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Radiative proton capture study of the giant dipole resonance in ^{55,57}Co†

J. V. Maher and L. Meyer-Schützmeister
Argonne National Laboratory, Argonne, Illinois 60439

E. L. Sprenkel-Segel
Illinois Institute of Technology, Chicago, Illinois 60616, and Argonne National Laboratory, Argonne, Illinois 60439

D. von Ehrenstein, R. J. Nemanich, and G. C. Kiang
Northern Illinois University, DeKalb, Illinois 60115, and Argonne National Laboratory, Argonne, Illinois 60439

J. F. Tonn
Northwestern University, Evanston, Illinois 60201

R. E. Segel
Northwestern University, Evanston, Illinois 60201, and Argonne National Laboratory, Argonne, Illinois 60439

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Extensive yield-curve and angular-distribution measurements have been made for the ^{54}Fe(p,γ_0) and the ^{56}Fe(p,γ_0) reactions. Both yield curves clearly show the envelope of the giant dipole resonance. The giant resonance appears to be broader in ^{57}Co and this is attributed to a greater isospin splitting and to the fact that proton emission from the two isospin components is expected to be more nearly equal. In both cases the angular distributions appear to be somewhat different for the two T components with the difference greater in ^{57}Co.

[NUCLEAR REACTIONS ^{54}Fe(p,γ_0), E_p=4.75–16.80 MeV, ^{56}Fe(p,γ_0), E_p=4.65–17.40 MeV; measured $\sigma(E_p)$, $\sigma(\theta)$ at many E_p values. Deduced for (γ,p_0)$\sigma(E_\gamma,\theta)$ in giant dipole resonance of ^{55,57}Co.]

INTRODUCTION

Much of the knowledge of the structure within the giant dipole resonance comes from radiative-capture experiments. One of the important structures is the splitting of the giant resonance, in all but self-conjugate nuclei, into two isospin components. The observation of this splitting has been reported in a number of nuclei,[1] with proton-capture experiments playing a major role in the identification of the isospin components. A theoretical expression for the variation of the energy splitting with mass number and ground-state isospin that appears to agree with most of the experimental data,[1] has been developed.[2] In the present work we examine isospin effects further by studying proton radiative capture through the giant resonance in two closely spaced isotopes.

In nuclei with but a small neutron excess, the γ-ray absorption strength can be expected to divide between the two isospin components in the ratio $T_>:T_<=1:T$, since an $E1$ γ ray is pure isovector.[3] Neutron emission is forbidden from $T_>$ states except for decays to analog states. On the other hand, both proton and neutron decay are allowed from the $T_<$ part of the giant resonance and therefore, the strength will be divided between these two channels. α emission from the $T_<$ states is also possible but is small even in lighter nuclei,[4] and is likely to be further inhibited by the Coulomb barrier in nuclei as heavy as Co. Table I gives the expected division of the total γ-ray strength under the assumption that the (γ,n) and (γ,p) reactions take up the entire reaction cross section. Using the expressions given in Table I, for the (γ,p) reaction in $T=\frac{1}{2}$ ^{55}Co, $T_>:T_<=5:1$ while in ^{57}Co this ratio is 1.5 : 1. These ratios illustrate that the (γ,p) reaction emphasizes the $T_>$ component of the giant dipole resonance. In the present work it is, of course, not all protons but just the ground-state protons that were studied, and the fraction of the total (γ,p) strength to the ground state can be expected to vary. Thus, the ratios given above can only be considered as indicative and are not firm predictions.

Studies of self-conjugate nuclei have revealed the puzzling phenomenon that the γ-ray angular distributions vary very little with energy even when the yield curve is rich in structure and shows violent variations with energy.[5] While

TABLE I. Division of total $E1$ γ-ray strength under the assumption that only the (γ,n) and (γ,p) reactions contribute significantly and that decay through analog states can be neglected.

	$T_<$	$T_>$
(γ,n)	$\frac{2T}{4T+3}$	0
(γ,p)	$\frac{T(2T+1)}{(T+1)(4T+3)}$	$\frac{1}{T+1}$

there is extensive angular-distribution data on the self-conjugate nuclei, little such data has been reported on the nuclei where two isospin components are expected. In the present work, therefore, in each isotope we have taken angular distributions at a large number of points spanning the entire energy region studied.

