitions in ^{42}Ca. Only transitions with $\Gamma_{\gamma_o} \geq .2$ keV are presented. Dotted lines indicate $T_>$ transitions $(T_i = 2)$.

Fig. 6. Calculated γ_1 dipole transitions in ^{42}Ca. Only transitions with $\Gamma_{\gamma_1} \geq .2$ keV are presented. Dotted lines indicate $T_>$ transitions $(T_i = 2)$. Only states with $J_i = 1^-$ were considered.

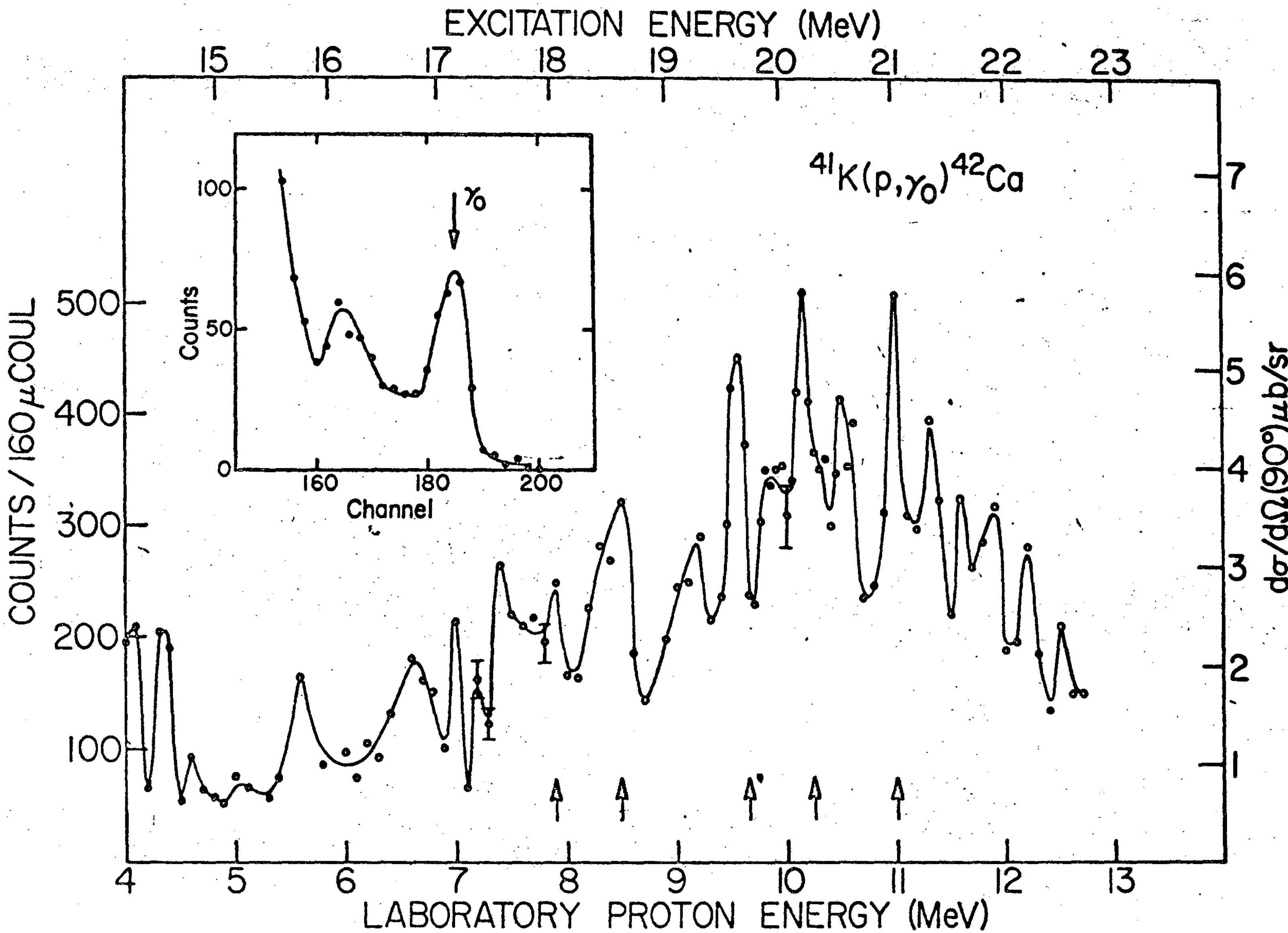

EXCITATION ENERGY (MeV)
15 16 17 18 19 20 21 22 23
$^{41}K(p,\gamma_0)^{42}Ca$
COUNTS / 160 μCOUL
100 200 300 400 500
dσ/dΩ(90°)μb/sr
1 2 3 4 5 6 7
Counts
0 50 100
γ_0
160 180 200
Channel
4 5 6 7 8 9 10 11 12 13
LABORATORY PROTON ENERGY (MeV)

