COO-535-593

STUDY OF THE EFFECTIVE TWO-BODY FORCE USING THE $^{54}Fe(^{3}He,t)$ CHARGE EXCHANGE REACTION*

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COO-535-593 UNCLAS STUDY OF THE EFFECTIVE TWO-BODY FORCE USING THE Fe-54 He-3,t) CHARGE EXCHANGE REACTION. Hayakawa, S. I.; Kraushaar, J. J.; Kunz, P. D.; Rost, E. (Colorado Univ., Boulder. Dept. of Physics and .... 1969. 13p. 34-4 UNLTD DIST

Differential cross sections were measured for the $^{54}Fe(^{3}He,t)^{54}Co$ reaction at 37.5 MeV. The T=1 states are well described using a conventional microscopic DWBA analysis with $(f_{7/2})^{-2}$ orbitals but similar analysis of the T=0 states indicates a serious discrepancy between theory and experiment.

* Work supported in part by the U. S. Atomic Energy Commission.

The angular distributions of charge exchange reactions, such as (p,n) and (^{3}He,t) in the medium-energy region, often show the forward-peaked, diffraction-like structure characteristic of a direct reaction mechanism. The analogue states are prominent in the excitation spectra of the target [1-3]; however, states of lower isospin are also observable and several studies of these have been undertaken [4-9]. The data may be analyzed in terms of a microscopic model framework [10,11] which is a generalization of a technique used for the study of direct inelastic scattering reactions. In this framework the reaction is treated in the distorted wave Born approximation (DWBA) assuming an effective two-body transition matrix between target nucleon k and projectile nucleon p of form

$$t_{kp} = \vec{\tau}_k \cdot \vec{\tau}_p \left(V_\tau + V_{\sigma\tau} \vec{\sigma}_k \cdot \vec{\sigma}_p \right) g\left(|\vec{r}_k - \vec{r}_p|\right) . \qquad (1)$$

The matrix element of the effective interaction, $V_{eff} = \sum_{kp} t_{kp}$, is then taken between product nucleus-projectile wave functions in initial and final states. Differential cross sections are then readily obtainable [10] and may be evaluated numerically using standard DWBA computer programs [12].

The microscopic model outlined above can be used to investigate the effective interaction, Eq. (1), if the nuclear wave functions are known [13]. This has been attempted using the $^{18}O(p,n)^{18}F$ reaction [4], the $^{14}C(p,n)^{14}N$ reaction [5], and recently with the $^{17,18}O(^3He,t)^{17,18}F$ reactions [7]. The results have been satisfactory for the T=1 analogue states; in particular, the $0^+ \rightarrow 0^+$ transitions permit only the V_τ term in (1) and consistent extractions of the strength are obtained from the different reactions. On the other hand, transitions to the T=0, J=$1^+, 3^+ \cdots$ states require the Gamow-Teller $V_{\sigma\tau}$ term and the agreement between theory and experiment is poor in these cases with order-of magnitude discrepancies between $V_{\sigma\tau}$ strengths extracted from different states.

In this note we report the measurement of $^{54}Fe(^{3}He,t)^{54}Co$ cross sections at 37 MeV incident energy for several low-lying T=0 and T=1 levels in ^{54}Co. This reaction has two advantages over the ones mentioned above; 1, the nuclear states involved are well-described by a single $(f_{7/2})^{-2}$ configuration [14] thus simplifying the analysis and 2, the nuclei are heavy enough so that DWBA calculations are more reliable. The latter statement is justified by study of antisymmetrization effects (e.g. knockout), stability of optical model parameters, and experience in applying DWBA inelastic-scattering calculations to light and medium-heavy nuclei [15]. It will be shown that the aforementioned problems do <u>not</u> go away and that the $V_{\sigma\tau}(\vec{\tau}_k\cdot\vec{\tau}_p)(\vec{\sigma}_k\cdot\vec{\sigma}_p)$ term cannot explain either the angular distribution or the strength of the odd-angular momentum transitions.