YIELD CURVES

The experimental arrangement was similar to that used in other radiative-capture experiments that have been done at Argonne.[5] In the present work, the γ rays were detected by two NaI(Tl) crystals, each 25 cm in diameter and 30 cm thick. Pileup was suppressed by circuitry that has been described previously[6]; the rest of the electronics was conventional. Targets were rolled iron foils whose thickness totaled about 2 mg/cm^2. The ^{54}Fe targets were enriched to 97.7%, while for the ^{56}Fe targets the enrichment was nearly 100%. Typical pulse-height spectra are shown in Figs. 1 and 2. In both ^{55}Co and ^{57}Co only the ground state is separated from other levels by as much as 1 MeV and therefore, only the ground-state transition was studied.

Yield curves as a function of proton energy with the crystals at 90° to the incident beam were taken in 50-keV steps. For the $^{54}\mathrm{Fe}(p,\gamma_0)^{55}\mathrm{Co}$ reaction, the $4.75 \leq E_p \leq 16.80$-MeV range was covered. When ^{56}Fe was bombarded, the range was from 4.65 to 17.40 MeV. Applying the principle of detailed balance, the yield curves for the $^{55}\mathrm{Co}(\gamma,p_0)$-$^{54}\mathrm{Fe}$ and $^{57}\mathrm{Co}(\gamma,p_0)^{56}\mathrm{Fe}$ reactions have been determined and these are shown in Figs. 3 and 4.

Both curves clearly show a giant-resonance envelope upon which considerable structure is superimposed. While in neither curve is there a clear indication of a splitting into two components, the

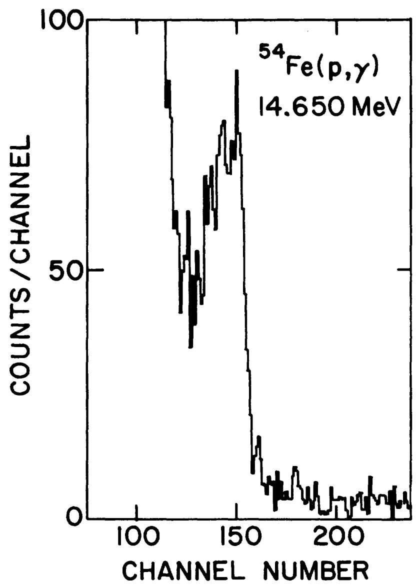

FIG. 1. Pulse-height spectrum from a 25-cm-diam 30-cm-thickNaI(Tl) crystal showing the ground-state γ ray from the $^{54}\mathrm{Fe}(p,\gamma)$ reaction. The spectrum was taken at a bombarding energy of 14.650 MeV with the crystal at 90° to the incident beam.

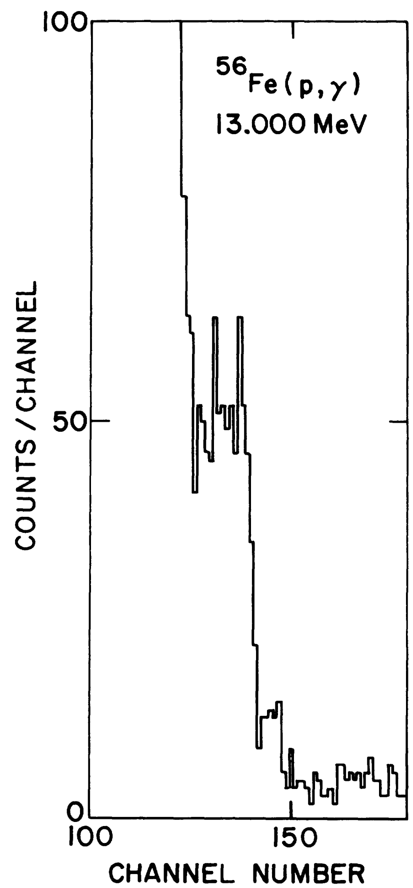

FIG. 2. Upper end of the pulse-height spectrum from the $^{56}\mathrm{Fe}(p,\gamma_0)$ reaction at $\theta = 90°$, $E_p = 13.000$ MeV.