Fig. 1

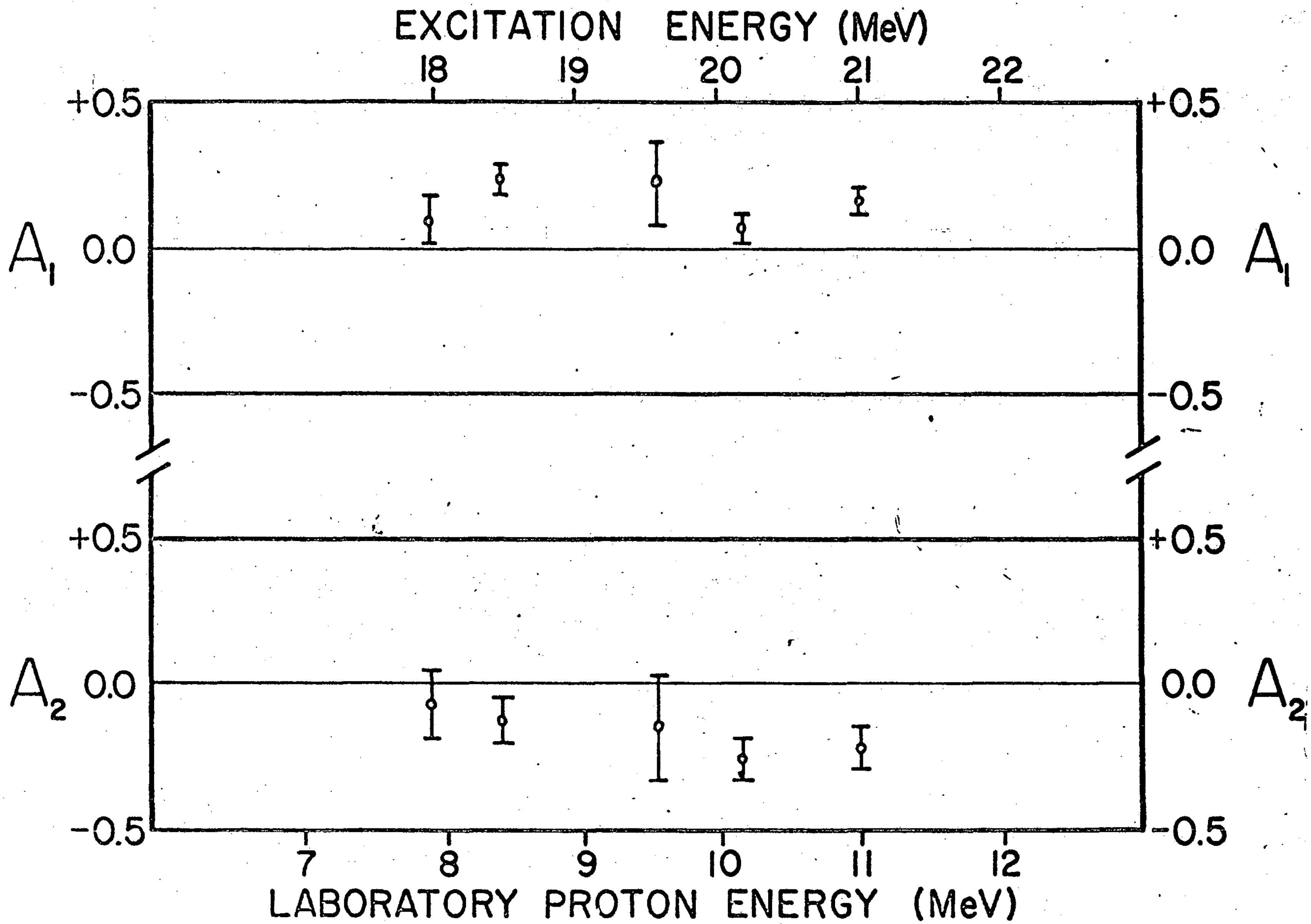

EXCITATION ENERGY (MeV)
18
19
20
21
22
+0.5
A_1
0.0
-0.5
+0.5
A_2
0.0
-0.5
7
8
9
10
11
12
LABORATORY PROTON ENERGY (MeV)

