$1/E$ dependence of the ^{7}Li$(p,n)^7$Be(g.s. + 0.43 MeV) total reaction cross section

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Activation measurements of the ^{7}Li$(p,n)^7$Be(g.s. + 0.43 MeV) total reaction cross section have been made at 12 proton energies between 60—200 MeV, with typical uncertainties of 8—14%. The measured total reaction cross section $\sigma(E)$ is observed to vary inversely with incident proton energy, and to agree very well, when extrapolated to lower energies, with previously published results in the energy range 25—45 MeV. A theoretical interpretation of this energy dependence is presented.

[NUCLEAR REACTIONS ^{7}Li$(p,n)^7$Be, $E=60-200$ MeV; measured total reaction cross section by activation analysis. Theoretical interpretation of the results.]

I. INTRODUCTION

The ^{7}Li$(p,n)^7$Be reaction has been extensively studied in the energy range up to 60 MeV. Differential cross section values for transitions to both the ground state and the first excited state ($E_x=0.429$ MeV) have been reported.[1–8] Precise measurements of the total reaction cross sections in the proton energy range 25—45 MeV were made by Schery *et al.*[2] using an activation technique. Zero degree neutron production cross sections have been measured at 15—25 MeV by Poppe *et al.*,[3] 15—30 MeV by McNaughton *et al.*,[4] 30—50 MeV by Romero *et al.*[5] and Batty *et al.*,[6,7] and at 40 and 60 MeV by Wachter *et al.*[8] More recently, we have reported[9] total reaction cross section measurements and neutron time of flight angular distributions to the ground state (g.s.) and first excited state (0.429) in ^{7}Be for $E_p=62$ and 120 MeV.

The ^{7}Li$(p,n)^7$Be reaction has also been used extensively to study aspects of the nuclear effective interaction, following the suggestions of Anderson, Wong, and Madsen,[10] by several authors; see, for instance, Ref. 11. Total cross sections for the reactions ^{7}Li$(p,p')^7$Li(0.478 MeV) and ^{7}Li$(p,n)^7$Be(0.429 MeV) have also been measured for proton energies between 23 and 52 MeV by Locard *et al.*[12] to obtain the energy dependence of the spin-isospin flip part of the effective interaction.

In the present study, the ^{7}Li$(p,n)^7$Be(g.s. + 0.429 MeV) total reaction cross section was measured in the proton energy range of 60—200 MeV. The results show a striking $1/E$ energy dependence in the measured $\sigma_T(E)$. This energy dependence has been reported in another case[13] but has not been noted for this reaction, nor has it been measured systematically in this intermediate energy region.

Several other studies also show a $1/E$ dependence, i.e., results[14] for the total cross sections for the ^{209}Bi$(p,xn)^{210-xn}$Po in the energy range 60—480 MeV and the cross sections for the interactions of fast neutrons (15—100 MeV) with ^{4}He.[15] The total n-p scattering cross section in the energy range 40—250 MeV (Ref. 16) also shows a $1/E$ dependence with values represented by the equation

$$\ln\sigma = -\ln E + 9.0 \,, \quad (1)$$

where σ is in mb and E in MeV.

For the ^{7}Li(p,n)^{7}Be(g.s. + 0.43 MeV) case reported here, a plane wave analysis indicates that the observed $1/E$ dependence of the total reaction cross section results essentially from energy terms arising from the angle integration, and requires a detailed cancellation between the energy dependent transition operator and absorptive effects in the energy dependent optical model.

II. EXPERIMENTAL TECHNIQUES AND RESULTS

The total production cross section for the ^{7}Li(p,n)^{7}Be(g.s. and 0.429 MeV) reaction was measured by observing the 478 keV γ ray following the 10.4±0.1% electron capture (EC) branch of ^{7}Be(53.29 d).[17] Proton beams of $E_p = 60-200$ MeV were obtained from the variable energy separated sector isochronous cyclotron at the Indiana University Cyclotron Facility (IUCF). Irradiations were performed in the neutron time-of-flight facility (NTOF) using Li metal targets and in the isotope production area using ^{7}LiCl targets. Metal targets of 100–200 mg/cm^2 thicknesses and 60–90 mg/cm^2 thick ^{7}LiCl targets (pressed into 1.5 cm diameter discs covered with 4 mg/cm^2 Al) were fabricated using 99.994% enriched ^{7}Li. The chemical form of LiCl was preferred to the metal as it could easily be stored over longer periods of time without oil or vacuum storage. Beam currents were monitored using an external Faraday cup. Total charge collection with uncertainties of ±5% were observed.

