Energy Dependence in (^{3}He, t) Transitions to Isobaric Analog Ground States*

W. L. Fadner and J. J. Kraushaar
Department of Physics and Astrophysics, University of Colorado, Boulder, Colorado 80302

and

S. I. Hayakawa
Foster Radiation Laboratory, McGill University, Montreal, Canada

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Transitions to the isobaric analog ground states of ^{50}Cr, ^{54}Fe, ^{62}Ni, and ^{90}Zr have been studied with the (^{3}He, t) reaction in the energy range of 21.4 to 37.5 MeV. Large variations in the shape of the experimental angular distributions were observed as a function of energy and target nucleus. These effects were poorly described by distorted-wave Born-approximation calculations based on a simplified shell-model theory. Calculations based on a generalized optical model, using different interaction terms for each nucleus, gave a somewhat better description. Interaction strengths, normalized to fit the data, required a significant decrease with increasing energy for both theoretical models. These effects were general, to a large extent independent of the optical-model parameter set used. The poor description, both in shape and in strength, of the energy dependence of the data is evidence of basic inadequacies in the theories as they are presently used.

I. INTRODUCTION

The (^{3}He, t) reaction has recently been used for a variety of nuclear-structure studies. In several of these studies,[1-3] discrepancies between experiments and distorted-wave Born-approximation (DWBA) calculations have been pointed out, particularly for transitions to excited states. A useful tool for an exploration of the adequacy of DWBA theoretical models is quasielastic scattering to isobaric analog ground states (IGS). These are generally strong transitions in which direct processes are expected to dominate.

In previous studies[1,2,4-6] of the (^{3}He, t) reaction on Ti and Ni targets, it was found that the excitation of the IGS was reasonably well described by either a microscopic (simplified shell-model) or a macroscopic (generalized optical-model) DWBA analysis.[7] However, there was substantial disagreement between different studies as to the interaction potential strength extracted from the macroscopic DWBA normalization to the data. Preliminary indications were that this strength might be energy-dependent.[8] Furthermore, studies[5,8] of the IGS of ^{48}Ca, ^{54}Fe, and ^{90}Zr showed that the shapes of the (^{3}He, t) experimental angular distributions for these nuclei did not follow the typical diffraction patterns predicted by DWBA calculations. The few available comparisons[5,8] of data taken with the same targets at different energies suggested that the shape effect might also be energy-dependent.

In order to investigate the energy dependence of the interaction potential strength as well as that of the angular-distribution shape, data for the targets ^{50}Cr, ^{54}Fe, ^{62}Ni, and ^{90}Zr at incident energies from 21.4 to 37.5 MeV were obtained. Some of the data have been previously reported.[5,8-10] The data for the ^{54}Fe target at 30.2 MeV were obtained from a paper by Bruge *et al.*[5] The data for the ^{54}Fe target at 24.0 MeV were taken by Rudolph and McGrath.[9] The bulk of the data were recently taken with the University of Colorado cyclotron, using techniques previously reported.[6,8]

The experimental angular distributions are shown in Fig. 1. The maxima and minima occur at approximately the angular positions expected for a direct reaction. Over all, the integrated cross sections show a mild increase with increasing energy. However, the relative heights of the maxima vary with energy and nucleus in an unexpected and complex fashion. This variation of relative maxima as a function of energy has distinct features for each nucleus.

The computer code DWUCK[11] was used for all calculations. Because a previous study[8] showed that inclusion of isospin-dependent terms in the optical parameters did not appreciably affect the results, we have in every case used identical ^{3}He and triton parameters in the calculations. Two different models were used to investigate these features.

II. MACROSCOPIC MODEL

A macroscopic description of the (^{3}He, t) transition to the IGS can be derived following an optical-model generalization summarized in other papers.[2,8] The solid curves in Fig. 1 are DWBA calculations with interaction terms consisting of a Woods-Saxon real well of depth V_{1V}, and a derivative Woods-Saxon imaginary well (surface form) of depth W_{1S}. The geometrical parameters of these terms were arbitrarily set equal to the corresponding optical-model parameters. This type of parametrization has been used in previous work,[1,2,4,8] with the real and imaginary terms having equal depths. For the study described here, the ratio V_{1V}/W_{1S} was determined for each nucleus so that the DWBA calculations fitted the data well. For parameter Set 1 shown in Table I, the values used were 3.0, 5.0, 1.0, and 9.2 for ^{50}Cr, ^{54}Fe, ^{62}Ni, and ^{90}Zr, respectively. The description of the data is good for most energies for each nucleus. Changing the ratios by more than about 20% degrades the agreement between theory and data. A similar interaction potential was tried using parameter Set 2, shown in Table I, and the parametrization described above. The ratios V_{1V}/W_{1S} were required to be much smaller for all nuclei than when using parameter Set 1, but the same general variation as a function of nucleus was found: values of 0.75, 0.70, 0.10, and 1.0 were required for ^{50}Cr, ^{54}Fe, ^{62}Ni, and ^{90}Zr, respectively. However, the description of the data