The experiment used 37.5 MeV ^{3}He ions extracted from the University of Colorado cyclotron [16]. The target was an isotopically pure self-supporting ^{54}Fe foil with a thickness of 1.07 mg/cm^2. Particle identification was accomplished by using a counter telescope consisting of a 171μ ΔE silicon surface-barrier detector and a 4700μ E-ΔE lithium-drifted silicon detector in conjunction with an ORTEC mass identifier and conventional electronics. The overall energy resolution was 100 to 120 keV FWHM. A typical triton spectrum is shown in Fig. 1. The spin assignments were tentatively taken from the work of Schwartz <u>et al</u>. [17] and are indicated on the figure for the states to be discussed here. The levels at 1.82 and 2.10 MeV were seen as doublets in the Scwartz <u>et al</u>. high-resolution experiments and our probable spin assignment is that of the dominant member of the doublet. Another 2^+ level, the analogue of the 2.96 MeV 2^+ level on ^{54}Fe is also seen in the spectrum. However, our spectrum indicates too many unresolved levels in the vicinity to justify analysis of this transition.

In the microscopic description of the $(^{3}He,t)$ reaction the description of the process is contained in the transition amplitude.

$$T_{fi} = \int \chi_f^{(-)}(\vec{r}) \langle \phi_f \psi(t) | V_{eff} | \psi(He) \phi_i \rangle \chi_i^{(+)}(\vec{r}) \, d\vec{r} \qquad (2)$$

where $\chi_i^{(+)}$ and $\chi_f^{(-)}$ are distorted waves describing the initial and final states of relative motion and the intrinsic states of the projectiles and nuclei are denoted by ψ and ϕ in an obvious notation. The operator V_{eff} is the sum of two-body t_{kp} elements in Eq. (1). By assuming simple relative S-state functions for ^{3}He and t, Madsen has shown [10] that

$$\langle \psi(t) | V_{eff} | \psi(He) \rangle \doteq \sum_k t_k \; ,$$
$$t_k = \vec{\tau}_k \cdot \vec{\tau} \, (V_\tau' + V_{\sigma\tau}' \, \vec{\sigma}_k \cdot \vec{\sigma}) \, g(|\vec{r}_k - \vec{r}|) \qquad (3)$$

with g(r) having essentially the same functional form as in Eq. (1) (taken to be of Yukawa form with range 1F) and $V' \approx 1.25$ V. The unsubscripted $\vec{\tau}$, $\vec{\sigma}$ and $\vec{r}$ variables now refer to the center of mass of the projectile. The optical model parameters needed to calculate the distorted waves were determined from the study of ^{3}He scattering on the Ni isotopes [3]. The parameters in the notation of reference 3 are:

V = 170.6 MeV	W = 18.5 MeV
r_o = 1.143 F	r_o' = 1.599 F
a = 0.721 F	a' = 0.829 F.

Identical parameters were used for the outgoing triton channel although better (^{3}He, t) angular distributions can be obtained by modifying the triton well [3]. No cutoffs or other non-locality modifications were employed although these can also improve the fits to the data.

The nuclear states in Eq. (2) take an especially simple form assuming the $(f_{7/2})^{-2}$ configuration assignment. In this case, the target ^{54}Fe nucleus has I=0, T=1, and the final ^{54}Co nuclear states are restricted to even I for T=1 and odd I for T=0. Thus the former states are connected only by the $V_\tau'(\vec{\tau}_k \cdot \vec{\tau})$ term in [3] while the others involve the $V_\tau'(\vec{\tau}_k \cdot \vec{\tau})(\vec{\sigma}_k \cdot \vec{\sigma})$ term and must proceed with spin flip.

Thus the selection rules are

$$J=I=L \qquad \text{for even } I,\ T=1$$
$$J=I=L \pm 1 \qquad \text{for odd } I,\ T=0, \tag{4}$$

where L, J are the orbital and total angular momentum transfer quantum numbers arising in the angular momentum decomposition of Eq. (3). The matrix element $\langle \phi_f | \Sigma_k t_k | \phi_i \rangle$ is then trivially factored into a radial and an angular part and the cross sections are obtained using standard techniques [19]. It is instructive to consider the reduced matrix elements [20] of the L, J component of $\Sigma_k \tau_k$ taken over the spin-angle coordinates of the target nucleons

$$\mathcal{M}_{LJ} \equiv \begin{matrix} \langle (f_{7/2})^{-2}, I=J=L \,\|\, Y^L \,\|\, (f_{7/2})^{-2}, 0 \rangle \\ \langle (f_{7/2})^{-2}, I=J=L\pm 1 \,\|\, (Y^L\sigma')^J \,\|\, (f_{7/2})^{-2}, 0 \rangle . \end{matrix} \tag{5}$$

