

TRANSMISSION COEFFICIENTS FOR LIGHT PROJECTILES BASED ON GLOBAL OPTICAL POTENTIALS

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CERTIFICATE

This is to certify that the thesis entitled “**TRANSMISSION COEFFICIENTS FOR LIGHT PROJECTILES BASED ON GLOBAL OPTICAL POTENTIALS**”, submitted in partial fulfilment of requirements for the degree of **Master of Science** with major in **Physics** of the College of Post Graduate Studies, G.B. Pant University of Agriculture and Technology, Pantnagar, is a record of bona fide research carried out by **Mr. Pravesh Dhyani, Id. No. 31816**, under my supervision, and no part of the thesis has been submitted for any other degree or diploma.

The assistance and help received during the course of this investigation have been acknowledged.

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We, the undersigned members of the Advisory committee of **Mr. Pravesh Dhyani, Id. No. 31816**, a candidate for the degree of **Master of Science** with major in **Physics**, agree that the thesis entitled **“TRANSMISSION COEFFICIENTS FOR LIGHT PROJECTILES BASED ON GLOBAL OPTICAL POTENTIALS”** may be submitted in partial fulfilment of the requirements for the degree.

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A nuclear reaction is initiated when a nucleon or nucleus collides with another nucleon or nucleus. Reactions are characterized by the incoming nuclei and outgoing reaction products. A complete description of a nuclear reaction involves other observables like relative energy of incoming and outgoing nuclei, the scattering angle of the outgoing products and spin of nuclei involved. The characteristics of the reactions induced by a given pair of incident nucleus/nuclei can be summarized in distributions of the frequency of their occurrence, called cross-sections.

The information obtained from cross-sections usually depends strongly on the internal structure of the initial and final nuclei. In fact, the comparison of experimental scattering observables with those obtained from various nuclear models can infer a great deal about the structure of individual nuclei.

At low energies and for all but the lightest nuclear systems, nuclear reactions are observed to occur on two very distinct time scales. Direct reactions occur promptly, on a time scale of 10^{-22} sec. Their contributions to the cross-sections vary smoothly with

energy. Compound nuclear reactions, which involve the formation of a quasi-bound intermediate complex state, occur on a time scale of 10^{-18} sec (several orders of magnitude larger). These reactions make contributions to the cross-sections that fluctuate rapidly with energy.

The objective of the optical model is to describe the prompt (direct) reactions. To separate the direct and compound nucleus reactions (theoretically), one assumes that the compound nucleus reactions do not contribute to the average scattering amplitudes due to their rapid fluctuations in energy. The scattering amplitudes for direct reactions are thus associated with the energy averaged amplitudes. The optical model potential is then defined as the potential which furnishes the energy averaged scattering amplitudes.

The optical model used to describe the interaction between two nuclei is inspired by the optical phenomenon. The nuclear medium diffracts one part of incident wave and another part of wave is refracted. Then this phenomenon can be characterized by a complex refractive index. The real part of the refractive index corresponds to the diffraction phenomenon and the imaginary part

to the refraction to the incident wave. The nuclear potential can be written:

$$U(r) = V(r) + iW(r) \quad \dots (1.1)$$

Where $V(r)$ is the real part of the potential and represents the elastic scattering. The imaginary part $W(r)$ is introduced to take into account absorption of the incident wave before it is re-emitted and represents inelastic collision.

To gain insight into complex potential of the form (1.1), we consider a plane wave solution of the corresponding Schrödinger equation

$$\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2}(E + V + iW)\psi = 0 \quad \dots (1.2)$$

viz. $\psi = e^{ikx} \quad \dots(1.3)$

The wave number is complex and is given by

$$k = \left\{ \frac{2m}{\hbar^2} [E + V + iW] \right\}^{1/2} \quad \dots(1.4)$$

and hence can be written as

$$k = k_R + i k_I, \quad \text{whence} \quad \dots(1.5)$$

$$\psi = e^{ik_R x} e^{-k_I x} \quad \dots(1.6)$$

This is the wave function for a travelling wave whose amplitude is decreasing as it advances; it therefore represents a stream of particles some of which are being absorbed.

Transmission coefficient is the probability that a projectile penetrates the potential barrier. These are important inputs to calculate reaction/scattering cross-sections within the framework of statistical theory.

If all values of ℓ are considered, the optical reaction cross-section is related to transmission coefficient as

$$\sigma_R = \pi\lambda^2 \sum_{\ell=0}^{\infty} (2\ell + 1)T_{\ell} \quad \dots (1.7)$$

The aim of the theoretical studies is to find suitable potential to describe smooth variations of scattering cross-section as a function of energy 'E' and target mass number 'A'.

An optical potential model with real and imaginary parts can provide total reaction cross-section σ_R below and above the barrier. Effects of both penetrability and transparency are contained in such a potential.