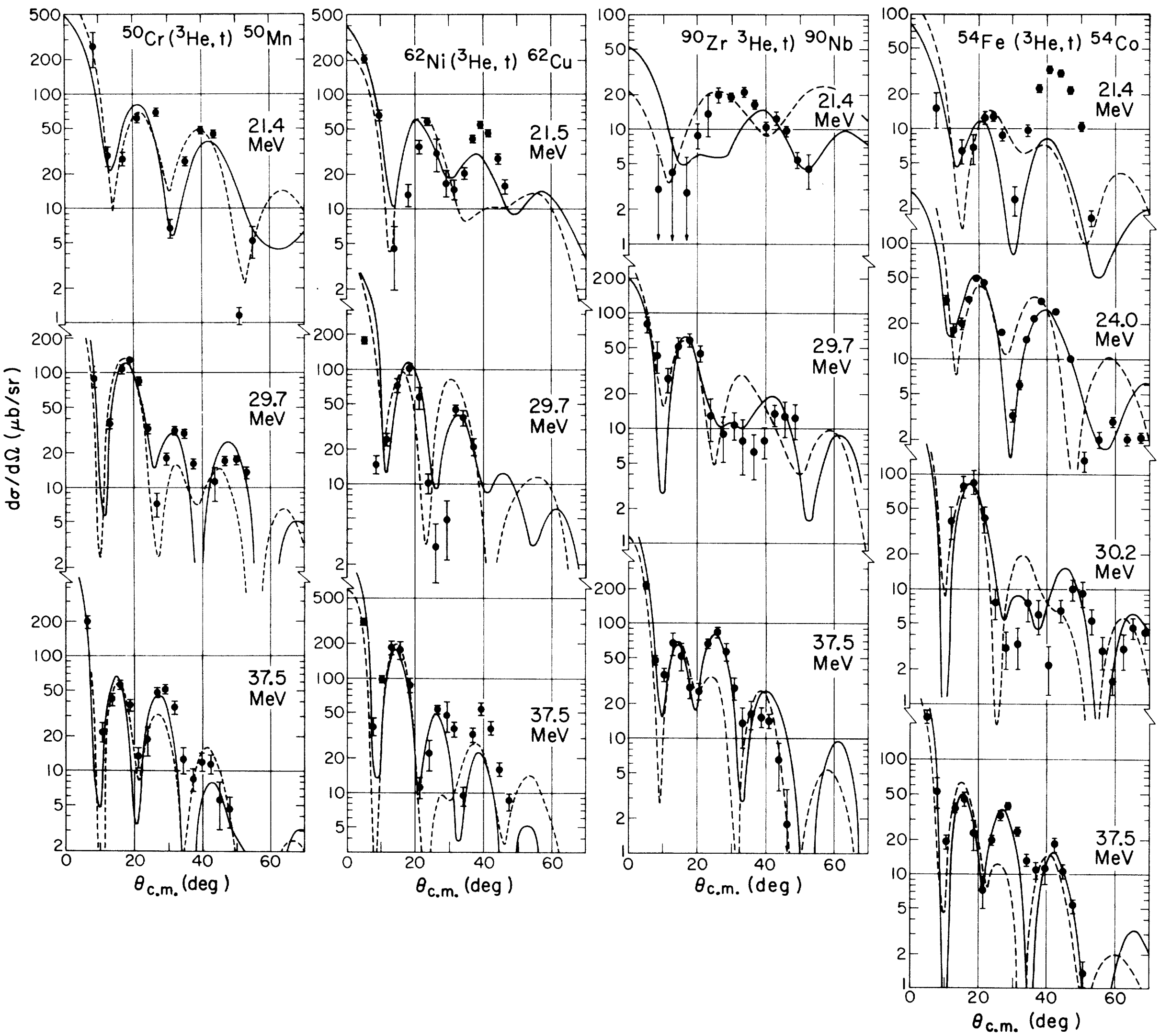

FIG. 1. Differential cross sections for (^{3}He, t) transitions to isobaric analog ground states of several nuclei. The solid curves represent DWBA calculations using parameter Set 1, Table I, and a generalized optical model with interaction terms selected for each nucleus to fit the data reasonably well. The dashed curves represent DWBA calculations using parameter Set 2 and a simplified shell model, with a Yukawa interaction of 1.0-F range.

