$K^{41}(He^3,p)Ca^{43}$ reactions. The first of these should excite $\frac{3}{2}^+$ hole states in Ca^{43} that are coupled to $1(f_{7/2})^4$ $T=1$ configurations more strongly than those coupled to $(1f_{7/2})^4$ $T=2$ configurations.

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High-Resolution Study of the $Fe^{54}(t,p)Fe^{56}$ Reaction*

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The $Fe^{54}(t,p)Fe^{56}$ reaction was studied with 12-MeV incident tritons using the Aldermaston tandem Van de Graaff and multigap spectrograph. The angular distributions of the protons are characterized by sharp structure. For eight cases where the spin and parity of the final state are known, the position of the first maximum agrees very well with predictions of the plane-wave Born approximation. These positions were then used for assigning spins and parities to many other levels. The only known unnatural parity state is excited two orders of magnitude less strongly than the strongly excited states, and has an unusual angular distribution. The collective 3^- state (4.51 MeV) is the most strongly excited state in the spectrum; it is shown that this is very difficult to explain. Other very strongly excited states are the ground and first excited states, 1^- states at 5.19 and 7.06 MeV, and a 6^+ (or 7^-) state at 5.15 MeV. The spin and parity assignments of all states up to 4.5 MeV are discussed in the light of other evidence; the principal correction is to change the assignment of the 3.122-MeV state from 5^+ to 5^-.

I. INTRODUCTION

It has been established for some time that (p,t) and (t,p) reactions, at least above 10 MeV, proceed predominantly by a direct-interaction mechanism in which two neutrons are transferred.[1] Some of the interesting advantages of using these reactions for nuclear-structure studies have been pointed out by Newns, Yoshida, Hintz, and others.[2,1] Unfortunately, application of the (p,t) reaction for such purposes has been hindered by the lack of energy resolution in accelerators with high enough energy to use such a large negative Q reaction, and (t,p) reaction studies have been limited by the difficulties of using highly radioactive tritium as a source material in accelerators. However, a 12-MeV triton beam was recently developed by the Aldermaston group and has been widely used in studies of (t,p), (t,d) and (t,α) reactions. The work reported here is one of these studies. It concerns the reaction $Fe^{54}(t,p)Fe^{56}$ which has a Q value of about 12.03 MeV.

II. PROCEDURES AND RESULTS

A thin target of Fe^{54} was bombarded with 12.01-MeV tritons from the Aldermaston Tandem Generator, and the emitted protons were analyzed and detected in the multi-angle magnetic spectrograph. The method has been described previously.[3] The target thickness was not measured, so that absolute cross sections were not

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[3] R. Middleton and S. Hinds, Nucl. Phys. **34**, 404 (1962).

TABLE I. Summary of results for $Fe^{54}(t,p)Fe^{56}$.