Irradiated targets containing 2–500 nanocuries of ^{7}Be activity were counted periodically in a standard geometry for 6–8 months in order to assure proper exponential decay. The samples were routinely counted using a 45 cm^3 Princeton Gamma Tech Ge(Li) detector whose resolution is 783 eV FWHM at 121.9 keV and whose efficiency was determined within ±3% using standard precision γ-ray reference sources.

Results of the present study are given in Table I and shown in Fig. 1. The error in counting statistics measured as the uncertainty in the decay curves of the ^{7}Be activity was 3–6%. Additional errors of 3% for the Ge(Li) γ-ray efficiency, 6% due to variations in target thickness, and 5% error in beam current integration, combine in quadrature to yield total uncertainties of 8.5–14.0% in the absolute cross section measurements. The data in Fig. 1 from 25–200 MeV are shown fitted to

$$\ln\sigma(E) = -(1.05\pm0.07)\ln E_p + (6.77\pm0.33) \,, \quad (2)$$

where E_p is the laboratory energy in MeV and $\sigma(E)$ in mb, with a correlation coefficient of 0.998.

TABLE I. Measured total cross sections for the ^{7}Li(p,n)^{7}Be(0 + 0.429 MeV) reaction.

Proton energy E_p (MeV)	Measured cross section (10^{-27} cm^2) mb
60.1	12.00±1.03
62.0	11.28±1.58
69.4	10.78±1.02
79.1	8.09±0.71
88.9	7.46±1.00
100.1	7.29±0.77
119.4	5.29±0.45
138.6	4.99±0.43
143.9	4.97±0.43
156.7	4.56±0.42
174.5	3.50±0.36
199.1	3.46±0.35

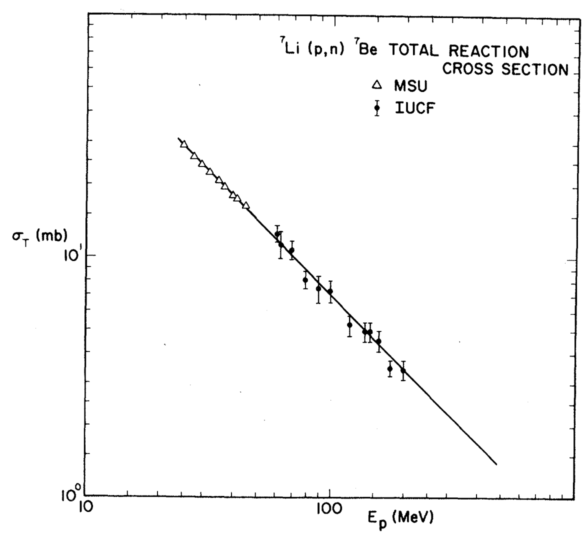

FIG. 1. The excitation function for the ^{7}Li(p,n)^{7}Be(g.s. + 0.429 MeV) total reaction cross sections. The solid line represents a $1/E$ dependence.

III. THEORETICAL CONSIDERATIONS

The distorted wave impulse approximation (DWIA) is a reasonable formalism for discussing inelastic proton scattering and charge exchange in the energy interval under discussion (60–200 MeV). Therefore, we adopt this framework for both the analytical and computer studies summarized below.