Fig. 2

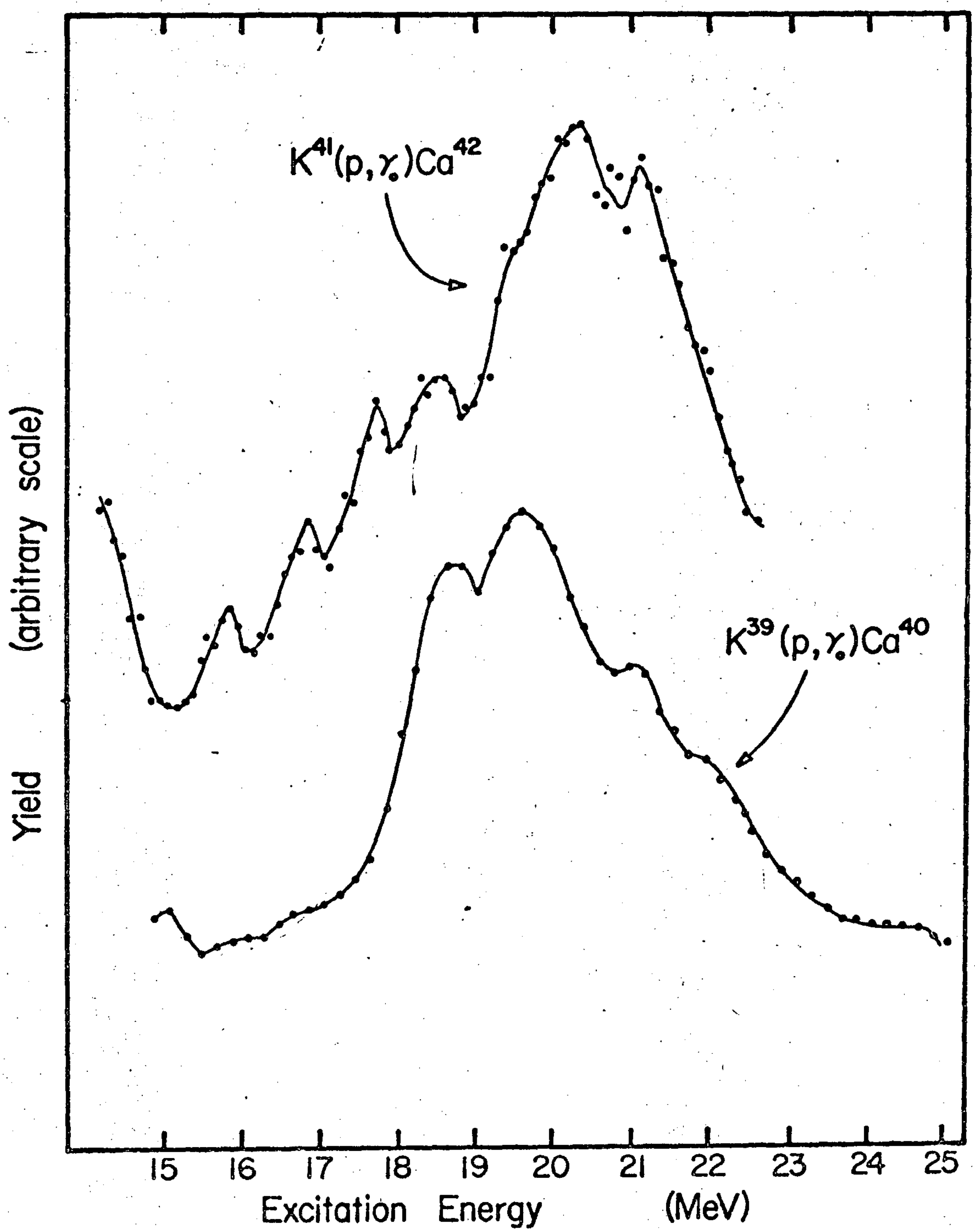

K41(p,γ0)Ca42
K39(p,γ0)Ca40
Yield (arbitrary scale)
15
16
17
18
19
20
21
22
23
24
25
Excitation Energy (MeV)