entire pattern is consistent with isospin splitting with the expected behavior. Specifically, it is quite reasonable that for these rather low T nuclei the width of each T component is greater than the energy difference between them, and therefore, the two envelopes are not resolved. For $T=\frac{1}{2}$ ^{55}Co, as explained above, the ^{55}Co(γ, p) reaction should be dominated by the $T_>$ part. In $T=\frac{3}{2}$ ^{57}Co where the (γ, p) would be expected to be more nearly equally distributed between the two components, the energy splitting should also be greater. The ^{55}Co(γ, p_0) yield curve can be interpreted as being dominated by a $T=\frac{3}{2}$ giant resonance centered at about 19.2 MeV with a smaller amount of $T=\frac{1}{2}$ strength centered at about 17 MeV. The ^{57}Co(γ, p_0) curve can be said to have the $T=\frac{5}{2}$ strength centered at about 20.4 MeV and the $T=\frac{3}{2}$ strength centered in the region of 17.2 MeV. In both cases the relative intensity of the two isospin components, which can only be very roughly estimated, appears to be consistent with the ratios derived from Table I, and the energy splittings are in agreement with the prescription given by Akyüz and Fallieros.[2]

When averaged over the fine structure, the maximum ^{55}Co(γ, p_0) cross section is about $2\frac{1}{2}$ times as great as the maximum ^{57}Co(γ, p_0) cross section. Both yield curves show a giant resonance above a nonresonant yield of about 12 μb/sr. Some of the useful information that can be extracted from the yield curves is given in Table II.

Only a very small fraction (<1%) of the giant dipole resonance in either ^{55}Co or ^{57}Co goes into the ground-state proton channel. While a trend of less and less of the total strength in proton emission to the ground state as the atomic number is increased is to be expected,[6] the strengths found

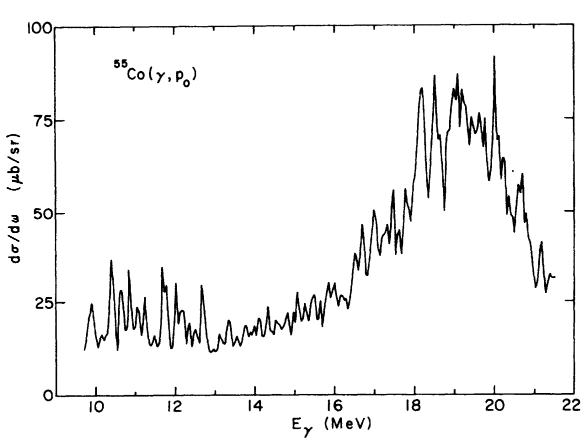

FIG. 3. Yield curve at 90° for the ^{55}Co$(\gamma,p_0)^{54}$Fe reaction obtained by applying detailed balance to the ^{54}Fe(p,γ_0) measured cross sections.

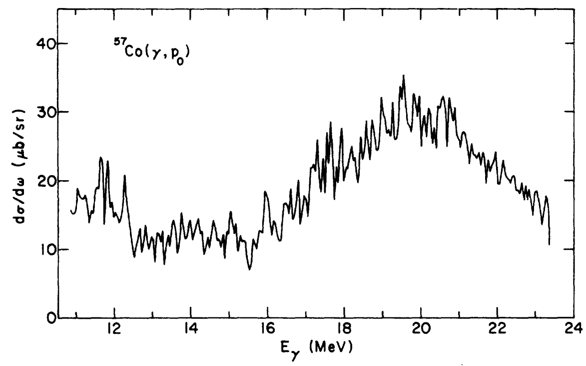

FIG. 4. Yield curve at 90° for the ^{57}Co(γ,p_0) reaction.

here are considerably less than those observed in the ^{60}Ni(γ, p_0) reaction.[7] An explanation can be found if it is remembered that both ^{55}Co and ^{57}Co contain a proton hole in the $f_{7/2}$ shell. Removal of a valence proton will leave, in effect, the configuration $(f_{7/2})^{-2}$ with four possible spin values of which only one, 0^+, is that of the ground state of the residual nucleus. On the other hand, ^{60}Ni, like most other nuclei in which the (γ, p_0) reaction has been studied, is even-even with all nucleons paired. Removal of an $f_{7/2}$ proton from ^{60}Ni must have a $\frac{7}{2}^-$ residual nucleus and this is the spin of the ground state of ^{59}Co. Generalizing the above argument, which is admittedly crude and contains oversimplifications, leads to the conclusion that there will be a tendency for the (γ, p_0) yield to be larger in even-even nuclei than in odd-Z nuclei.