The optical model provides the basis for many theoretical analyses and for evaluations of nuclear cross-sections that are used in providing nuclear data for applied purposes. In addition to

offering a convenient means for calculation of reaction, shape elastic and total cross-sections, optical model potentials are widely used in quantum mechanical pre-equilibrium and direct-reaction theory calculations and, most importantly, in supplying particle transmission coefficients for Hauser-Feshbach statistical theory used in nuclear data evaluations.

In the present work, we have compared transmission coefficients computed by empirical expressions of **Murthy *et al.*, (1982)** with those of computed by global potential of **Wilmore and Hodgson (1964)** and **Koning and Delaroche (2003)** in case of neutron, **Becchetti and Greenlees (1969b)** and **Koning and Delaroche (2003)** for proton, **Lohr and Haeberli (1974)** for deuteron, **Becchetti and Greenlees (1969a)** for triton and ^3He , and **Huizenga and Igo (1961a)** for ^4He . We have also included transmission coefficients data, calculated by SCAT-2 and different specific global potentials [EMPIRE-2.19] for neutron and proton projectiles. We have also proposed simple empirical relations and parameters for neutron's transmission coefficients for energy greater than 50 MeV.

The theme of the present work is presented in five chapters. In Chapter 2, a review of literature related to the present work, is

presented briefly. A brief overview regarding the methods used, is presented in Chapter 3. Chapter 4 contains the detail of the present analysis followed by results and discussion. Finally, summary of the work done in the present investigation is given in Chapter 5.

Chapter 2 ***Review of Literature***

2.1 The Spherical Optical Model

2.1.1 Basic Notions

Considering two interacting particles whose coordinates are \vec{r}_1 and \vec{r}_2 in the laboratory system, we postulate a potential $V(\vec{r}_1, \vec{r}_2)$ that acts between them. The corresponding Schrödinger equation is

$$\left[-\frac{\hbar^2}{2m_1} \nabla_1^2 - \frac{\hbar^2}{2m_2} \nabla_2^2 + V(\vec{r}_1, \vec{r}_2) - E \right] \Psi(\vec{r}_1, \vec{r}_2) = 0, \quad \dots(2.1)$$

where E is the total kinetic energy of the system.

This two-body problem is reduced to a one-body problem in the center of mass system. The coordinate \vec{R} of the center of mass is defined by

$$(m_1 + m_2) \vec{R} = m_1 \vec{r}_1 + m_2 \vec{r}_2, \quad \dots(2.2)$$

the relative coordinate \vec{r} of the two particles is

$$\vec{r} = \vec{r}_1 - \vec{r}_2, \quad \dots(2.3)$$

and their reduced mass is

$$\mu = \frac{m_1 m_2}{m_1 + m_2}. \quad \dots(2.4)$$

Ignoring the center of mass motion, the transformed Schrödinger equation is

$$\left[-\frac{\hbar^2}{2\mu} \nabla^2 + V(\mathbf{r}) - E \right] \Psi(\mathbf{r}) = 0. \quad \dots(2.5)$$

We consider the case where the potential V is local and central (axially symmetric about the incident direction) and defined by

$$V(\mathbf{r}, \mathbf{r}') = V(r) \delta(\mathbf{r} - \mathbf{r}'). \quad \dots(2.6)$$

For $V = 0$ (free propagation), the solution of (2.5) is the incident plane wave

$$\Psi(\mathbf{r}) = \exp(i\vec{k} \cdot \vec{r}), \quad \dots(2.7)$$

where \vec{k} is the wave vector with $k^2 = 2\mu E / \hbar^2$.

For $V \neq 0$, a spherical outgoing wave interferes with the incident plane wave and the asymptotic form of the wave function is

$$\Psi(\vec{r}) = \exp(i\vec{k} \cdot \vec{r}) + \frac{1}{r} f(\theta) \exp(ikr). \quad \dots(2.8)$$

2.1.2 The Scattering Equation

The basic scattering equation is

$$\left[-\frac{\hbar^2}{2\mu} \nabla^2 + V(\mathbf{r}) - E \right] \Psi(\mathbf{r}) = 0, \quad \dots(2.9)$$

where E is the total kinetic energy in the center-of-mass system

$$E = E_{\text{lab}} \frac{m_2}{m_1 + m_2} = E_{\text{lab}} \frac{\mu}{m_1} . \quad \dots(2.10)$$

Performing the usual decomposition into partial waves

$$\psi(\vec{r}) = \psi(r, \theta, \phi) = \sum_{\ell=0}^{\infty} \frac{u_{\ell}(r)}{r} P_{\ell}(\cos\theta), \quad \dots(2.11)$$

the radial wave equation becomes for a central potential

$$\left[\frac{d^2}{dr^2} + k^2 - \frac{2\mu}{\hbar^2} U(r) - \frac{\ell(\ell+1)}{r^2} \right] u_{\ell}(r) = 0. \quad \dots(2.12)$$

These equations have to be solved in the internal region of the nucleus for a given potential $U(r)$. In the external region, where $U(r)=0$, the independent solutions are the regular and irregular Coulomb functions, F_{ℓ} and G_{ℓ} .