The differential cross section for nucleon-nucleus scattering is given in the DWIA by[18]

$$\frac{d\sigma}{d\Omega}=\frac{E_fE_i}{(2\pi\hbar^2c^2)^2}\frac{k_f}{k_i}\int \chi_f^{-*}(r_p)\langle J_fM_f\,|\sum_{j=1}^{A}t_{jp}[\,|J_iM_i\rangle\chi_i^{+}(r_p)]_{\rm anti}\,, \tag{3}$$

where $E_f(E_i)$ and $k_f(k_i)$ are the final (initial) relativistic reduced energy and wave number, respectively. The χ's are the usual nucleon-nucleus distorted waves, $\langle J_fM_f\,|$ and $|\,J_iM_i\rangle$ denote the final and initial nuclear states. The t_{jp} are the projectile target nucleon t matrices, often obtained from free nucleon-nucleon scattering data.[19,20] The bracket $[\;]_{\rm anti}$ indicates that one antisymmetrizes the projectile and target single particle states. This means that, ultimately, when one has reduced Eq. (3) to a sum of two particle (projectile, bound nucleon) matrix elements, direct and exchange terms will be present. Since in the present activation experiments one is concentrating on the sum of two angle integrated inelastic differential cross sections, the actual expression of interest is obtained from Eq. (3) via

$$\sigma=\int\frac{d\sigma_1}{d\Omega}d\Omega+\int\frac{d\sigma_2}{d\Omega}d\Omega$$
$$=\sigma_T({\rm g.s.})+\sigma_T(0.429\ {\rm MeV})\,. \tag{4}$$

We focus below on possible sources for the observed energy dependence of the total inelastic cross section for a particular state. In general, of course, there are several sources that contribute. The interesting point is that they can be easily estimated in "realistic" models and that their predicted behavior can be different for different types of states (i.e., depending on the spin, parity, and isospin exchange). The behavior is also often different depending on whether one is looking at a total cross section or a differential cross section at fixed momentum transfer q (both as a function of projectile bombarding energy). These ideas have also been discussed in connection with pion-nucleus inelastic scattering.[21]

Adopting the DWIA, there are three possible sources of energy dependence for the total inelastic cross section leading to a particular final state. We neglect the trivial $(E_fE_ik_f)/(k_i)$ factor in the following discussion, but of course we include it in the numerical examples. Because of the relatively large nucleon mass and the relatively low Q value of the reactions considered, this factor is of negligible importance in obtaining a *kinetic energy* dependence of the cross section.

The factors to be considered are (1) energy terms arising from the angle integration, (2) energy dependence of the transition operator, $\sum t_{jp}$, and (3) absorptive effects in the energy dependent optical potential.

A complete investigation of the relative importance of the three factors above, including distorted waves, requires numerical calculations. In the plane wave limit, however, one can obtain analytic expressions exhibiting the expected kinetic energy dependence arising from effects 1 and 2 above. Therefore, it is instructive to consider the plane wave expression for the angle-integrated inelastic cross section to a particular final state. This expression is given, for transitions involving p shell nucleons and adopting harmonic oscillator orbitals, by

$$\sigma=\int\frac{d\sigma}{d\Omega}d\Omega=\frac{E_fE_i}{(2\pi\hbar^2c^2)^2}\frac{k_f}{k_i}2\pi t_0^2\int_0^{\pi}\sin\theta d\theta\left[\left[\frac{1}{q^2+\mu^2}\pm\frac{1}{k_f^2+\mu^2}\right]e^{-q^2b^2/4}(\alpha+\beta q^2b^2)\right]^2\,. \tag{5}$$

In obtaining expression (5) we have assumed harmonic oscillator orbitals, a single term Yukawa interaction for the transition potential, neglected any spin dependence, and used the asymptotic energy approximation for the knockon exchange amplitude. The constants α and β depend on the particular transition under consideration and refer to orbital angular momentum transfers of zero and two, respectively. The symbol t_0 denotes the strength constant associated with the t matrix $[t_{jp} \equiv (t_0 e^{-\mu r_{jp}})/\mu r_{jp}]$. The $\pm$ sign in front of the exchange term depends on spin and isospin variables and is not important for our general considerations. The momentum transfer q is related in the usual manner to the scattering angle via

$$q^2 = k_f^2 + k_i^2 - 2k_f k_i \cos\theta \ . \tag{6}$$

Although the interaction assumed in obtaining Eq. (5) is not explicitly energy dependent, the exchange term induces an energy dependence which is made manifest by the appearance of k_f^2 in the denominator of the exchange term. It has been found recently that representing the N-N t matrix by sums of interactions of the local Yukawa form allows one to obtain excellent fits to nucleon-nucleon scattering data in the energy region under consideration.[20] Studies of the type discussed here provide related but complementary means for determining the validity of the DWIA and/or the accuracy of using the free nucleon-nucleon t matrix, unchanged, in the many-body environment.