(1) Excitation (this work)	(2) Energy[a] (p,p')	(3) (MeV)[a] (p,α)	(4) Angle of max[b] (deg)	(5) L	(6) Max.[c] intensity	(7) Total σ[d] 0°–90°
0	0	0	0	*0*	11 000	3800
0.85	0.846	0.842	20	*2*	2400	2700
2.09	2.084	2.088	34	*4*	240	400
2.66	2.655	2.654	20	*2*	1110	1770
2.95	2.937	2.951	0	*0*	600	650 (2.95 and 2.96 together)
2.96	2.953	2.955	20	*2*	260	
3.12	3.105	3.122	39	5(6)	390	1130
3.37	3.362 / 3.376	3.375 / 3.391	20	2	780	1020
3.44	3.442	3.450	20	2	24	66
3.60	3.601	3.606	0	0	1520	640
...	3.754	3.756	...	...	...	...
3.83	3.826	3.832	20	2	280	410
...	3.852	...	...	...	...	...
4.05	4.049	4.051	~27	?	~10	50
4.10	4.097 / 4.114	4.100 / 4.120	~34	*4*	38	170
4.30	4.296	4.297	0	0	270	340
4.40	4.398	4.397	22	2	360	550
4.46	4.458	4.460	22 / 45	?	52 / 52	220
4.51	4.508	4.513	27	*3*	2100	5600
...	4.541	4.542	...	...	...	...
...	4.556	4.557	...	...	...	...
4.61	4.612	4.610	20	?	38	110
...	4.660	4.663	...	...	...	...
...	4.685	4.691	...	...	...	...
...	4.700	...	...	...	...	...
4.73	4.737	4.740	0	0	30	...
4.82	4.814	4.818	~25	...	12	...
4.88	4.870 / 4.880	4.877 / 4.886	22	2	260	510
5.05	5.025	5.034	12	1?	170	400 (both 5.05 rows together)
5.05	5.035	5.059	27	3?	140	
...	5.106	...	...	...	...	...
...	5.128	5.133	...	...	...	...
5.15	5.142	5.156	50	(6)(7)	550	2300
5.19	5.187 / 5.194	5.190	12	1	2100	2000
...	5.230	5.234	...	...	...	...
5.26	5.253	5.261	~25	...	25	115
5.29	5.283	5.288	0	0	770	380
...	5.298	5.313	...	...	...	...
5.40	5.402	...	0	0	200	190
...	5.456	5.455	...	...	...	...
5.48	5.489	5.491	0	0	75	...
5.51	5.508	5.510	23	2	990	1560
...	5.540	...	...	...	...	...
5.58	5.565 / 5.588	5.566 / 5.591	19	2	450	640
5.61	5.617	5.625	0	0	630	290
...	5.678	5.676	...	...	...	...
5.70	5.694	5.700	~20	?	42	133
...	5.727	...	...	...	...	...
5.81	...	...	~30	?	130	490
5.86	...	...	20–40	?	64	320
5.93	...	...	20	2	66	134
5.97	...	...	25	2,3	600	1090
6.06	...	...	~18	2	95	180
6.08	...	...	~24	3?	120	460
6.11	...	...	0	0	800	490
6.13	...	...	8	...	35	156
6.25	...	...	20	...	120	300
6.27	...	...	0 / 35	...	~75 / ~65	230
6.33	...	...	10–50	...	~35	143
6.37	...	...	0–30	...	~80	278
6.43	...	...	0	?	330	580
6.57	...	...	0	0	62	134
6.62	...	...	45	?	80	390
6.66	...	...	25	3	100	300
6.70	...	...	0	0	440	460
6.78	...	...	25	3	400	460; 1490 (6.78 and 6.80 together)
6.80	...	...	0	0	900	
6.87	...	...	42	>5	330	1240
6.94	...	...	17	1(2)	160	330
6.99	...	...	0	0	300	610 (both 6.99 rows together)
6.99	...	...	25	2,3	230	
7.06	...	...	10	1	2000	3000
7.13	...	...	0	0	1100	1100
7.17	...	...	22	2(3)	160	370
7.22	...	...	0	0	1040	1150
7.29[e]	...	...	0	0	910	1100
7.38	...	...	~23	2(3)	170	550
7.42[e]	...	...	25	...	260	820
7.48	...	...	0.30	?	160	690
7.58	...	...	23	2,3	~100	320
7.63	...	...	27	3	230	580
7.67	...	...	~25	?	130	420
7.72	...	...	0	?	870	1520
7.78[d]	...	...	22	2,3	500	1093
7.84	...	...	20	2	370	800
7.87	...	...	20	?	190	790
8.05	...	...	20	2	320	910
8.12	...	...	25	?	340	1060
8.24	...	...	0	?	350	1040

[a] Reference 4.
[b] Where angular distributions have two nearly equal maxima, both are listed.
[c] For cases where angular distributions are peaked at 0°, intensity is given at 5°.
[d] The normalizations of columns (6) and (7) are the same.
[e] Widths indicate that these are unresolved multiplets.

obtained. The over-all energy resolution was about 20 keV; it was not appreciably worse at back angles than at forward angles, which indicates that target thickness was not the controlling factor in energy resolution.

Proton groups corresponding to transitions to various states of the final nucleus (Fe^{56}) were identified, and the excitation energies of the final states are listed in Table I. Only those states are included in Table I whose corresponding proton groups were clearly identified at more than half of the angles studied.

Energy levels of Fe^{56} known from (p,p') and (p,α) reaction[4] studies are listed in Table I. In general, the correspondence between them and the energies determined here is reasonably accurate. There is little difficulty in identifying corresponding levels up to about 5.8 MeV. Above that energy, levels in the (p,p') experiment come at such close energy intervals that the correspondence can no longer be made, so that data above 5.8 MeV from Ref. 4 are not included.

Angular distributions were obtained for the proton groups leading to all levels shown in Table I. For the cases in which statistics were good enough to be meaningful, the angular distributions are shown in Figs. 1 to 9. A few cases in which statistics were sufficiently good are omitted because the data indicate that the groups are a poorly resolved doublet (this includes doublets at about 2.96, 5.05, 6.10, 6.99, and 7.42 MeV).

The angle at which the angular distribution is peaked and the relative intensity at that peak are also listed in Table I; for angular distributions that are peaked at 0°, the intensity is given at 5° which is the smallest angle at which measurements were made. The final

[4] G. Brown, S. E. Warren, and R. Middleton (to be published).