2.1.3 Phenomenological Optical Potential

The first analysis of elastic scattering data used a square well which was then replaced by a more realistic form:

$$U(r) = Vf(r) + iWg(r) \quad \dots(2.13)$$

Where V and W are well depth of real and imaginary parts of the potential. The form factors $f(r)$ and $g(r)$ depend on the distance 'r' between the two nuclei (projectile and target). As the nucleon-nucleon interaction is a short range interaction, the potential $Vf(r)$, which is approximately the sum of nucleon-nucleon interactions, has the same behavior. The nucleons in the core of the nucleus undergo only the interaction of their closest neighbors. Due to this saturation of the nuclear force, $Vf(r)$ is uniform inside the nucleus and then decreases exponentially in the surface region.

The real potential

The real potential has a Woods-Saxon form factor

$$f(r) = \left[1 + \exp\left(\frac{r - R_1}{a_1}\right) \right]^{-1} \quad \dots(2.14)$$

where $R_1 (= r_1 A^{1/3})$ is the measure of nuclear radius. The parameter 'a₁' determines the diffuseness of the nuclear surface.

The imaginary potential

The imaginary potential form factor can be either surface peaked or in volume. A surface peaked form factor can have either a derivative Woods-Saxon shape

$$g(r) = 4a_2 \frac{df(r)}{dr} = 4 \exp\left(\frac{r - R_2}{a_2}\right) \left[1 + \exp\left(\frac{r - R_2}{a_2}\right)\right]^{-2} \text{ with } R_2 = r_2 A^{1/3},$$

...(2.15)

or a Gaussian shape

$$g(r) = \exp\left[-\left(\frac{r - R_2}{a_2}\right)^{-2}\right] \text{ with } R_2 = r_2 A^{1/3},$$

...(2.16)

which is sometimes used for low energy neutrons.

A volume form factor has a Woods-Saxon shape

$$f(r) = \left[1 + \exp\left(\frac{r - R_3}{a_3}\right)\right]^{-1} \text{ with } R_3 = r_3 A^{1/3}.$$

...(2.17)

The spin-orbit potential

A spin-orbit term is necessary to take account of the polarization that results from a scattering interaction. The spin-orbit form factor has a Thomas shape, which has universally been adopted.

Thomas Shape:

$$h(r) = \frac{1}{r} \frac{df(r)}{dr} = \frac{1}{ra_4} \exp\left(\frac{r - R_4}{a_4}\right) \left[1 + \exp\left(\frac{r - R_4}{a_4}\right)\right]^{-2},$$

...(2.18)

with $R_4 = r_4 A^{1/3}$.

The spin-orbit coupling constant C_{so} is nearly equal to 2 fm^2 and

$$\vec{\ell} \cdot \vec{s} = [j(j+1) - \ell(\ell+1) - s(s+1)] \quad \text{for spin } 1/2 \text{ particles}$$

$$\vec{\ell} \cdot \vec{s} = [j(j+1) - \ell(\ell+1) - s(s+1)]/2 \quad \text{for spin } 1 \text{ particles}$$

The r_i and a_i ($i = 1, 4$) are the geometric parameters of the spherical optical model.

The Coulomb potential

A Coulomb potential $V_c(r)$ is also added to the potential $V(r)$, if the incident particle has a charge. It represents the potential created by incident particle charge and target nucleus charge.

For practical purposes the Coulomb potential $V_c(r)$ of the target nucleus is assumed to be the potential due to an uniformly charged sphere of radius $R_c = r_c A^{1/3}$

$$V_c(r) = \frac{Z_1 Z_2 e^2}{r} \quad \text{if } r > R_c$$

$$= \frac{Z_1 Z_2 e^2}{2R_c} \left(3 - \frac{r^2}{R_c^2} \right) \quad \text{if } r \leq R_c \quad \dots(2.19)$$

where Z_1 and Z_2 are the charges of the incident particle and the target nucleus.

With all these contributions, the complex optical potential becomes

$$U(r) = V_c(r) - V_r f(r) - i [W_s g(r) + W_v f(r)] \vec{\ell} \cdot \vec{s} C_{so} V_{so} h(r), \quad \dots(2.20)$$

where the five terms represent a Coulomb potential, a real volume potential, an imaginary surface potential, an imaginary volume potential and a spin-orbit potential, respectively. $h(r)$ is the form factor.