It is useful to make the substitution in Eq. (5)

$$U = q^2 = k_f^2 + k_i^2 - 2k_f k_i \cos\theta \ , \tag{7a}$$

$$dU = 2k_f k_i \sin\theta d\theta \ , \tag{7b}$$

which allows

$$\sigma = \frac{A}{k_f k_i} \int_{U_{\min}}^{U_{\max}} dU e^{-Ub^2/2} (\alpha + \beta U b^2) \times \left[\frac{1}{U+\mu^2} \pm \frac{1}{k_f^2+\mu^2} \right]^2 , \tag{8}$$

where

$$U_{\min}^{\max} = k_f^2 + k_i^2 \pm 2k_f k_i \tag{9}$$

and

$$A = \frac{E_f E_i t_0^2 \pi}{(2\pi\hbar^2 c^2)^2} \frac{k_f}{k_i} \ . \tag{10}$$

For our particular case $k_f \sim k_i$ and k is large enough so that, to better than 99% accuracy, one can use as the upper and lower limits in Eq. (6), infinity and zero, respectively. One immediately observes a $1/E$ dependence in Eq. (8) from the $(k_f k_i)^{-1}$ factor in front of the integral.[22] (We are in a regime where nonrelativistic kinematics are sufficiently accurate.) This means that to observe a $1/E$ dependence, effects 2 and 3 must largely cancel. We now demonstrate that separately they cannot be small. The expected energy dependence of the transition operator can be obtained by looking at the energy dependence of the effective interactions dominant at low q (where the present structure form factors peak). The relevant terms t_τ and $t_{\sigma\tau}$ at low q are predicted to decrease in the region from 60 to 200 MeV by $\sim$40% and 15%, respectively. Since the square of the t matrix is used in the cross section, it is clear that substantial energy variation could occur from the energy dependence of t. Of course one could imagine that the extra angle integration and its different effects on the direct and exchange term significantly change the energy dependence. To investigate this point we assume a t matrix with a Yukawa form and range $\mu = 1$ fm^{-1} and an oscillator parameter $b = 1.7$ fm. Using the asymptotic energy approximation to evaluate the exchange term, one finds that t^2 $(q=0)$ would decrease (increase) by $\sim$25% (60%) in going from 50 to 200 MeV if one assumes an even (odd) state interaction. In order to study the predicted energy dependence of total cross sections for such an interaction, we have carried out the indicated integration in Eq. (8) and inserted the parameters given above. For reference purposes, we exhibit the analytic result for $L=0$ (i.e., $\beta=0$) transfers below. One obtains

$$\sigma(L=0) = \frac{A\alpha^2}{k_f k_i} \left\{ \frac{b^2}{2} e^{\mu^2 b^2/2} E_i(-\mu^2 b^2/2) + \frac{1}{\mu^2} + \frac{2}{b^2(k_f^2+\mu^2)^2} \pm 2 \frac{1}{(k_f^2+\mu^2)} [-e^{-\mu^2 b^2/2} E_i(-\mu^2 b^2/2)] \right\} , \tag{11}$$

where E_i is the usual exponential integral function. Using the parameters given above one finds that the expression in braces decreases (increases) by $\sim$35% (100%), for the case of an even (odd) state for a change of proton energies from 50 to 200 MeV. Thus the energy dependence of the cross section is, in fact, slightly greater than that of the force. Clearly the angle integration does not wash out the transition operator energy dependence. For $L=2$ transfer similar behavior is obtained. In this case again the energy dependence of the integrated cross section [without the $(k_f k_i)^{-1}$ factor] is more pronounced than that of the transition operator squared.

IV. THEORETICAL RESULTS

The g.s. of ^{7}Li and ^{7}Be have spin and parity values $J^\pi = \frac{3}{2}^-$; the first excited state in ^{7}Be(0.429 MeV) has $J^\pi = \frac{1}{2}^-$ values. Thus the ^{7}Li$(p,n)^7$Be reaction to the ground and 0.429 MeV states may proceed via the isospin term of the effective interaction with or without a spin flip transition. Possible quantum numbers in the exchange are indicated in Table II.