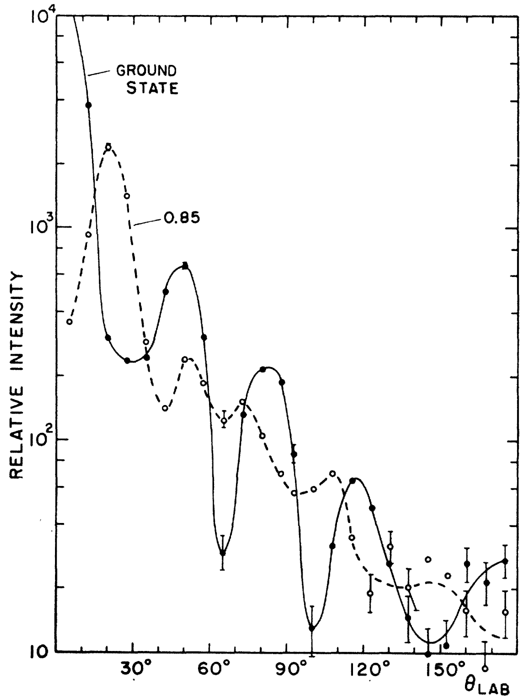


FIG. 1. Angular distributions of protons from $Fe^{54}(t,p)$ reactions leading to ground (0^+) and first excited (2^+) states of Fe^{56}.

column of Table I is the total cross section integrated over the forward hemisphere.

III. ANALYSIS

A. Angular Distributions

As yet there has been little work on distorted-wave Born approximation studies, so that the best tool available for analyzing the angular distributions is the plane-wave Born approximation (PWBA). Experience has shown that it is reasonably valid for predicting the position of the first maximum in the angular distribution for a wide variety of direct reactions.

In PWBA, the angular distribution is given by $j_L(qR)$ where j is the spherical Bessel function, L is the angular momentum transfer, q is the momentum transfer, and R is the radius at which the transfer takes place. The best fit to the data here is obtained with $R=8.1$ F. The fit to the locations of the first maxima in the angular distribution is shown in Table II. The experimental results are from transitions to states of known spin and parity, and hence of known L. The agreement is excellent, so that one is fairly confident in assigning L values to unknown transitions. The angular distributions are grouped according to these assignments in Figs. 2–8.

TABLE II. Angles of first maxima in $j_L(qR)$, and of first maxima in measured angular distributions for transitions of known L. The value of R has been adjusted to obtain the best fit; it is 8.1 F.

L	0	1	2	3	4	5	6
$\theta_{(j_L)}$	0	12°	20°	27°	33°	39°	46°
$\theta_{(\mathrm{Expt})}$	0	···	20°	27°	34°	···	···

The angular distributions assigned as $L=0$ are shown in Fig. 2; they are all characterized by a very strong maximum at 0°. Although in a few cases the similarity ends there, there is generally reasonable regularity

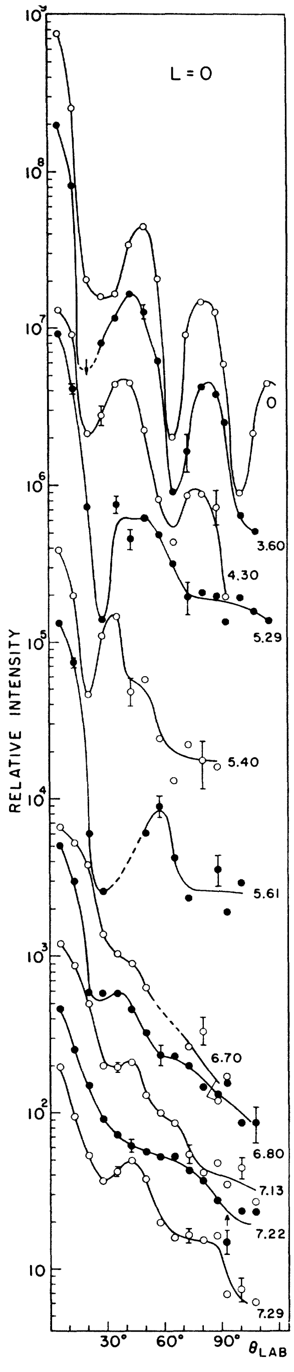


FIG. 2. Angular distributions of protons from $Fe^{54}(t,p)$ reactions which are classed as $L=0$ transitions. Numbers are excitation energies of final states in MeV. Error bars are standard deviations due to counting statistics. The ground state was previously known to be 0^+.