Fig. 3

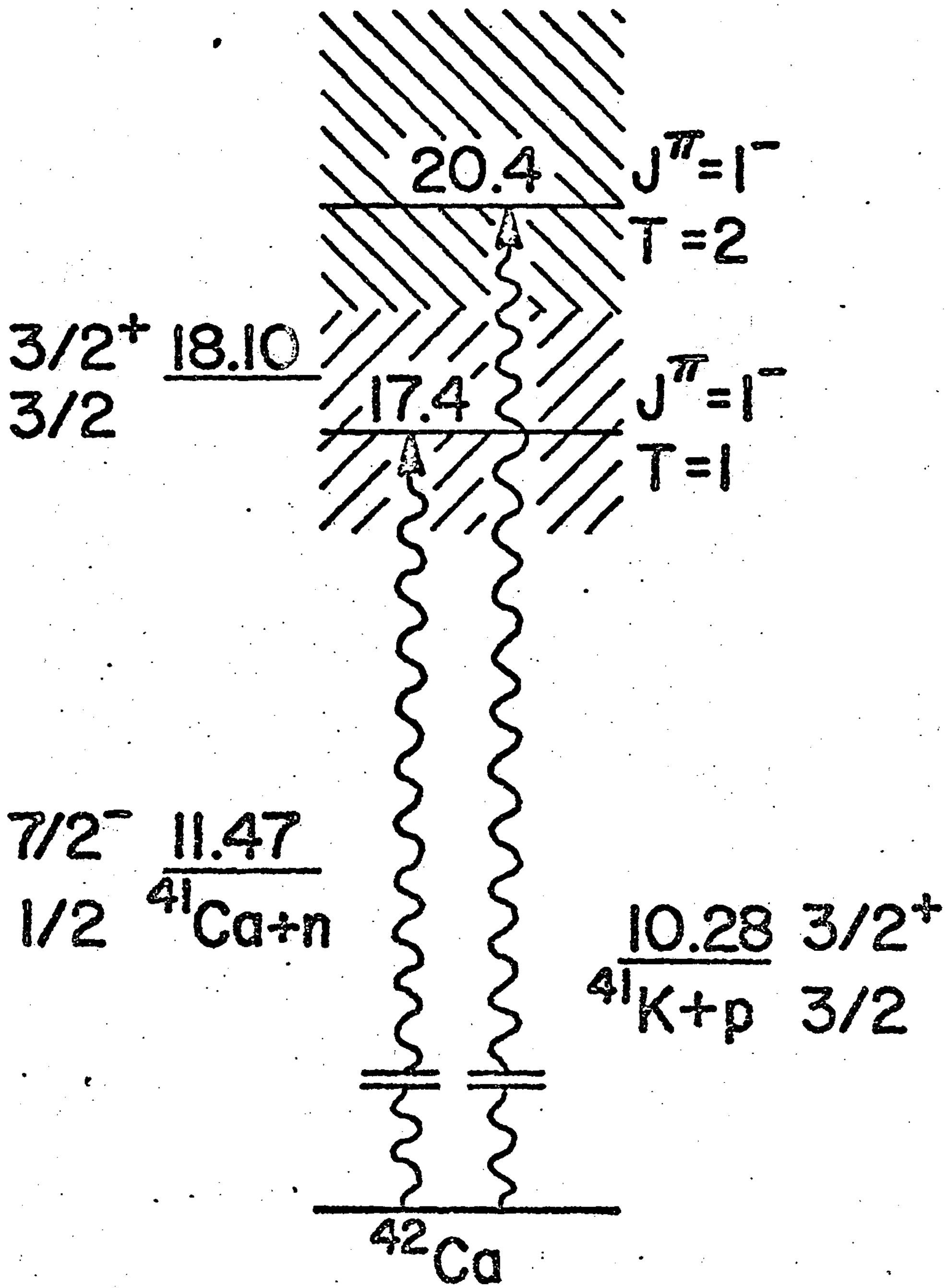