2.1.4 The Energy Dependence of the Parameters

The depth V of each potential may have an energy dependence of the form

$$V = V_0 + V_1 \times E + V_2 \times E^2 + V_3 \times E^3 + V_4 \ln(E) + V_5 \sqrt{E}. \quad \dots(2.21)$$

The reduced radii r_i and the diffusivities a_i may have a linear energy dependence

$$r_i = r_i^0 + r_i^1 \times E, \quad a_i = a_i^0 + a_i^1 \times E, \quad i=1,4. \quad \dots(2.22)$$

2.1.5 Non-Local Potential

If the potential is non-local (NL), then an approximate “equivalent local” (L) potential can be found using the following relation (**Perey and Saxon, 1964**) (local energy approximation)

$$V_L \approx \exp\left(-\frac{1}{4}\beta^2 K^2\right) V_{NL} \quad \text{with} \quad \dots(2.23)$$

$$K^2 \approx k^2 + \frac{2U}{\hbar^2} - \frac{1}{4V_{NL}} \left(V_{NL}'' + \frac{V_{NL}'}{r} \right), \quad \dots(2.24)$$

where β is the non-locality range.

This equation is solved by an iteration procedure, whereupon a final estimate is obtained by Aitken's delta process (**Smith, 1969**).

$$V \approx V_6 - \frac{(V_6 - V_5)^2}{V_6 - 2V_5 + V_4}, \quad \dots(2.25)$$

where the subscripts represent the iteration order.

2.2 Specific and Global Potential

Nuclear potential can be specific or global. Specific potentials are limited to a narrow energy range and/or a narrow nuclear mass range, while global potentials, which have more parameters and are usually less accurate, are functions of energy and nuclear mass and therefore be used in a wider range of applications.

2.3 Physical Background to the Optical Model:

Low energy neutron scattering cross-sections for all nuclei show resonances. Some of the resonances are sharper whereas others are weak. The density of resonances may be higher in one region and low in another etc. These are general features of low energy neutron scattering for all nuclei. Square well potential with real part only, predicts the value of neutron capture cross-sections

that are too low and suggests that the cross-section varies but slightly with energy, displaying widely spaced resonances, contrary to reliable experimental evidence (**Bethe, 1935**).

In place of the above, compound nucleus (CN) model was proposed by **Bohr (1936)**. According to which whenever an incident nucleon enters the nucleus, it is always absorbed and a compound nucleus is formed having one or more highly excited states. The mode of disintegration of the compound nucleus is independent of the specific way in which it has been formed.

This strong absorption model was able to account for the observed large capture cross-sections and closely spaced resonances, but it fell short of providing a satisfactory quantitative explanation of the variation of cross-section with increasing energy.

Feshbach et al., (1947), and Feshbach and Weisskopf (1949) had proposed a model especially suited to the high-energy region in which the target nucleus was taken to be a perfectly absorbing “black sphere”, gained strong support when it was shown by **Feshbach et al., (1949)** to give a good fit to experimental 90 MeV neutron scattering data on various nuclei obtained by **Cook et al., (1949)**.

Cook et al., (1949) measured total cross-sections of H, D, Li, Be, C, N, O, Mg, Al, Cl, Cu, Zn, Sn, Pb and U for 90 MeV neutrons. These measurements indicated that the nuclei are partially transparent to high energy neutrons.

A further important step was taken by **Feshbach et al., (1954)** in demonstrating complex optical model, which was equally well capable of describing low-energy scattering data. They proposed a simple model for the description of the scattering and compound nucleus formation by nucleons impinging upon complex nuclei. They conceived the idea that target nucleus is represented by a complex potential $U = V+iW$ for any projectile. As a first approximation, they used a potential whose real part V was rectangular potential well and whose imaginary part was a constant fraction of the real part $W = \zeta V$. This model was used to reproduce the total cross-sections for neutrons, the angular dependence of the elastic scattering, and the cross-section for the formation of the compound nucleus.

Initially, the complex potential was taken to be a square well with all the nuclear charge essentially on nuclear surface; this because of the simplicity of model and because of its apparent success for Al (**Le Levier and Saxon, 1952**). However, for heavier nuclei, the square well results were in marked disagreement with

the experimental cross-sections of **Gugelot (1952)**, **Burkig and Wright (1951)**, and **Cohen and Neidigh (1954)**. The square well predicts large scattering at large angles even if the square well parameters are permitted to vary over an extensive range and if the nuclear charge is assumed to be distributed over the nuclear volume.

Woods and Saxon (1954) assumed a rounded edge potential of the form

$$U(r) = \frac{V + iW}{1 + e^{(r-R)/a}}, \text{ where } R=r_0A^{1/3} \quad \dots(2.26)$$

They have shown that rounding the nuclear potential significantly modifies the cross-sections. As 'a' increases and the rounding becomes greater, the large angle cross-sections decrease for the heavier elements and computed cross-sections are actually very close to the experimental ones.