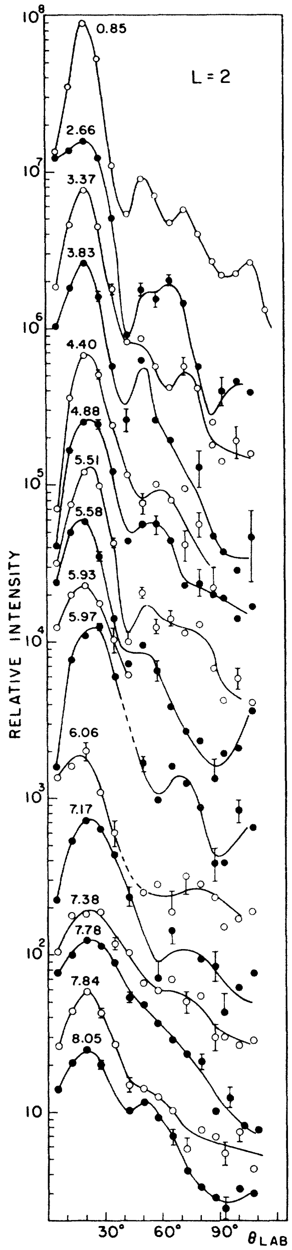


FIG. 3. Angular distributions of protons from $Fe^{54}(t,p)$ reactions which are classed as $L=2$ transitions. Numbers are excitation energies of final states in MeV. Error bars are standard deviations due to counting statistics. The 0.85- and 2.66-MeV states were previously known to be 2^+.

about the first minimum and the second maximum (if it is assumed to be split in two for the 5.29- and 5.40-MeV states); and for the three states below 5 MeV, there is a strong similarity out to at least 90°.

For the angular distributions assigned as $L=2$, shown in Fig. 3, there is again a reasonable similarity up to the second maximum for most cases. The dissimilarity between the 0.85- and 2.66-MeV cases, both of which are known to be $L=2$, is about as bad as the dissimilarity between either and the worst of the unknown cases; this gives one confidence that the detailed differences may be ignored in assigning L values. There is further evidence for this in Fig. 4 which shows

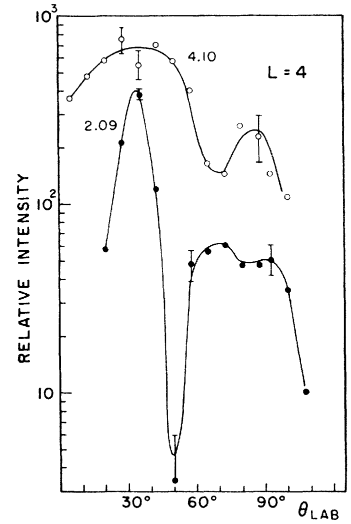


FIG. 4. Angular distributions of protons from $Fe^{54}(t,p)$ reactions which are classed as $L=4$ transitions. Numbers are excitation energies of final states in MeV. Error bars are standard deviations due to counting statistics. Both the 2.09- and 4.10-MeV states were previously known to be 4^+.

angular distributions for the two cases known to be $L=4$. While they are both peaked at the same angle—about 34°—they are strikingly dissimilar in the widths of the peak.

Cases assigned as $L=3$ are shown in Fig. 5. These include a few angular distributions also shown in Fig. 3, since there is some doubt as to whether they are $L=2$ or $L=3$. In all unknown cases, the first peak occurs at a smaller angle than for the known $L=3$ at 4.51 MeV, and the regularities at larger angles are rather dubious at best.

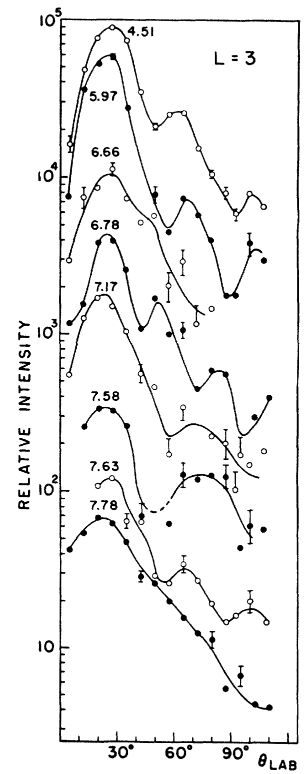


FIG. 5. Angular distributions of protons from $Fe^{54}(t,p)$ reactions which are classed as $L=3$ transitions. Numbers are excitation energies of final states in MeV. Error bars are standard deviations due to counting statistics. The 4.51-MeV state was previously known to be 3^-.

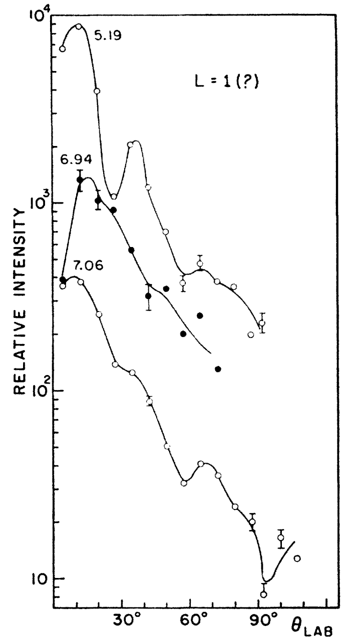


FIG. 6. Angular distributions of protons from $Fe^{54}(t,p)$ reactions which are classed as $L=1$ transitions. Numbers are excitation energies of final states in MeV. Error bars are standard deviations due to counting statistics. None of these states had previously known spins or parities.