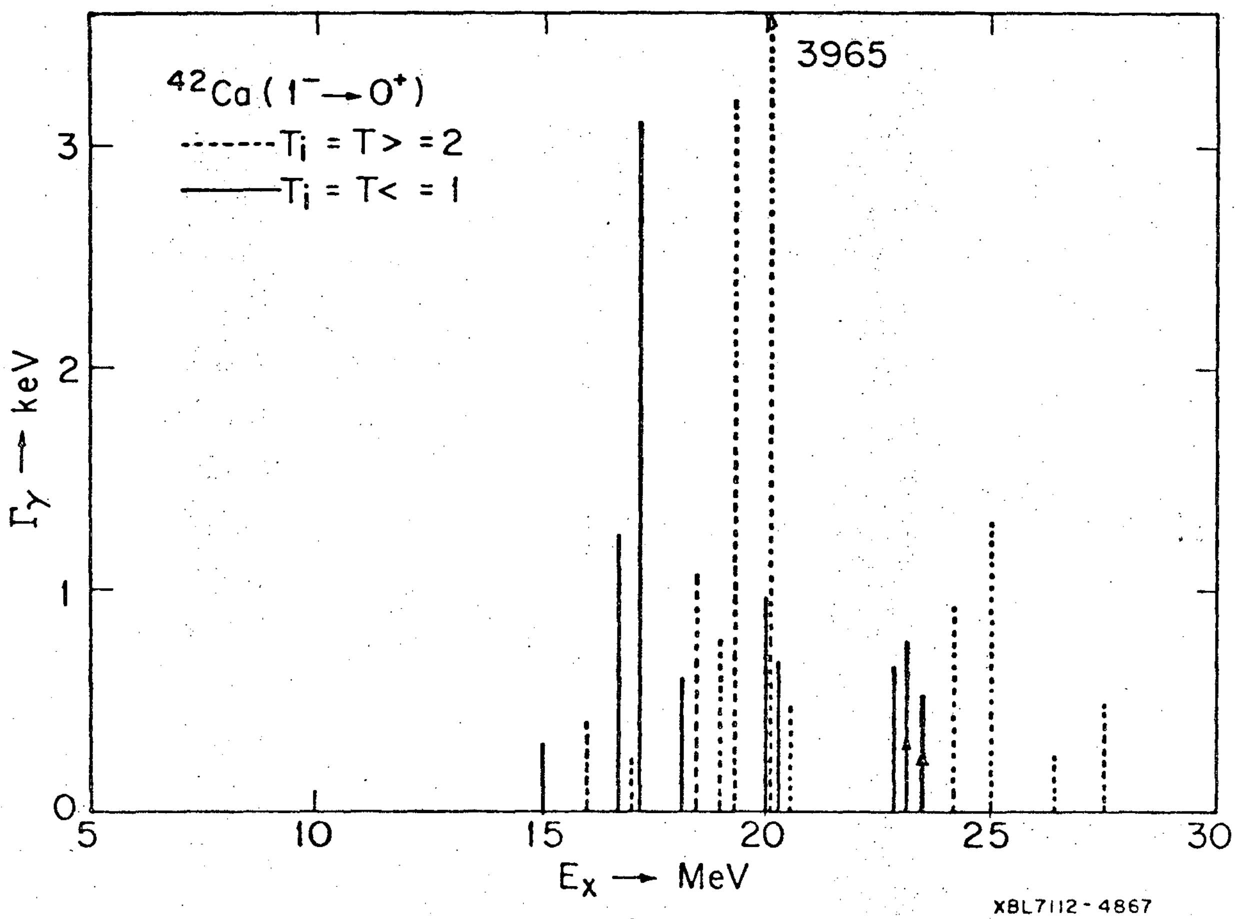