The optical potential comprised a real central part $V_c(r)$ to represent the Coulomb interaction, together with a real Woods-Saxon part and an imaginary (surface – absorption) part with a derivative Woods-Saxon form factor:

$$U(r) = V_c(r) + V_0 f(r) + i Wg(r) \quad \dots(2.27)$$

where $f(r) = \frac{1}{1 + \exp\{(r - R) / a\}} \quad \dots(2.28)$

$$\text{and } g(r) = 4a \frac{\partial f(r)}{\partial r} = 4 \exp\left(\frac{r-R}{a}\right) \left[1 + \exp\left(\frac{r-R}{a}\right)\right]^2 \quad \dots(2.29)$$

A similar course was pursued by **Martin et al., (1968)** in the analysis of elastic and inelastic scattering distributions of 5.95-MeV neutrons on the light nuclei ^{27}Al , ^{28}Si , ^{31}P and ^{32}S , using the equivalent local potential of **Wilmore and Hodgson (1964)** corresponding to the non-local potential of **Perey and Buck (1962)** with provision for spin-orbit coupling.

2.4 Optical Potential Parameters:

2.4.1 Neutron Potentials

Perey and Buck (1962) proposed an energy independent non-local optical potential for elastic scattering of neutrons from nuclei. They assumed potential form factor that of a real Woods-Saxon form plus an imaginary term having the shape of a derivative of a Woods-Saxon form and included a real local spin-orbit potential of the usual Thomas form. They obtained parameters of the potential solely from the fitting of the differential cross-sections for lead at 7 MeV and 14.5 MeV, which are used to calculate the

elastic differential cross-sections, total and reaction cross-sections on some elements ranging from Al to Pb at various energies from 0.4 MeV to 24 MeV.

An overall local neutron potential equivalent to that of **Perey and Buck (1962)** has been derived by **Wilmore and Hodgson (1964)**.

A local potential (based upon a non-local formalism) that sets out to account for all neutron data from 1 to about 200 MeV has been proposed by **Engelbrecht and Fiedeldey (1967)**.

Becchetti and Greenlees (1969b) established “global” prescriptions for nucleon optical potential parameters, following upon a reformulation of the optical model by **Greenlees et al., (1968)**. Sets of overall parameters to fit cross-section for neutron over the range $A = 54\text{--}209$, $E_n = 1\text{--}29$ MeV (Lab), and for protons over the range $A = 45\text{--}208$, $E_p = 7\text{--}40$ MeV (Lab), were adduced using alternative volume-absorption (Woods-Saxon) or surface-absorption (derivative Woods-Saxon) imaginary potentials conjoined with a Woods-Saxon real potential and a Thomas spin-orbit potential.

2.4.2 Proton Potentials

Perey (1963) derived a local proton potential from an extensive analysis of elastic-scattering data between 9 and 22- MeV

and gave formulae to obtain the value of the parameters of the optical model as a function of mass number and energy.

From an independent analysis of proton scattering data between 11 and 18 MeV **Buck (1963)** deduced the phenomenological set of local optical potential parameters for protons based upon strong-coupling theory.

Schulz and Wiebicke (1966) deduced the “global” parameters for proton. They applied non-local optical potential for elastic scattering, used by **Perey and Buck (1962)** to protons and calculated differential cross-sections for various elements in the energy range of 7 to 22 MeV.

2.4.3 Potentials for Composite Particles:

Zeidman et al., (1961) adduced a very rough prescription for the energy dependence of a deuteron potential containing both volume and surface absorption terms.

Newman et al., (1967) obtained a set of average parameters from the analysis of scattering of 34.4 MeV deuterons by various elements ranging from ^{12}C to ^{93}Nb .

Watanabe (1958) has combined neutron and proton potentials to derive a meaningful optical potential for deuteron.

Rook (1965) set real nucleon potentials to $V_0^{(n)} \cong V_0^{(p)} = 52$ -MeV and improved the real part of the deuteron potential by the inclusion of a Coulomb term $V_c(r)$. The deuteron potential depth was thence found to be almost twice of the nucleon potentials, namely $V_0^{(d)} = 94$ MeV.

Satpathy et al., (1969) derived energy dependent surface-absorption deuteron potentials that reproduced the measured differential cross-sections for elastic scattering of 4-15 MeV deuterons on various targets (e.g., Al, Ti, Fe, Cu and Zn).

Daehnick et al., (1980) have presented global optical model potential for elastic deuteron-nucleus scattering from 12 to 90 MeV.

Barz et al., (1968) have derived a set of optical parameters for 12 MeV tritons from an analysis of (t, p) angular distributions at 12 MeV on a range of nuclei.

A rough prescription of **Scott et al., (1968)**, which has been found to yield a set of optical parameters in good agreement with available scattering data for ^3He .

Igo (1959a, 1959b) concluded that the α -scattering process involves essentially a surface interaction and fitted the experimental data with a complex exponential potential of the form

$$V(r) = -1100 \exp\left[-\frac{-1.17 A^{1/3}}{0.574}\right] - i \left\{ 45.7 \exp\left[-\frac{-1.40 A^{1/3}}{0.578}\right] \right\} \text{MeV} \quad \dots(2.30)$$

Calculations by **Huizenga and Igo (1961a)** of α -particle reaction cross-sections and transmission coefficients for energies to 46 MeV and targets of atomic number $Z=10$ to 92 used the same form of potential. Their results are tabulated (**Huizenga and Igo (1961b)**).