Transition densities based on shell-model wave functions calculated by Cohen and Kurath[23] for states in $A = 7$ nuclei were used in DWIA calculations. Single particle wave functions for the bound particle were assumed to be of harmonic-oscillator form with an oscillator parameter $b = 1.73$ fm.

All calculations were done using the code DWBA-70 (Ref. 24), in which exchange contributions are calculated exactly. Relativistic effects were also included in the calculations. Optical potentials were obtained from the $p + {}^{12}$C analysis done by Comfort and Karp[25] in the energy range 20–185 MeV.

The effective nucleon-nucleus interaction V^{eff} generally used in DWIA calculations is the t matrix for free nucleon-nucleon scattering. Love and Franey[26] have parametrized the t matrix at several energies based on N-N scattering phase shift results at these energies. Values of the parameters are quoted at each energy. Picklesimer and Walker[20] (P-W) have similarly derived a N-N transition matrix fitted to all the 50–400 MeV differential cross section and polarization N-N data. It is a sum of spin and isospin dependent central, spin-orbit, and tensor complex local interactions with a sum of Yukawa radial shapes. Values obtained by Picklesimer and Walker[20] and Love and Franey[26] for the relevant components of the central force at $q = 0$ are presented versus nucleon energy in Fig. 2. We have used both sets of t matrices to study the energy dependence of the total activation cross section in ^{7}Be.

The momentum transfer, q, at $E_p = 50$ MeV for the ^{7}Li$(p,n)^7$Be(g.s.) transition ranges from $q_{\min} = 5.0$ MeV/c ($\theta = 0°$) to $q_{\max} = 535$ MeV/c ($\theta = 180°$), while at 300 MeV it ranges from $q_{\min} = 2.0$ MeV/c to $q_{\max} = 1360$ MeV/c. Terms in the effective interaction are both energy and momentum dependent. The central terms of the N-N t matrix are dominant at small momentum transfers where the nuclear form factors also peak. This indicates that the use of central forces only, for simple analytic predictions of total cross sections at 50 and 300 MeV, is reasonable. Note that the important $t_{\sigma\tau}$ and t_τ interactions *decrease* with increasing energy in the range under consideration. We, of course, include all terms in the t matrix in the computer calculations.

TABLE II. Quantum number transfers in the reaction ^{7}Li$(p,n)^7$Be(0 + 0.429 MeV).

J_i^π	$J\pi_f$	ΔL	ΔS	ΔJ
$\frac{3}{2}^-$	$\frac{3}{2}^-$	0	0	0
		0	1	1
		2	0	2
		2	1	1
		2	1	2
		2	1	3
$\frac{3}{2}^-$	$\frac{1}{2}^-$	0	1	1
		2	0	2
		2	1	1
		2	1	2

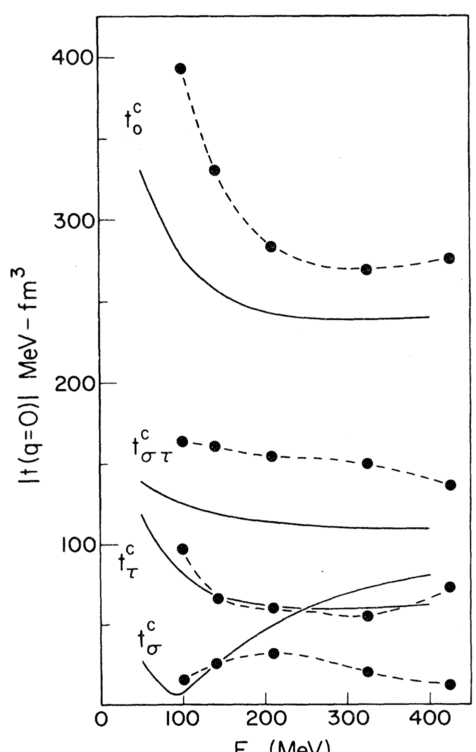

FIG. 2. Values of the effective N-N interaction at $q = 0$ as calculated by Picklesimer and Walker (Ref. 20) (smooth curves) and as calculated by Love and Franey (Ref. 26) (points joined by dashed lines to guide the eye).