The cross sections are proportional to $|\mathcal{M}_{LJ}|^2$, the values of which are given in Table 1. These values give the dominant cross section dependence on L and J (the integration over projectile coordinates and radial integrals yield only a weak dependence on L, J). The striking feature in Table 1 is the large preference for L=J-1 over L=J+1 for spin-flip transitions with odd J. Thus in the incoherent sum over L the term with the higher L gives negligible contribution to the (^{3}He, t) cross section.

The comparison of the microscopic model predictions with the experimental data is given in Fig. 2. The transitions to T=1 states in ^{54}Co in Fig. 2a are reasonably well described, the low value of V_τ' for the 4^+ state being explained by difficulties in resolving the state and possibly also by fragmentation of the analogue 4^+ level. The extracted value for V_τ' is in reasonable agreement with the V_τ'=52 MeV value extracted for the ^{18}O(^{3}He, t) transitions. The T=0 transitions, on the other hand, are not in agreement. The microscopic model predicts the angular distribution being given essentially by the <u>lower</u> L value, but the data are better fitted with the <u>higher</u> L value for a given J transition. Also, the normalization is unsatisfactory, viz. Hansen <u>et al</u>. [7] in their (^{3}He, t) work find $V_{\sigma\tau}' \approx 3/4 V_\tau'$ whereas we need

$V'_{\sigma\tau} \approx 2V'_{\tau}$. If the value $V'_{\sigma\tau}$=35 MeV given by Hansen et al. [7] is used, the data are under-predicted by an order of magnitude.

It is clear that a serious disagreement exists in applying the microscopic model for (^{3}He,t) transitions to non-analogue spin-flip transitions. This cannot be due to inadequacies in the nuclear $(f_{7/2})^{-2}$ configuration assignment; it is probably also not due to knockout or other exchange type mechanisms which might dominate for light nuclei. Possible suggestions are:

1) The effective interaction requires tensor terms in Eq. (3).

2) The reaction process assumed in Eq. (2) is insufficient.

The tensor terms could arise on the two-body interactions, Eq. (1), or in the overlap in Eq. (3). In the latter case, the ^{54}Fe(p,n)^{54}Co reactions should agree with microscopic model predictions. Unfortunately, the fact that cross sections are underpredicted suggests to us the failure of the simple one-step reaction assumption in the DWBA analysis of non-analogue spin-flip (^{3}He,t) scattering. However, it may be possible to describe such effects phenomenologically using "core-polarization" effects as in recent microscopic inelastic scatterin analyses [11]. In order to agree with the experimental results such terms must be important for the non-analogue charge-exchange reactions.

We acknowledge valuable conversations with H. H. Duhm and wish to thank W. Fadner for help in taking the data.

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20. The Racah definition of reduced matrix elements is employed, i.e.

$$\langle jm | T_Q^k | j'm' \rangle = (-1)^{2k} (2k+1)^{-\frac{1}{2}} (j'k\, m'Q | jm) (j \| T^k \| j').$$