A list of barrier penetrabilities for α -particles based upon Igo's exponential potential has also been presented by **Rasmussen (1959)**.

2.4.4 Nucleon Potentials for Which Transmission Coefficients Have Been Tabulated

Emmerich (1958) has computed and listed neutron penetrabilities for a volume-absorption optical potential.

An extensive tabulation of neutron transmission coefficients from 0.1 to 5 MeV has been issued by **Auerbach and Perey (1962)** for two optical potentials that both included spin-orbit parameters.

A graphical representation of **Perey and Buck (1962)** neutron transmission coefficients has been presented by **Lindner (1966)**.

Meldner and Lindner (1964) have also published the results of transmission-coefficient computations for neutron and proton in graphical form, optical surface-absorption potentials of Perey type having been employed in both cases.

Mani, Melkanoff and Iori have compiled tables of neutron penetrabilities (**Mani et al., 1963a**) and proton penetrabilities (**Mani et al., 1963b**), respectively up to energies of 50 MeV for the entire mass region from $A = 15$ to $A = 230$, using the **Bjorklund-Fernbach (1958)** potential.

Chapter 3 ***Materials and Methods***

We have calculated transmission coefficients (T_ℓ) for light projectiles (n, p, ^2H , ^3H , ^3He and ^4He) based on simple empirical expressions obtained by **Murthy *et al.*, (1982)** by fitting the available T_ℓ 's from global optical potentials. These expressions were smooth functions of target mass number and projectile energy. The expressions and parameters for neutron have been extended up to 100 MeV. The T_ℓ 's values have been compared with the values available in the literature.

3.1 EMPIRE CODE

EMPIRE is a modular system of nuclear reaction codes, comprising various nuclear models and designed for calculation over a broad range of energies and incident particles.

There is subroutine in the code for calculating the T_ℓ 's which is one of the important inputs in calculating various nuclear reactions cross-sections. We have used this subroutine to calculate T_ℓ 's involving global as well as specific optical model potentials.

3.2 Hill-Wheeler Expression

In 1953 D.L. Hill and J.A. Wheeler (**Hill and Wheeler, 1953**) gave the formula for the penetration of the ℓ^{th} partial wave through a parabolic barrier as a function of energy E:

$$T_\ell = \left[1 + \exp \left\{ \frac{2\pi(E_\ell - E)/\hbar\omega_\ell}{\hbar} \right\} \right]^{-1} \quad \dots(3.1)$$

where T_ℓ is the transmission coefficient and E_ℓ and $\hbar\omega_\ell$ are the barrier height and curvature given by,

$$E_\ell = V(R_\ell) = V_N(R_\ell) + V_c(R_\ell) + \frac{\hbar^2 \ell(\ell+1)}{2\mu R_\ell^2} \quad \dots(3.2)$$

$$\hbar\omega_\ell = \left| \frac{\hbar^2 V''(R_\ell)}{\mu} \right|^{1/2} \quad \dots(3.3)$$

where R_ℓ is the barrier radius, μ is the reduced mass, V_N is the real part of the optical potential and V_c is the Coulomb potential.

3.3 Parameterized Empirical Expressions Obtained by Murthy, Gupta and Chatterjee for the Transmission Coefficients

We consider the system where the projectiles (Z_p, A_p) interact with the target (Z_T, A_T) at a centre-of-mass energy E (MeV).

The parameterized form of transmission coefficient is

$$T_\ell = N \left[1 + \exp \left\{ \ell(\ell+1) - L/D \right\} \right]^{-1} = Nf(\ell) \quad \dots(3.4)$$

where the “transmission diffuseness”, D , is energy dependent.

The values of the parameters in the empirical prescription for the transmission coefficients were determined by a fit to the values obtained from optical model calculations employing various global optical parameter sets. The **Wilmore-Hodgson (1964)** potential for neutron, the **Becchetti-Greenless (1969b)** potential for proton, **Becchetti-Greenless (1971)** potential for ^3H and ^3He , and the **Lohr-Haeberli (1974)** potential for deuteron had been used. For alpha particles the T_ℓ values over the mass range 20-206 and energy range 2-46 MeV were taken directly from the tabulation of **Huizenga and Igo (1961b)**.