A statistical analysis was made of the yield curves using the methods given by Ericson[8] and previously applied to (p, γ) data.[9] The autocorrelation function

$$R(\epsilon)=\left\langle\left(\frac{\sigma(E)}{\langle\sigma\rangle}-1\right)\left(\frac{\sigma(E+\epsilon)}{\langle\sigma\rangle}-1\right)\right\rangle , \tag{1}$$

was computed for both yield curves. Figure 5 shows the autocorrelation function obtained for the ^{54}Fe(p, γ_0) reaction. In both cases, a rather small mean square deviation $[R(0)]$, ~4% for ^{54}Fe(p, γ_0) and ~2% for ^{56}Fe(p, γ_0) was found. Using a 2-MeV averaging interval in the determination of the average cross section, the char-

TABLE II. Integrated strengths in the ^{55}Co(γ,p_0) and ^{57}Co(γ,p_0) yield curves. Strengths are given in MeV mb.

	^{55}Co(γ,p_0)	^{57}Co(γ,p_0)
Area under main resonance	2.59	1.04
$\int\sigma dE$ over entire range studied	5.27	2.98
Classical dipole sum $=60\frac{NZ}{A}$	825	853

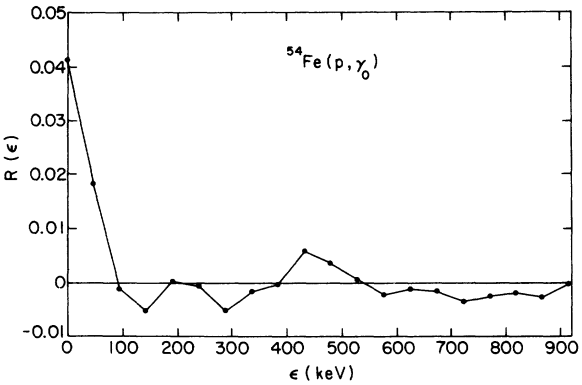

FIG. 5. Autocorrelation function computed for the ^{54}Fe(p,γ_0) yield curve. In obtaining the average cross section an averaging interval of 2.25 MeV was used.

acteristic c.m. coherence widths $\Gamma = 43$ keV for ^{54}Fe(p,γ_0) and 33 keV for ^{56}Fe(p,γ_0) were found. Both are less than the 48-keV step size, which means that they are, in reality, only upper limits. Compound level widths much less than 50 keV are what would be expected for nuclei in this mass region excited to 20 MeV. Because the effective energy resolution, which was essentially determined by the target thickness, was large compared to Γ, the fluctuations were damped and the smaller mean square deviation found for the ^{56}Fe(p,γ) yield curve might be due to Γ being smaller in ^{57}Co.

One of the main reasons for performing the statistical analysis was to search for intermediate structure. To this end $R(0)$ was computed as a function of the averaging interval. If there is a significant intermediate-structure component, $R(0)$ should rise, plateau, and then continue to rise.[9] No such behavior is present (Fig. 6) and it is thus concluded that if there is a significant intermediate structure, in each case it must be less than about 100 keV wide.

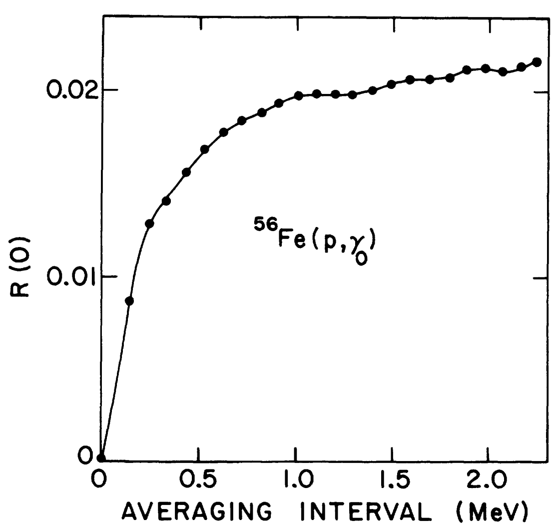

FIG. 6. Mean square deviation vs averaging interval for the ^{56}Fe(p,γ_0) yield curve.