20.4
$J^{\pi}=1^{-}$
T = 2
3/2+ 18.10
3/2
17.4
$J^{\pi}=1^{-}$
T = 1
7/2- 11.47
1/2 ^{41}Ca+n
10.28 3/2+
^{41}K+p 3/2
^{42}Ca

Fig. 4



^{42}Ca (1$^-$ → 0$^+$)
Ti = T> = 2
Ti = T< = 1
3965
Γγ → keV
0
1
2
3
5
10
15
20
25
30
Ex → MeV
XBL7112-4867

Fig. 5

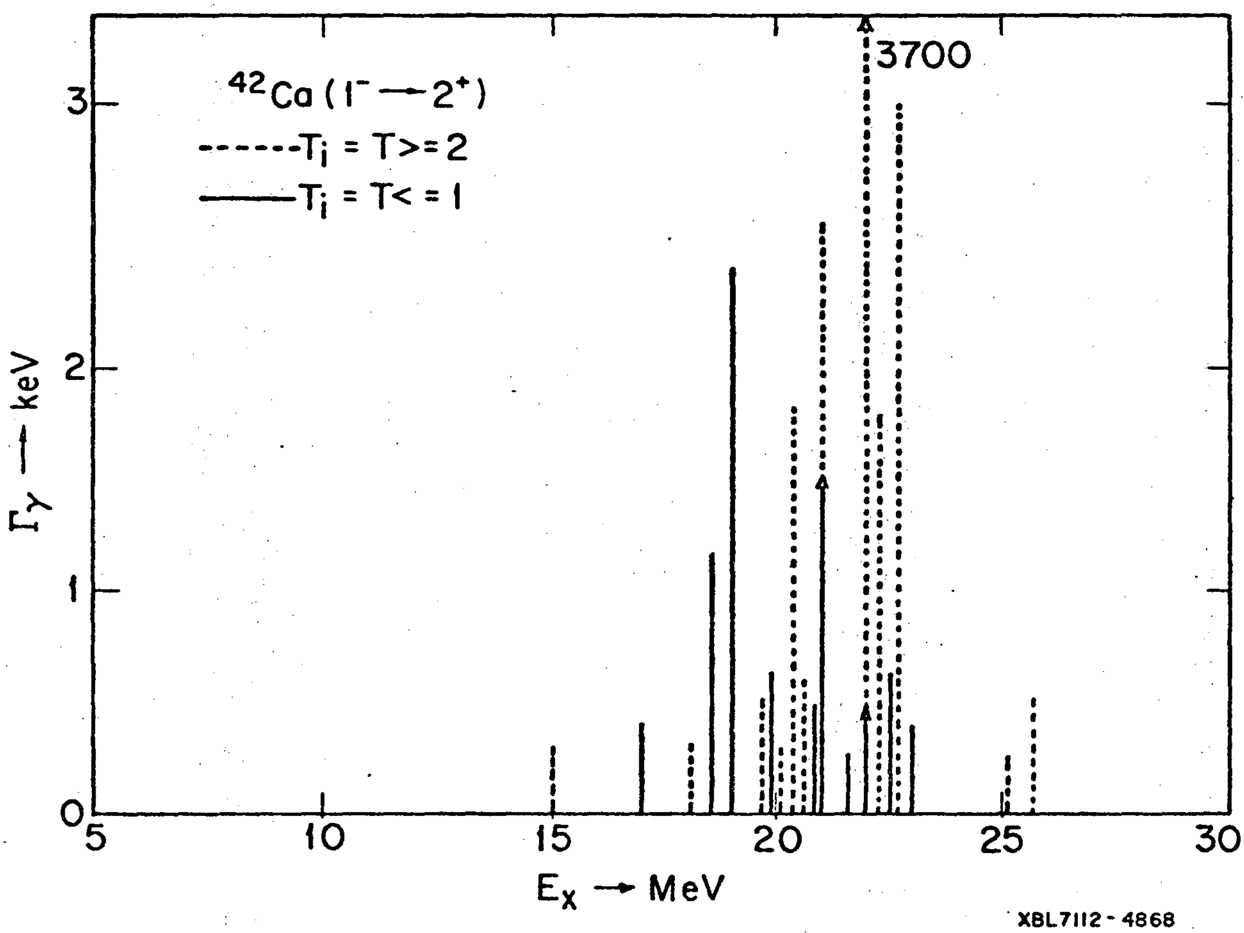

3700
^{42}Ca (1$^-$ ⟶ 2$^+$)
------ T_i = T> = 2
—— T_i = T< = 1
3
2
1
0
5
10
15
20
25
30
Γ_γ ⟶ keV
E_x ⟶ MeV
XBL7112 - 4868

Fig. 6

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