Figure 6 shows the three angular distributions assigned as $L=1$ on the basis of Table II. This includes two very high intensity cases at 5.19 and 7.06 MeV. There is a reasonably strong similarity between these two angular distributions at all angles. The assignment of the 6.94-MeV level is rather uncertain.

In Fig. 7 are shown the three cases assigned as $L>4$. At the top of the figure are shown the locations of the first maxima in the angular distribution for $L=0$ to 4. From their systematic regularity, one is strongly

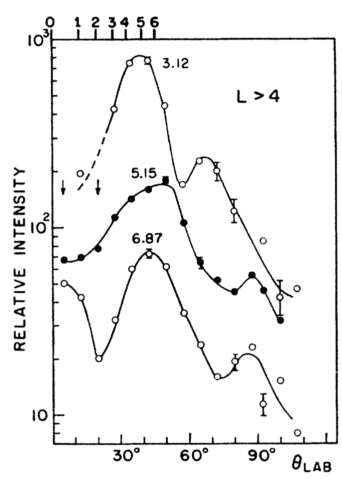


FIG. 7. Angular distributions of protons from $Fe^{54}(t,p)$ reactions which are classed as $L>4$ transitions. Numbers are excitation energies of final states in MeV. Error bars are standard deviations due to counting statistics. None of these states had previously known spins or parities, although the 3.12-MeV state had been incorrectly assigned (see text). Lines and figures at the top are locations of first maxima in angular distributions for corresponding L-values according to the plane wave Born approximation (cf. Table II).

tempted to conclude that the 3.12-MeV state is 5^- (i.e., $L=5$), and that the 5.15-MeV case is $L=6$ or 7. The 6.87-MeV transition has a rise in the forward direction which might be explained as due to a weak $L=0$ state at nearly the same energy. On the other hand, there is no apparent shift in the energy with angle, so that if there is a doublet, the spacing must be no more than about 10 keV.

Cases where the angular distributions are too unusual to allow L-assignments with any degree of confidence are shown in Fig. 8. The states included here below 7

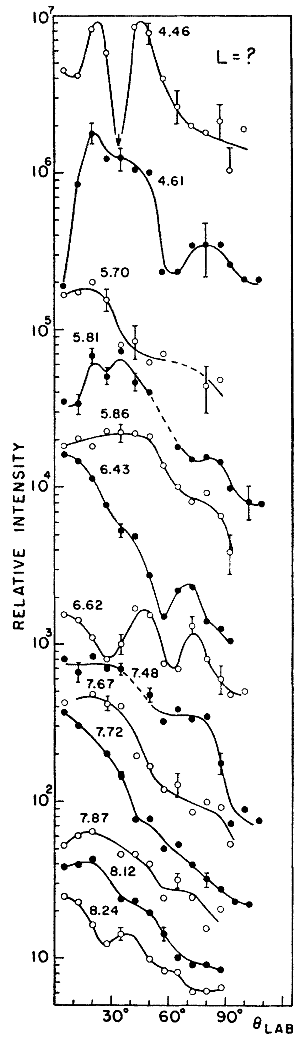


FIG. 8. Angular distributions of proton groups from $Fe^{54}(t,p)$ reactions for which no L classification can be made. Some of these may be unresolved multiplets. Numbers are excitation energies of final states in MeV. Error bars are standard deviations due to counting statistics.

MeV are all rather weakly excited; weak transitions might proceed by reaction mechanisms other than two-neutron stripping. The higher energy states may well be unresolved multiplets, but the whole situation at high excitation is far from clear. Even cases in this region that have been assigned definite L values have angular distributions that are not too similar beyond the first maximum to those for the same L value at lower energy.