3.3.1 Parametric Forms for Charged Particles

Using a transmission-diffuseness which is energy dependent but ℓ -independent required the formula for T_ℓ to be split into two domains,

$$T_\ell = Nf(\ell), \quad \ell(\ell+1) \leq L \quad \dots(3.5)$$

$$= \frac{1}{2} N \exp \left\{ \frac{\ell(\ell+1) - L}{D'} \right\}, \quad \ell(\ell+1) > L$$

Expressions (3.5) describe transmission coefficients for the light charged particles. The parameter N is given by,

$$N = 1.153 - 1.02 A_T^{-1/3} \quad \dots(3.6)$$

for proton and is unity for the other charged particles. The other parameters L , D and D' are functions of A_T and E and were found to be well represented by

$$L = \left(\frac{2\mu R^2}{\hbar^2} \right) \left(E - V_N(R) - V_c(R) \right) + \frac{r_4}{E} \quad \dots(3.7)$$

$$D = d_1 A_T^{1/3} E + d_2 A_T + d_3 \quad \dots(3.8)$$

$$D' = \left(d'_1 A_T^{1/3} + d'_2 A_T^{2/3} \right) E + d'_3 A_T + d'_4 \quad \dots(3.9)$$

with $R(\text{fm}) = r_1 A_T^{1/3} + r_2 E^{1/2} + r_3 \quad \dots(3.10)$

and $\frac{2\mu}{\hbar^2} (\text{fm}^{-2}) = 0.0482 \frac{A_P A_T}{A_P + A_T} \quad \dots(3.11)$

Here the real part of the optical potential is given by

$$V_N(R)(\text{MeV}) = -V_o \left[+ \exp \left(- \frac{r_o}{A_T^{1/3}} \right) a \right]^{-1} \quad \dots(3.12)$$

where V_o , r_o and 'a' are parameters of the global potentials listed in Table 3.1 and the Coulomb potential is given by

$$V_c(R) (\text{MeV}) = 1.44 Z_P Z_T / R \quad \dots(3.13)$$

The parameters r_1 to r_4 , d_1 to d_3 and d'_1 to d'_4 were determined by fitting T_ℓ values and are listed in Table 3.2.

Table 3.1 Optical model parameters for the real part

Projectile	References	V_o (MeV)	r_o (fm)	a (fm)
Neutron	Wilmore-Hodgson (1964)	$47.01 - 0.267E$ $-0.0018E^2$	$1.322 - 7.6 \times 10^{-4} A_T$ $+4 \times 10^{-6} A_T^2$ $-8 \times 10^{-9} A_T^3$	0.66
Proton	Becchetti-Greenless (1969b)	$54.0 - 0.32E_{lab}$ $+24 \left(\frac{N_T - Z_T}{A_T} \right)$ $+0.4Z_T / A_T^{1/3}$	1.17	0.75
Deuteron	Lohr-Haerberli (1974)	$91.33 + 2.2 \frac{Z_T}{A_T^{1/3}}$	1.05	0.86
Triton	Becchetti-Greenless (1971)	$165.0 - 0.17 E_{lab}$ $-6.4 \left(\frac{N_T - Z_T}{A_T} \right)$	1.2	0.72
Helium-3	Becchetti-Greenless (1971)	$151.9 - 0.17 E_{lab}$ $+50 \left(\frac{N_T - Z_T}{A_T} \right)$	1.2	0.72
Alpha	Huizenga and Igo (1961b)	50.0	$1.17 + 1.77 / A_T^{1/3}$	0.576

Table 3.2 Parameters determined by Murthy, Gupta and Chatterjee by a fit to various transmission coefficients

Projectiles	r_1	r_2	r_3	r_4	d_1	d_2	d_3	d'_1	d'_2	d'_3	d'_4
Neutron	1.285	-0.38	1.87	-4.93	0.042	0.021	2.80	-	-	-	-
Proton	1.730	-0.49	2.27	-2.0	0.0	0.041	4.18	0.087	0.0	0.019	1.47
Deuteron	1.580	-0.25	3.29	-5.0	0.153	0.026	1.52	0.133	0.048	-0.050	4.50
Triton	1.257	-0.42	5.44	0.0	0.097	0.022	6.71	0.799	-0.079	0.001	1.26
Helium-3	1.638	-0.38	4.09	0.0	0.154	0.043	3.07	0.593	0.0	-0.168	4.44
Alpha	1.451	-0.26	3.74	0.0	0.137	0.025	4.53	0.238	0.0	0.031	3.09

3.3.2 Parametric Forms for Neutrons

Expression for transmission coefficients for neutron includes a derivative term, and is given by

$$T_\ell = N_1 f(\ell) - N_2 df(\ell)/d\ell \quad , \quad N_1 f(\ell) \geq N_2 df(\ell)/d\ell$$

$$= N_1 f(\ell) \quad , \quad N_1 f(\ell) < N_2 df(\ell)/d\ell$$
...(3.14)

where N_1 and N_2 are parameterized as

$$N_1 = 1.09 - 0.085 \sqrt{E}$$
...(3.15)

$$N_2 = 7.94 - 12.98 A_T^{-1/3} + 76.38 A_T^{-1/3} E^{-1/2} - 37.55 E^{-1/2}$$
...(3.16)

The other parameters L and D were found to be adequately described by

$$L = \left(\frac{2\mu R^2}{\hbar^2} \right) \left[\epsilon - V_N(R) + r_4 \right]$$
...(3.17)

where D , R and V_N are of the same form as equations (3.8), (3.10) and (3.12). The parameters r_1 to r_4 and d_1 to d_3 were obtained by fitting T_ℓ values and are given in Table 3.2.