TABLE I. Optical-model parameter sets. Set 1 has been used in several previous studies. Sets 2 and 3 are new energy-dependent sets from T. H. Braid, T. W. Conlon, H. H. Chang, and B. W. Ridley, to be published. E refers to the projectile energy in MeV. Notation here is in accordance with Ref. 8 except that R and I subscripts refer to real and imaginary terms, respectively.

	V_{0V} (MeV)	r_R (F)	a_R (F)	W_{0V} (MeV)	W_{0S} (MeV)	r_I (F)	a_I (F)
Set 1	170.60	1.14	0.712	18.50	···	1.600	0.829
Set 2	$182.87-0.02E$	1.10	0.763	···	$160.03-1.944E+0.0135E^2$	1.222	0.807
Set 3	$137.98-0.148E$	1.10	0.853	···	$150.65-2.019E+0.0142E^2$	1.308	0.751

was not as good using parameter Set 2 as it was using Set 1.

It should be possible to make deductions concerning the neutron excess from the interaction terms required to fit the (^{3}He, t) data, as discussed in previous papers.[8, 12] However, since the interaction terms required depend upon the optical-parameter set used, the conclusions may not be unique. Nevertheless, it has been shown that different interaction prescriptions are required for different nuclei, and this leads one to believe that it may be possible to relate these prescriptions to details of nuclear structure.

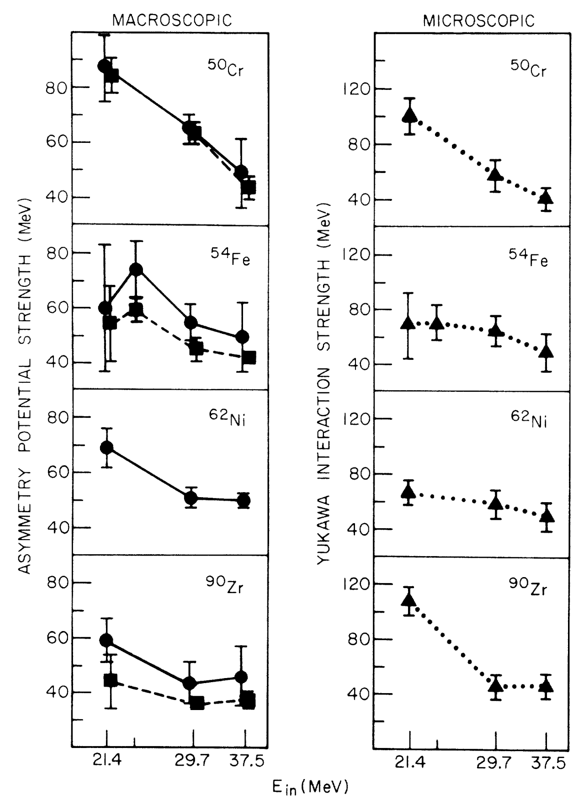

FIG. 2. Interaction strengths as a function of incident energy. The circular data points and solid lines represent interaction potential strengths for the generalized optical (macroscopic) model, using parameter Set 1 and $V_{1V}=W_{1S}$. The square data points and dashed lines are for the same conditions except that $V_{1V}/W_{1S}=3.0$, 5.0, 1.0, and 9.2, respectively, for the targets ^{50}Cr, ^{54}Fe, ^{62}Ni, and ^{90}Zr. The triangular data points and dotted lines represent the Yukawa interaction strength (with range 1.0 F) for a simplified shell (microscopic) model, using energy-dependent parameter Set 2. The same general results were found using other parameter sets.