B. Unnatural Parity States

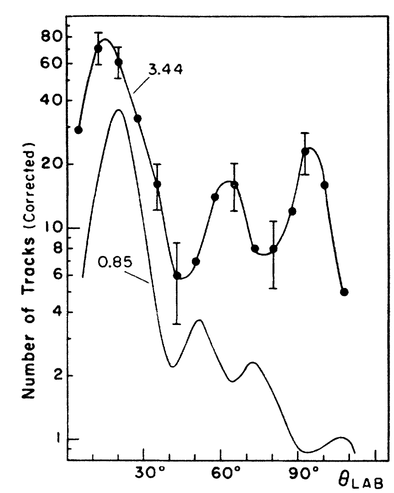
Perhaps the simplest feature of a (t,p) reaction on an even-even (0^+) target proceeding by two neutron transfer is that only "natural parity" states should be excited, provided that the interaction is not strongly spin dependent. This is due to the fact that the two neutrons in the triton are very predominantly in a singlet S state, so that the transferred angular momentum and parity are determined exclusively by the orbital angular momentum L with which the two neutrons enter the nucleus. Thus the angular momentum and parity of the final state are L and $(-1)^L$, respectively, whence states of angular momentum I and parity $(-1)^{I+1}$ cannot be excited. These latter are the so called "unnatural parity" states, 0^-, 1^+, 2^-, 3^+, $\cdots$.

There are three known states of unnatural parity in Fe^{56}—a 1^+-3^+ doublet at 3.44 MeV, and a 3^+ state at about 3.86 MeV. The 3.86-MeV state was not detected, although the sensitivity is not good because of the proximity to the 3.83-MeV state which is rather strongly excited. The 3.44-MeV state is nearly the most weakly excited state listed in Table I. Its angular distribution, shown in Fig. 9, is not similar to any of the others; it is peaked midway between the expected peaks for $L=1$ and $L=2$, and the relative intensity at large angles is considerably greater than usual. A transfer of two neutrons in a triplet state could be due to components of that type in the triton wave function, or to a spin dependence in the interaction. In either case, a comparison of the excitation probability for the 3.44-MeV state with that of neighboring states suggests that such effects have only a few percent of the probability of the normal transfer process.

C. Relative Intensities

It has often been pointed out[2] that coherence effects play an important role in determining transition rates in (t,p) reactions. Yoshida,[2] using the quasiparticle formalism, showed that the cross section for exciting

FIG. 9. Angular distribution of protons leading to 3.44-MeV state which is believed to be an unnatural parity (3^+, 1^+) doublet. The $L=2$ angular distribution for the 0.85-MeV state is shown for comparison.



the ground state is

$$\frac{d\sigma}{d\Omega}(G) \propto |\sum_j (j+\tfrac{1}{2})U_jV_j|^2, \qquad (1)$$

and for exciting collective 2^l-pole vibrational states is

$$\frac{d\sigma}{d\Omega}(\text{vib-}l) \propto \left|\sum_{j_1j_2} U_{j_1}U_{j_2}(U_{j_1}V_{j_2}+V_{j_1}U_{j_2})\frac{M_{j_1j_2}{}^2}{E_{j_1}+E_{j_2}-\hbar\omega_l}\right|^2, \qquad (2)$$

where U_j and V_j are the emptiness and fullness of the single-particle state j, j_1, and j_2 are any two single-particle states that can be coupled to give the collective state of angular momentum l and parity $(-1)^l$, E_{j_1} and E_{j_2} are their single quasiparticle energies, and $M_{j_1j_2}$ is a matrix element connecting them. Both of these expressions are the squares of sums of terms all having the same sign, so that large cross sections are expected.

The most strongly excited states, with their relative cross sections, are listed in Table III. This list includes

TABLE III. Most strongly excited states in $Fe^{54}(t,p)Fe^{56}$ reactions, and their relative total cross sections (integrated over the forward hemisphere).

Excitation energy (MeV)	4.51	0	7.06	0.85	5.15	5.19
I^π	3^-	0^+	1^-	2^+	$6^+,7^-$	1^+
Relative cross section	55	38	30	27	23	20

the ground state and the collective 2^+ and 3^- vbirational states, as expected from the above discussion. This would suggest that some of the other states listed there might have collective properties. This would not be too difficult to accept for the 6^+ or 7^- state at 5.15 MeV, but this explanation does not seem possible for the 1^- states at 7.06 and 5.19 MeV, as no 1^- collective states are expected from present theories in this energy region. One expects several 1^- states above 8 or 9 MeV from $p_{3/2}d_{5/2}$ and other combinations of p or f with s or d neutrons (cf. Sec. E), but it is difficult to explain how such states could be lowered as far down as 5.19 MeV without the help of collective effects.

The fact that the 3^- collective state is the most strongly excited state in the spectrum is perhaps the most unexpected feature of these results. According to Eq. (2), either state j_1 or state j_2 must be partly full—i.e., for it, U_jV_j must be different from zero. Since Fe^{54} has an essentially closed shell of 28 neutrons, U_jV_j should be close to zero for all states. Another way of expressing this difficulty is that the 3^- state is understood to be composed of particle-hole pairs, whereas a (t,p) reaction excites two particle states. Thus, to qualify on both counts, a single particle state must have both particles and holes, a situation that does not occur for a closed-shell nucleus.