ANGULAR DISTRIBUTIONS

For the ^{54}Fe(p,γ_0) reaction, angular distributions were taken every 500 keV from 7.5 to 17.0 MeV and in somewhat smaller, irregular steps down to 4.90 MeV. In the ^{56}Fe(p,γ_0) study, angular distributions were taken every 500 keV from 6.0 to 16.5 MeV and also at 16.90 MeV. In both cases, a five-point (30, 60, 90, 120, 150°) angular distribution was taken with each crystal and the results were averaged. The distributions were expressed as the usual Legendre-polynomial sum: $W(\theta) = A_0[1 + \sum_{n=1}^{4} a_n P_n(\cos\theta)]$. The coefficients that were extracted from the data are shown in Fig. 7 for ^{54}Fe(p,γ_0) and in Fig. 8 for ^{56}Fe(p,γ_0).

Except perhaps at the lowest energies below the giant-resonance region, the coefficient a_4 in the ^{54}Fe(p,γ_0) reaction is indistinguishable from zero. The coefficient a_3 is also near zero throughout,

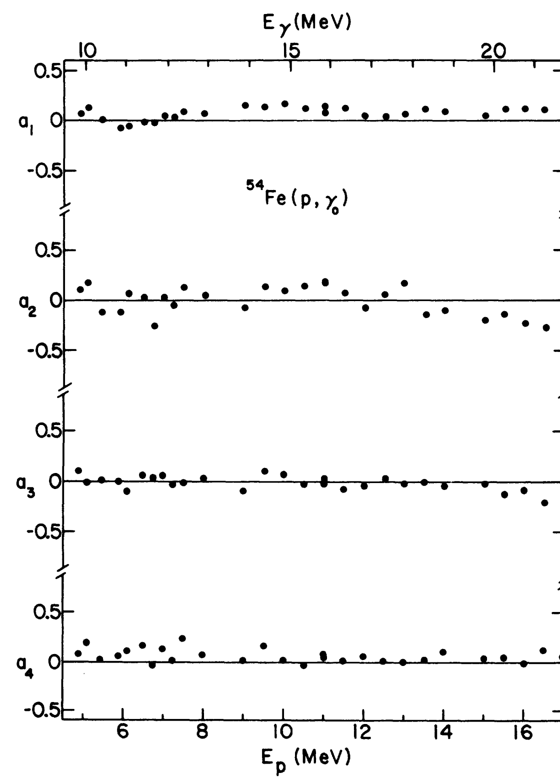

FIG. 7. Coefficients obtained when the ^{54}Fe(p,γ_0) angular distributions are expressed as a sum of Legendre polynomials.

possibly starting to go negative at the high-energy end. These null or nearly null results for the higher coefficients are, of course, expected if dipole radiation is to be dominant. The coefficient a_2 seems to average to zero below the main giant resonance, to be slightly positive on the low side of the main peak and slightly negative on the high side. It is noteworthy that the energy where a_2 changes sign, $E_\gamma \approx 18$ MeV, is just about the point where the speculations about the yield curve put the dividing line between the $T_<$ and the $T_>$ part of the giant resonance. Finally, a_1 is slightly positive throughout, reflecting the forward peaking that is usually observed in photonuclear reactions.

In the ^{56}Fe(p, γ_0) reaction the coefficients a_1, a_3, and a_4 exhibit a behavior that is similar to their behavior in the ^{54}Fe(p, γ_0) reaction. While it is true that a_4 appears to be positive throughout, the effect is small, $a_4 \approx 0.06$ in the giant-resonance region, and probably attributable to experimental error. The coefficient a_2 is also somewhat similar in the two reactions, but the effects in the ^{56}Fe(p, γ_0) reaction are more pronounced. Here a_2 is positive on the low side of the giant resonance, reaching a value of about 0.35 at $E_\gamma \approx 16.5$ MeV, and then becomes slightly negative throughout the middle and upper part of the region. The crossover is at about 18.5 MeV which again is in the region where it is thought that $T_>$ starts to dominate.