Distorted wave (DW) calculations were done for all possible ΔJ transfers (Table II) at $E_p=40$, 80, 120, 160, 200, and 300 MeV using the P-W t matrix. Similar calculations also were done but with optical potential strengths equal to zero ($V=W=V_{so}=0$). We denote these calculations as plane wave (PW) calculations. The ratio N^D between the DW and PW results may be considered as a measure of distortion effects.

Values for the total cross section (g.s. plus the 0.429 MeV state) versus energy for the DW and PW calculations are plotted in Fig. 3. Also plotted is N^D, the ratio between these two calculations. Note that N^D increases with increasing energy in the range 40–200 MeV.

The DW calculations may be expressed as

$$\ln\sigma_T=-0.9\ln E \,, \tag{12}$$

indicating that the $1/E$ energy dependence is not exactly reproduced. Also the absolute magnitude of the calculated cross section needs to be multiplied by a factor of 1.6 to reproduce the experimental values.

The energy dependent distortion factor $N^D = (\sigma_T)_{\rm DW}/(\sigma_T)_{\rm PW}$ represents a quantity that essentially depends on the distortion effects of the incident and outgoing waves. The fact that N^D increases with energy demonstrates that the effect of distortions, taken alone, would cause deviations from the observed $1/E$ dependence.

The calculations above show that the experimentally observed $1/E$ dependence of σ_T is likely due to several effects as indicated previously; each one of these effects has a different energy dependence and when combined produces the observed results.

We also have calculated the total reaction cross section at $E_p=80$, 120, and 200 MeV using the 100, 140, and 200 MeV t matrices from Love and Franey.[26] The calculated total reaction cross section at $E_p=120$ MeV, 5.32 mb, agrees very well in with the experimental value 5.29 ± 0.45 mb. At the other two energies the calculation gives results slightly different from the empirical ones.

We present in Fig. 4 the energy dependence of the DW calculations as obtained using the P-W t matrix[20] (circles), the Love-Franey[26] t matrices and the empirical results represented by the solid line.

V. SUMMARY

We have reported activation measurements of the ^{7}Li(p,n)^{7}Be(g.s. + 0.43 MeV) total reaction cross section in the energy region $T_p^{\rm lab}=60-200$ MeV. The total sum of the experimental (p,n)

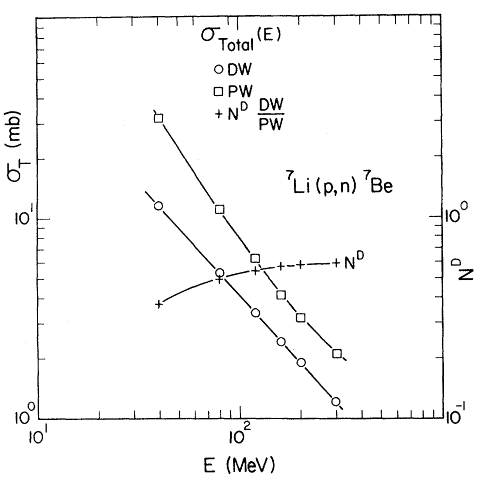

FIG. 3. Values of the total ^{7}Li(p,n)^{7}Be(g.s. + 0.429 MeV) reaction cross section versus energy calculated using the Picklesimer and Walker N-N t matrix. The circles represent the DW cross section while the squares represent the plane wave cross section. The ratio $(\sigma_T)_{\rm DW}/(\sigma_T)_{\rm PW}$ (distortion factor N^D) represents distortion effects.