III. MICROSCOPIC MODEL

The microscopic model includes certain details of the shell-model orbitals of participating nucleons. Descriptions of this formalism are found elsewhere.[2, 13] A Yukawa interaction with a range of 1.0 F was assumed between the projectile and a nucleon bound in the $1f_{7/2}$, $1f_{7/2}$, $1f_{5/2}$, and $1g_{9/2}$ shells for ^{50}Cr, ^{54}Fe, ^{62}Ni, and ^{90}Zr, respectively. A calculation assuming the target particle to lie in the next highest orbital in each case produced no appreciable variation in the shape of the angular distribution, and therefore it is unlikely that configuration mixing in the parent nucleus would have any important effect upon the shapes obtained using this theory.[2] Similarly, small changes in binding energy or excitation energy had little effect upon the shapes.

Reasonable agreement with the data was found for certain nuclei at certain energies, but not for others. Differences in results occurred for different parameter sets, but no set seemed to be significantly better than others in describing the entire range of nuclei and energies. Recent analysis of elastic ^{3}He scattering data has provided strong support for the 130-MeV family for the mass-3 optical-model parameters. However, for those parameter sets examined (specifically 2 and 3 in Table I), the sets with about 170-MeV real well depth described the data somewhat better than those with about 130-MeV real well depth. Basically, no parameter set could be selected as preferable on the basis of the description of the data. Typical theoretical angular distributions, using optical-model parameter Set 2 (see Table I) are shown as dashed lines in Fig. 1. Although one has somewhat more confidence in the method of determining the form factor using the microscopic model, it is not in general as effective in describing the data as the macroscopic model described above.

IV. INTERACTION STRENGTHS

The interaction strengths required to fit the data are summarized in Fig. 2. The error bars are in some cases large owing to the aforementioned inadequacies of the theory in describing the data. For both the macroscopic and microscopic models, a general tendency towards decreasing strength with increasing energy is evident. These energy-dependent effects are essentially independent of the parameter set used. This is illustrated in Fig. 3 for the microscopic model. Similar results are obtained for the macroscopic model. The extracted strengths may differ by an over-all constant for different parameter sets, but the general dependence remains essentially the same. It will be noted that the degree of energy dependence varies for different nuclei. This is partly because the magnitudes of the experimental angular distributions as a function of energy vary for the different nuclei. For example, the first maxima for ^{54}Fe and ^{62}Ni are considerably smaller ($\frac{1}{3}$ to $\frac{1}{4}$ magnitude) at 21.4 MeV than at 37.5 MeV. The first maximum for ^{50}Cr at 21.4 MeV is about equal to that at 37.5 MeV. The DWBA predictions more closely agree with the relative magnitudes for ^{54}Fe and ^{62}Ni. The energy dependence shown in Fig. 2 brings out an important discrepancy between present DWBA calculations and the data.