D. Level Structure of Fe^{56}

The known levels of Fe^{56} up to 4.4 MeV are listed in Table IV. Except where noted below, the previous assignments are from decay-scheme studies[5] of Mn^{56} and Co^{56}. For the six states below 3 MeV, there is perfect agreement with this experiment. At 3.12 MeV, we find a 5^- (or 6^+) state, whereas previously assigned levels are 3^- (from inelastic electrons scattering[6] and the fact that it gamma decays predominantly to the 0.85-MeV 2^+ state), and 5^+. The 5^+ assignment is based on the assumption that it is fed by an allowed beta decay from $Co^{56}(4^+)$ and that it gamma decays only to the 2.08-MeV 4^+ state. However, the evidence that the beta decay is allowed is only that its log*ft* value, 7.3, is smaller than log*ft* for the allowed transition to the 2.08-MeV 4^+ state (8.7). This would seem to be rather weak evidence, and a log*ft* value of 7.3 could very well correspond to a first-forbidden transition; indeed it is much closer to the average for these than to the average for allowed transitions. Thus, the assignment could just as well be 5^-, which would be in agreement with our assignment. Our possible 6^+ assignment is excluded as this would require a second-forbidded beta decay.

The assignments for the 3.368-MeV state are in agreement. There is no evidence here for the 3.388-MeV state; it is believed to be of high spin because it is strongly excited in (p,α) reactions[4] where a $(2I+1)$ intensity rule is operative. The 1^+-3^+ doublet at 3.44 MeV has been discussed in Sec. B.

The decay scheme studies indicate that a state at 3.60 MeV decays by gamma emission to the 0^+ ground state; this would exclude a 0^+ assignment. In the (t,p) experiments, however, an $L=0$ transition is found at this energy. This dilemma was resolved by Shapiro, Hinrichsen, Middleton, and Mohindra[7], who in a very high energy resolution study with (p,p'), found this level to be a doublet; there is some evidence from this work that it may even be a triplet.

The ambiguity in the previous assignments for the 3.83-MeV state seems to be resolved in this work; the state is 2^+. The 3.86-MeV state is not noticeably excited in (t,p) as expected from its unnatural parity. The 4.05-MeV state is so weakly excited in (t,p) that no clear conclusions about its assignment can be reached.

At least one member of the 4.10-MeV doublet is known to be 4^+ from angular-correlation work; this is confirmed by the (t,p) results. The other may be either 3^+ or 4^+.

At both 4.296 and 4.392 MeV, the decay scheme work indicates 4^+ or 3^+ states, whereas the (t,p) angular distributions indicate 0^+ and 2^+ states, respectively. The only ready explanation for this discrepancy is that these states are both doublets. In view of the large number of doublets already known in Fe^{56}, this explanation is not difficult to accept.

TABLE IV. Spin-parity assignments for levels in Fe^{56}.

Excitation energy (MeV)	Spin and parity Previous	This expt.
0	0^+	0^+
0.845	2^+	2^+
2.085	4^+	4^+
2.659	2^+	2^+
2.942	0^+	0^+
2.960	2^+	2^+
3.119	3^-	...
3.122	5^+	5^-
3.368	2^+	2^+
3.388	6^+(?)	...
3.445	$3^+(1^\pm)$	not 1^-
3.450	$1^\pm$	not 1^-
3.601	...	0^+
3.607	$2^+,1^\pm$	...
3.754	...	...
3.833	$2^+, 1^\pm$	2^+
3.858	3^+	...
4.046	$4^+,3^+$	...
4.099	$4^+,3^+$ } 4^+	4^+
4.116	$4^+,3^+$	
4.296	$4^+,3^+$	0^+
4.392	$4^+,3^+$	2^+
4.459	...	...
4.510	3^+	3^+

E. Shell-Model Considerations

The low-lying shell-model configurations of Fe^{56} can be considered as states of Fe^{54} plus two nuetrons in the $p_{3/2}$, $f_{5/2}$, $p_{1/2}$, and $g_{9/2}$ single-particle states. From a knowledge of the single-particle energies of these states and the energies of the states of Fe^{54} we can easily calculate the zeroth-order energies of the various configurations of Fe^{56}. The actual states of Fe^{56} are mixtures of these configurations. In most cases we may assume that only configurations of about the same energy mix strongly, and the mixture gives states at about that energy. Thus a listing of the spins and parities of configurations in a given energy region serves as a guide to the spins and parities of states expected in that region.