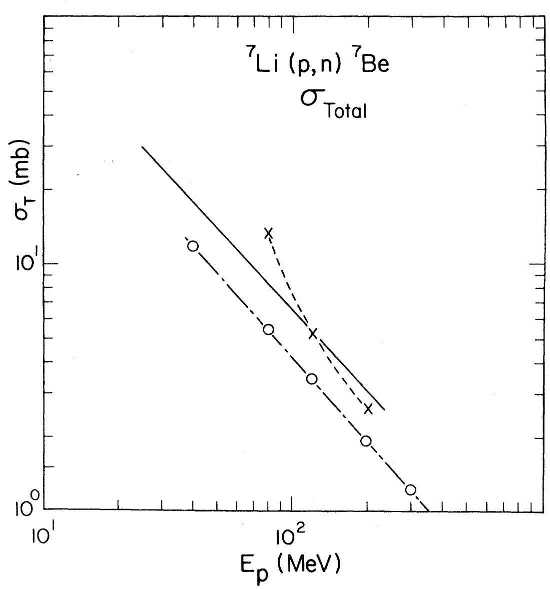

FIG. 4. The energy dependence of the ^{7}Li(p,n)^{7}Be(g.s. + 0.429 MeV) reaction cross section. The empirical results are represented by the solid line. Calculations using the Love-Franey t matrices are indicated by crosses while those obtained using the Picklesimer-Walker t matrix are indicated by circles.

cross sections leading to the ground and first excited states of ^{7}Li are characterized, to a high degree of accuracy, by a $1/E$ dependence in the energy range from 25 to 200 MeV. We have shown that for plane waves and an energy independent t matrix the $1/E$ dependence is expected in the DWIA. However, it was also found that adoption of either realistic energy dependent distorted waves or transition matrices could result in substantial deviations from the simple $1/E$ dependence. In fact, in more detailed numerical calculations using the DWIA and transition operators fitted to the free N-N data, theoretical predictions in qualitative agreement with the $1/E$ dependence are obtained. This occurs in the present case because of a cancellation of effects due to (a) the decrease in the flux lost from the elastic channel as the energy increases, and (b) a decrease in the strength of the effective transition operators as energy increases. The agreement between theory and experiment is not completely satisfactory, however. Using a transition operator suggested by Picklesimer and Walker,[20] the observed $1/E$ dependence is obtained but the total reaction cross section is consistently underestimated. Predictions of the total reaction cross section with the t matrix parametrized by Love and Franey[26] are roughly correct in magnitude but exhibit a shape different from $1/E$. Both calculations employ the same standard distorted waves obtained from fits to elastic proton scattering.[25]

Comparing theory to experimental total cross sections for exciting a given final nuclear state via (p,p') or (p,n) as a function of projectile energy is a useful additional way to study intermediate energy proton-nucleus reactions. If one uses distorted waves fitted to elastic scattering and transition densities obtained from electron scattering, one primarily tests the appropriateness of the various components of the t matrix in the many-body environment. While corrections to the t matrix associated with the presence of a many-body medium (Pauli blocking, boson absorption, Δ-medium reactions, etc.) are potentially important, there remains a significant amount of theoretical and experimental research to be done. The energy variability of intermediate energy proton accelerators should be used to measure both differential cross sections at fixed q and the total reaction cross section as a function of incident proton energy. The cancelling effects due to optical potential and transition operator energy dependence observed here will not always occur. For other transitions filtering out different spin-isospin components of the transition operator, one may find, due to the constancy or slight increase of the resulting t matrix with energy, substantial deviations from the observed $1/E$ dependence. (Note the relevant optical potential is controlled by the same combination of t-matrix terms for all transitions, while the effective transition operator involved in reaching a particular final state depends on detailed orbital angular momentum, spin and isospin selection rules.) In this regard, the energy dependence of total reaction cross sections associated with high spin states, with form factors peaking at high q, where tensor and spin-orbit pieces of the t matrix can be dominant, are attractive candidates for study. For low spin states, studies in the region 300 – 800 MeV (in addition to the energy dependent studies 50 – 200 MeV discussed in this paper) would be interesting because the energy dependent effects of $t_{\sigma\tau}$ and the optical potential would be expected to reinforce each other. This occurs because the t_0^c term contributing strongly to the optical potential increases while $t_{\sigma\tau}$ continues to decrease in the higher energy regime.[25]

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[22]For the direct term the argument presented here can be easily generalized to include distorted waves. In this case, Eq. (8) contains an extra integration variable Q, $U \rightarrow Q$ in the integrand, and an extra function $f(Q)$ appears in the integrand. The extra function $f(Q)$ has the effect of smearing out the momentum space q integrand. To the extent that one is in a region where the distortions are effectively energy-independent (for example, in an interval where the nucleus appears as a black disk) and if the smearing does not invalidate the approximation of replacing the $U_{\max}$ and $U_{\min}$ limits by ∞ and 0, respectively, one still recovers the $1/E$ dependence for the *direct* term.

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