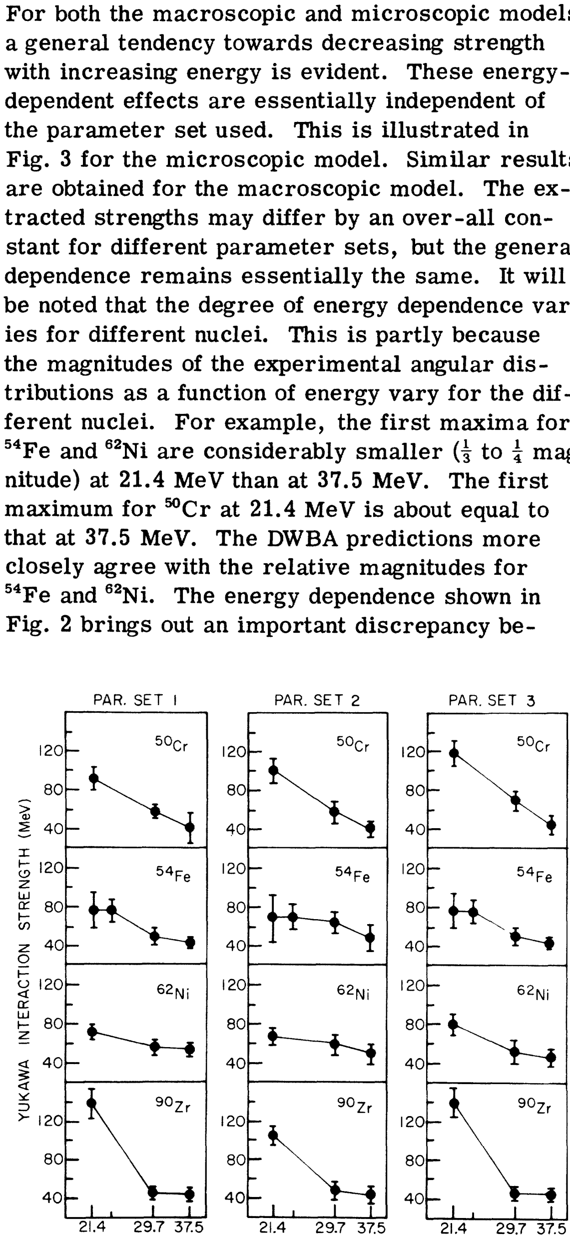

FIG. 3. Yukawa interaction strengths for the microscopic model, as a function of incident energy for three optical-model parameter sets. The Yukawa interaction range was 1.0 F. The lines are intended to guide the eye.

As mentioned earlier, it had been reported in a previous paper[8] that extracted interaction (macroscopic model) potential strengths, W_1, obtained in different studies differed significantly. Studies[2,6,8] at an incident energy of 37.5 MeV gave a value of W_1 of 40–60 MeV, while others[1,4,5] at 25 and 30 MeV gave values of W_1 ranging from 80 to 140 MeV. Furthermore, a value of about 95 MeV was obtained for W_1 from an analysis[14] of elastic scattering of ^{3}He and triton particles at 20 MeV. The energy-dependent effects seen in Fig. 2 account for much of the discrepancy in W_1 values obtained. The remaining difference is undoubtedly due to the use of different optical-model sets and uncertainties in obtaining the W_1 values. Consistency in the extracted strengths can only be expected for similar parameter sets and for data taken at the same energy.

It might be suspected that a possible cause of the increased strength at lower energies would be compound-nucleus effects. It is also evident that descriptions of the shapes of the angular distributions using the macroscopic model are not as good at 21.4 MeV as at the higher energies. (On the other hand, the quality of the microscopic descriptions are about the same at all energies.) However, there is evidence that compound-nucleus effects are not important for this reaction, even at the lower incident energies used here. For all nuclei, except possibly ^{90}Zr, there is a sharp diffractionlike structure of the angular distributions, with deep minima. These features are characteristic of a direct reaction rather than a compound-nuclear reaction. In studies of the excited states of ^{54}Co using the (p,n) reaction at 13.0[15] and 14.5 MeV,[16] a state at 1.61 MeV was strongly populated. However, at 22.8 MeV[17] the same state was not seen in the (p,n) reaction. In $(^3\mathrm{He},t)$ studies at 21.4,[18] 24.0,[9] and 26.0 MeV,[19] as well as at higher energies, this same state was not seen above the background. These results for the 1.61-MeV state are in contrast to the results for other states in this region which were strongly populated in all of the studies. These facts taken together strongly suggest that the 1.61-MeV state is primarily excited through compound-nuclear processes, and that compound contributions are not important for either the (p,n) reaction at 22.8 MeV or higher or the $(^3\mathrm{He},t)$ reaction at 21.4-MeV or higher incident energies.

It is not too surprising that an energy dependence is required in the isospin-dependent terms of the generalized optical model, since energy dependence has frequently been found to be important in other optical-model terms. The percent variation of the isospin-dependent term over the range of 21.4- to 37.5-MeV incident energy was found to be about a 25 to 50% decrease, as compared with a 14 to 17% decrease in the isospin-independent imaginary terms found in optical parameter Sets 2 and 3 in Table I. The variation of the microscopic strength required to fit the data is of the same order as the macroscopic-strength variation just mentioned, but this effect is not directly analogous to the energy dependence frequently seen in optical-model parameters.

V. SUMMARY

Experimental angular distributions from the excitation of isobaric analog ground states using the (^{3}He, t) reaction show striking energy-dependent variations. Each nucleus examined showed an individual energy-dependent variation in the shape of the angular distributions. The only method now available to describe these shapes reasonably well for many energies is through use of DWBA calculations using a generalized optical model with different *ad hoc* interaction potential prescriptions for each nucleus and each optical parameter family. A DWBA theory based upon a simplified shell model gives rather poor over-all agreement with the data. Interaction strengths for both of these DWBA models show an appreciable energy dependence which is now seen as a major cause of discrepancies previously noticed between different studies. Although DWBA formulations are still of use in (^{3}He, t) studies, the poor description of the energy dependence, in shape and in strength, is evidence of basic inadequacies in the theories as they are presently used.

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