Table 1

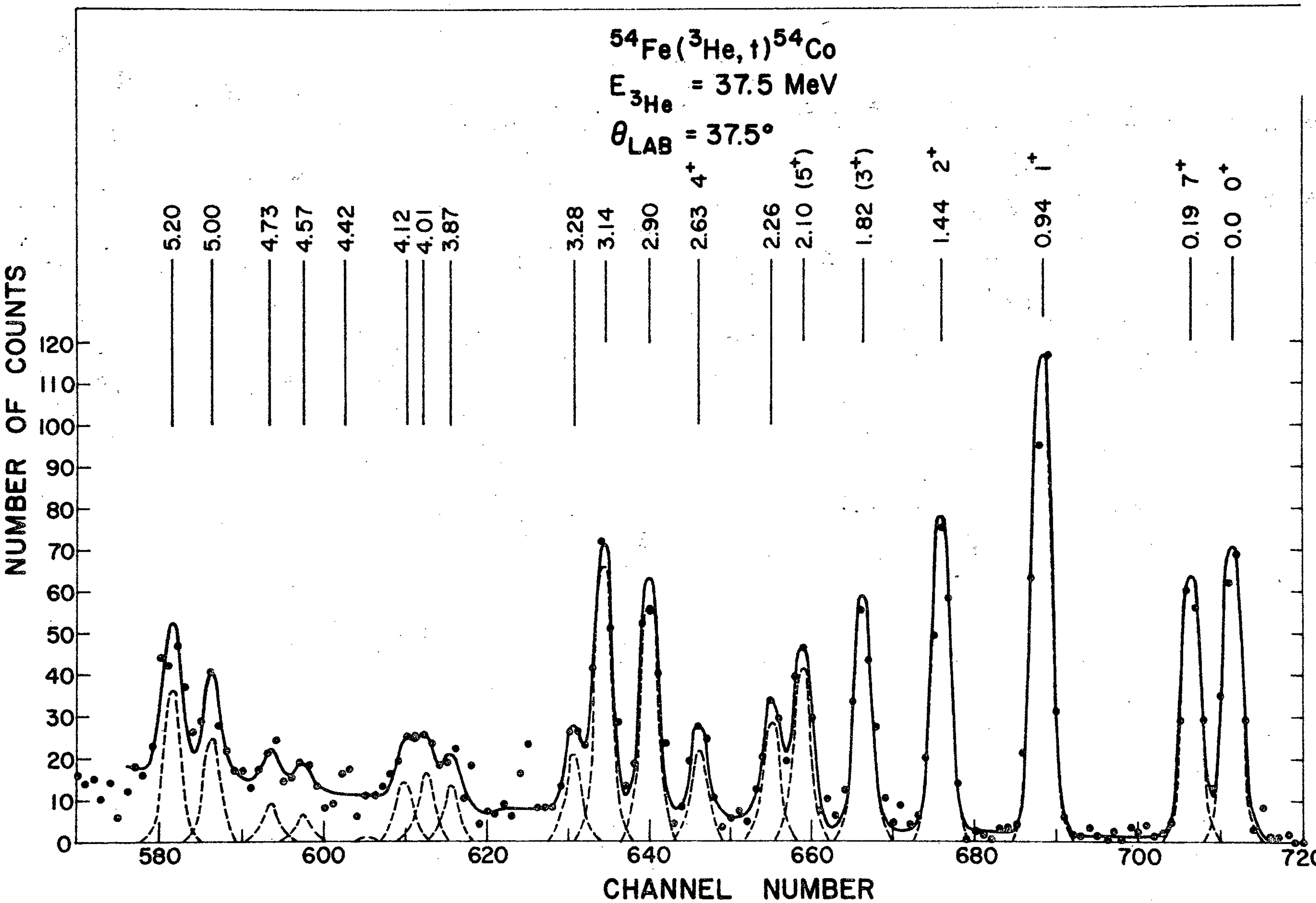
Squares of reduced matrix elements of the two-body interaction taken over nuclear spin-angle coordinates. See Eq. (5) of text.

L	J	$4\pi\lvert\mathcal{M}_{LJ}\rvert^2$
0	0	1.000
2	2	1.191
4	4	1.052
0	1	1.286
2	1	0.286
2	3	1.571
4	3	0.156
4	5	2.532
6	5	0.050
6	7	6.119

Figure Captions

Fig. 1 Spectrum of tritons at 37.5° due to the $^{54}Fe(^{3}He,t)^{54}Co$ reaction with 37.5 MeV incident ^{3}He ions. Spin assignments for low-lying levels are taken from reference 17 and are indicated for those levels whose cross sections are studied. The dotted lines are the result of a least-squares Gaussian fitting program [18] for each peak; the solid line denotes the sum of the other peaks fitted to the data.

Fig. 2 Differential cross sections for the $^{54}Fe(^{3}He,t)^{54}Co$ reaction. The solid curves are microscopic-model DWBA fits to the data with $V'_{\sigma\tau}$ or V'_{τ} strengths. The fits in Fig. (2b) are presented assuming a single L value; however, the microscopic model prediction is essentially the same as that with the lower L value.