There are some very important exceptions to the above generalization. The most notable one is the 0^+ ground state of Fe^{56} which is lowered because of "pairing" interactions by about 3 MeV—this is the odd-even mass difference—below the energy of the lowest configuration. Thus, excitation energies of states in Fe^{56} are generally about 3 MeV higher than the energies of their configurations. The one- and two-phonon vibrational states are also lowered into the energy gap,

[5] P. Kienle and R. E. Segel, Phys. Rev. **114**, 1554 (1959). V. R. MacDonald and M. Grace (private communication).

[6] Ballicard and Barieau, Nucl. Phys. **36**, 476 (1962).

[7] R. Middleton (unpublished).

and in general, collective states lie considerably lower than the lowest configuration of which they are composed.

In order to apply these ideas quantitatively, we must start with the energies of the single-particle neutron states. Unfortunately, the situation here is somewhat clouded by the strong intermixing of $p_{3/2}$ and $p_{1/2}$ states in the spectrum of the single-particle nucleus, Fe^{55}. However, a reasonably accurate estimate of the single-particle energies is

$$p_{3/2}=0\,,$$
$$f_{5/2}=0.5\text{ MeV}\,,$$
$$p_{1/2}=2.0\text{ MeV}\,,$$
$$g_{9/2}=3.0\text{ MeV}\,.$$

The excited states of Fe^{54} are the 2^+ state at 1.5 MeV, and then several even-parity states at about 2.5 MeV. The various configurations and their zeroth-order energies are listed in Table V.

The $Fe^{54}(t,p)$ reaction should excite only the configurations listed in Table V which are of the form $Fe^{54}(0^+)+2$ neutrons, and which are of natural parity. It should therefore only excite states containing these configurations. Up to 5.0 MeV, this includes only 0^+, 2^+, and 4^+ states. Of the 19 experimentally observed states listed in Table I, 14 are either 0^+, 2^+, or 4^+, and three are unassigned. The remaining two exceptions are the 3.12-MeV 5^- and the 4.51-MeV 3^- states. According to Table V, no negative-parity states are expected below 6.0 MeV; this conclusion does not even depend on the assumption tacitly made above that the $f_{7/2}$ neutron state is full in Fe^{54}. The only known explanation for these 5^- and 3^- states lying nearly 3.0 and 1.5 MeV, respectively, below the zeroth-order energy of their lowest configuration is that they are strongly collective. This, of course, is well known to be the case for the 4.51-MeV 3^- state, but such a strongly collective

TABLE V. Configurations of Fe^{56}.

Configuration	I^π	Configuration energy (MeV)	Excitation energy in Fe^{56} (MeV)
$Fe^{54}(0+)+p_{3/2}{}^2$	$0^+,2^+$	0	3.0
$Fe^{54}(0+)+p_{3/2}f_{5/2}$	$1^+,2^+,3^+,4^+$	0.5	3.5
$Fe^{54}(0+)+f_{5/2}{}^2$	$0^+,2^+,4^+$	1.0	4.0
$Fe^{54}(2+)+p_{3/2}{}^2$	$2^+,0^+,1^+,2^+,3^+,4^+$	1.5	4.5
$Fe^{54}(0+)+p_{1/2}p_{3/2}$	$1^+,2^+$	2.0	5.0
$Fe^{54}(2+)+p_{3/2}f_{5/2}$	$1^+,2^+,3^+;\ 0^+,1^+,2^+,3^+,4^+$ $1^+,2^+,3^+,4^+,5^+$ $2^+,3^+,4^+,5^+,6^+$	2.0	5.0
$Fe^{54}(0+)+p_{1/2}f_{5/2}$	$2^+,3^+$	2.5	5.5
$Fe^{54}(2+)+f_{5/2}{}^2$	$2^+,0^+,1^+,2^+,3^+,4^+$ $2^+,3^+,4^+,5^+,6^+$	2.5	5.5
Numerous positive parity states built on 2.5-MeV states of Fe^{54}		2.5	5.5
$Fe^{54}(0+)+p_{3/2}g_{9/2}$	$3^-,4^-,5^-,6^-$	3.0	6.0

5^- state is not expected. This state may be difficult to explain theoretically. The same difficulty would be encountered in explaining the 3^- state at 3.12 MeV; that assignment, based on inelastic electron scattering,[6] is perhaps open to some question. It might well be that the (e,e') experiment excited the 5^- state.

According to Table V, one might expect to find, below about 4.5-MeV excitation the following numbers of states: three 0^+, two 1^+, five 2^+, two 3^+, and three 4^+ states. Among the experimentally assigned states there are four 0^+, one or two 1^+, five or six 2^+, two to six 3^+, and two to six 4^+ states. The extra states could be explained as two- and three-phonon vibrational states or as states from slightly higher energy in Table V. In any case the agreement is as good as can be expected from such crude considerations. The possible 6^+ state at 3.388 MeV could be explained as a three-phonon vibrational state.

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