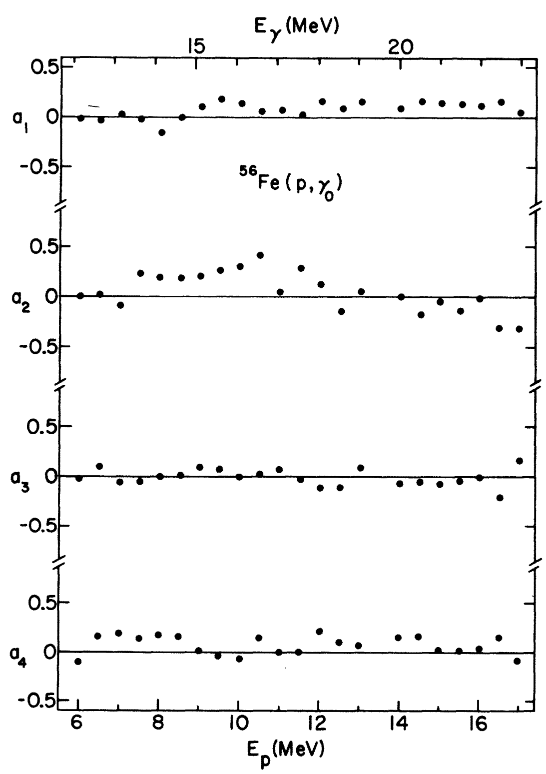

FIG. 8. Angular-distribution coefficients for the ^{56}Fe(p, γ_0) reaction.

Although the effects are small in both cases, the data do seem to indicate a systematic difference in the angular distributions through the $T_<$ and $T_>$ parts of the giant dipole resonance. Furthermore, the difference is more pronounced in ^{57}Co than it is in ^{55}Co. That the pattern of angular distributions observed in the present work is at least qualitatively in accord with expectations follows from considering which excitations contribute to each isospin component. A schematic picture applicable to any nucleus with a neutron excess is shown in Fig. 9 where it can be seen that, while all excitations that have a $T_>$ component also have a $T_<$ one, there are some excitations that contribute only to $T_<$. As the neutron excess increases so does the fraction of pure $T_<$ excitations and it is this phenomenon that gives rise to the deviation from the simple isospin–Clebsch-Gordan coefficients in the division of strength between the two isospin components.[10]

Where the neutron excess (and hence T) is small, the configurations of the two isospin components are similar and this may be the reason that the angular distributions show only a rather small change in going from the lower to the upper part of the giant-resonance region. The change is greater in $T=\frac{3}{2}$ ^{57}Co than it is in $T=\frac{1}{2}$ ^{55}Co and this too is in accord with the theoretical picture. It should be remembered that no such systematic variation of the γ-ray angular distributions has been observed in any of the many self-conjugate nuclei that have been studied.[5]

Finally, we note that while both yield curves show rapid fluctuations, the angular distributions, and in particular the coefficient a_2, do not show strong variations on a similar energy scale. This behavior is reminiscent of that observed in the self-conjugate nuclei where the angular distributions are nearly constant throughout the entire giant-resonance region.

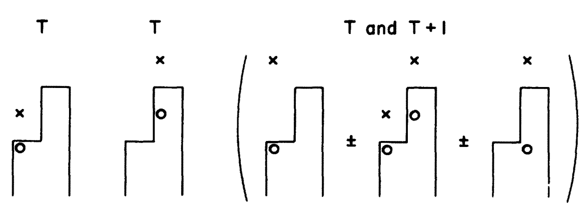

FIG. 9. Shell-model schematic showing isospin of various particle-hole excitations.

SUMMARY

The yield curves and angular distributions obtained for the $^{54}Fe(p, \gamma_0)$ and $^{56}Fe(p, \gamma_0)$ all support the picture of a giant resonance split into two isospin components with the energy splitting and relative strengths in accordance with the theoretical expectations. Neither the splitting nor the partition of strength is more than very roughly determined in the present work, but both do seem to show the correct behavior with increasing T_z. Perhaps the best identification of the two components comes in the angular-distribution data where it appears that there is a small but significant change in the γ-ray angular distribution in passing from the $T_<$ to the $T_>$ region. Why the further fragmentation (which the structure in the yield curve assures must be taking place) does not lead to major variations in the angular distributions, remains a mystery.

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