54Fe(3He, t)54Co
E3He = 37.5 MeV
θLAB = 37.5°
5.20
5.00
4.73
4.57
4.42
4.12
4.01
3.87
3.28
3.14
2.90
2.63 4+
2.26
2.10 (5+)
1.82 (3+)
1.44 2+
0.94 1+
0.19 7+
0.0 0+
NUMBER OF COUNTS
CHANNEL NUMBER

Fig. 1

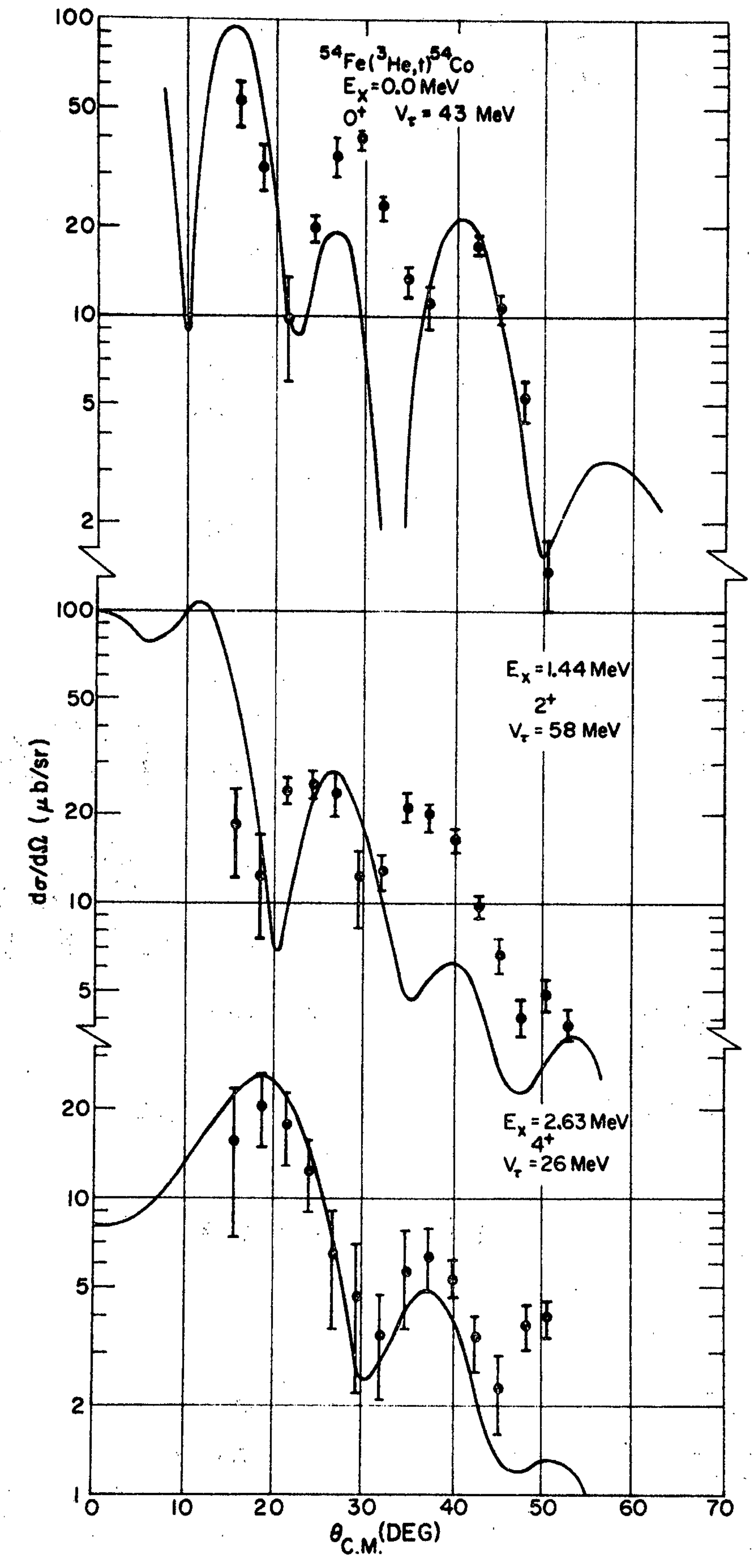
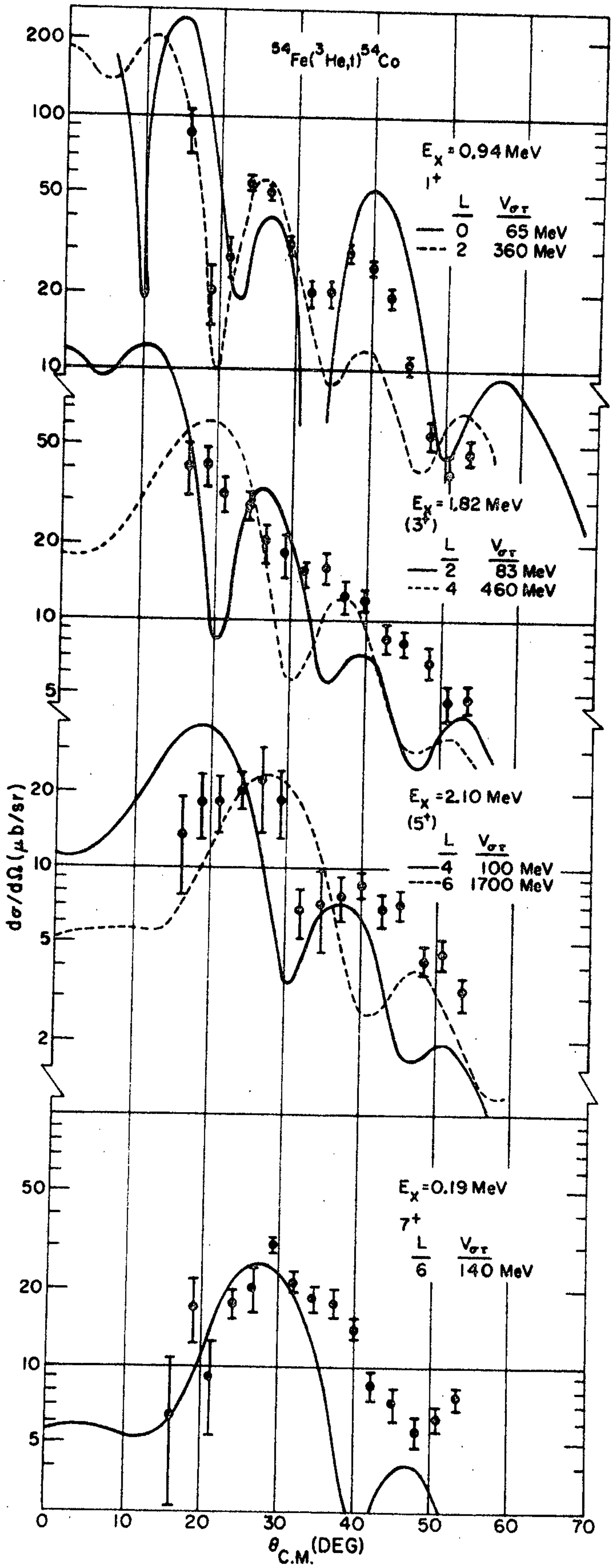

$^{54}Fe(^3He,t)^{54}Co$
E_X = 0.0 MeV
0^+ V_τ = 43 MeV
E_X = 1.44 MeV
2^+
V_τ = 58 MeV
E_X = 2.63 MeV
4^+
V_τ = 26 MeV
$d\sigma/d\Omega$ (μb/sr)
$\theta_{C.M.}$(DEG)

Fig. 2a



$^{54}Fe(^3He,t)^{54}Co$
E_x = 0.94 MeV
1+
L V_στ
0 65 MeV
2 360 MeV
E_x = 1.82 MeV
(3+)
L V_στ
2 83 MeV
4 460 MeV
E_x = 2.10 MeV
(5+)
L V_στ
4 100 MeV
6 1700 MeV
E_x = 0.19 MeV
7+
L V_στ
6 140 MeV
dσ/dΩ (μb/sr)
θ_C.M.(DEG)

Fig. 2b