The present study aims to programme the above equations (3.4-3.17) in FORTRAN 77. Listing of the programmes is given in Appendix A and B. Simple relations and parameters for neutron have been proposed for energy greater than 50-MeV [up to 100-MeV]. The success of the simple expressions is shown in Figs. 1-4 given in the next chapter.

Chapter 4 *Results and Discussion*

The motivation of present work is to compare transmission coefficients up to 50 MeV for light projectiles (n, p, ^2H , ^3H , ^3He and ^4He), using parameterized empirical expressions given by **Murthy et al., (1982)**, which is based on Hill-Wheeler formula (**Hill and Wheeler, 1953**), with those of EMPIRE-2.19 global optical potentials as well as specific potentials. Moreover, empirical relations and parameters have been proposed, which are capable of predicting transmission coefficients for nuclei over the target mass range 20-209 and energy range 50-100 MeV in case of neutron as projectile (figs. 1-4).

The programs employing parameterized empirical expressions have been written in FORTAN-77 and the listing is given in appendix A and B. We have plotted transmission coefficients (T_ℓ) values against projectile's orbital angular momentum (ℓ) values. The comparison of transmission coefficients computed on the basis of different global and specific potentials is also shown in Figs. 1-16.

Transmission coefficients for $n+^{20}\text{Ne}$ and $n+^{107}\text{Ag}$, are given in Tables 4.1-4.4. Tabular results for other projectile and target combinations are available but have not been included just to avoid the bulkiness of the thesis. The first column of the table represents orbital angular momentum (ℓ) values of projectiles. The second column represents transmission coefficients calculated using **Wilmore and Hodgson (1964)** global potential. The third column represents transmission coefficients calculated using parameterized empirical expressions of **Murthy et al., (1982)**. The fourth column represents transmission coefficients calculated using our proposed empirical relations and parameters. The fifth column represents transmission coefficients calculated using **Koning and Delaroche (2003)** global potential.

A proposed empirical fit to predict transmission coefficients for 50-100 MeV neutron projectile and target mass range 20-209, is as follows-

$$N_1=1.09-0.083\sqrt{E}, \quad N_2 = 7.94 - 12.98 A_T^{-1/3} + 76.38 A_T^{-1/3} E^{-1/2} - 35.56 E^{-1/2},$$

$$r_1=1.485, \quad r_2=-0.32, \quad r_3=1.87, \quad r_4=-4.93,$$

$$d_1=0.042, \quad d_2=0.121, \quad d_3=6.80$$

From Figs. 1-16 it is clear that

- i. Transmission coefficients for n, p, ^2H , ^3H , ^3He and ^4He generated from simple empirical expressions are smooth functions of target mass number (A_T), projectile energy (E) and projectile orbital angular momentum (ℓ).
- ii. The parametric form of **Murthy et al., (1982)** predicts T_ℓ values for heavier projectiles (^2H , ^3H , ^3He and ^4He) excellently as compared to neutron and proton.
- iii. In general, transmission coefficients calculated for n, p, ^2H , ^3H , ^3He and ^4He using empirical expressions of **Murthy et al., (1982)** reproduce the optical model values satisfactorily over the target mass range 20-209 and energy up to 50 MeV.

In case of neutron/proton as projectile we have also compared the T_ℓ values based on the empirical expressions with those of SCAT-2 as well as different global and specific potentials. The important observations are as follows-

We have found, in general, from Figs. 1-4 that in case of neutron as projectile

- i. At particular energy, on increasing ℓ value, first transmission coefficient increases and then decreases.

- ii. Transmission coefficients computed by **Murthy et al., (1982)** empirical expressions are in better agreement with those of computed using **Wilmore and Hodgson (1964)** global potential [EMPIRE 2.19(Global)c], for energy up to 50 MeV. Expressions of **Murthy et al., (1982)** are not so good at energy higher than 50 MeV. In this energy range our proposed empirical relations and parameterization are in better agreement with **Wilmore and Hodgson (1964)** global potential than empirical expressions of **Murthy et al., (1982)**.
- iii. **Koning and Delaroche (2003)** global potential is in better agreement with different specific potentials than other global potentials.
- iv. Transmission coefficients computed by **Koning and Delaroche (2003)** global potential are in better agreement with those of computed by SCAT-2 than those of other global potentials.

It is clear from figs. 5-8 that, in general, in case of proton as projectile

- i. Transmission coefficients computed by global potential of **Koning and Delaroche (2003)** are not so good in agreement with those of computed by SCAT-2, unlike in case of neutron as projectile.
- ii. All global potentials and available specific potentials are almost in good agreement with one another.

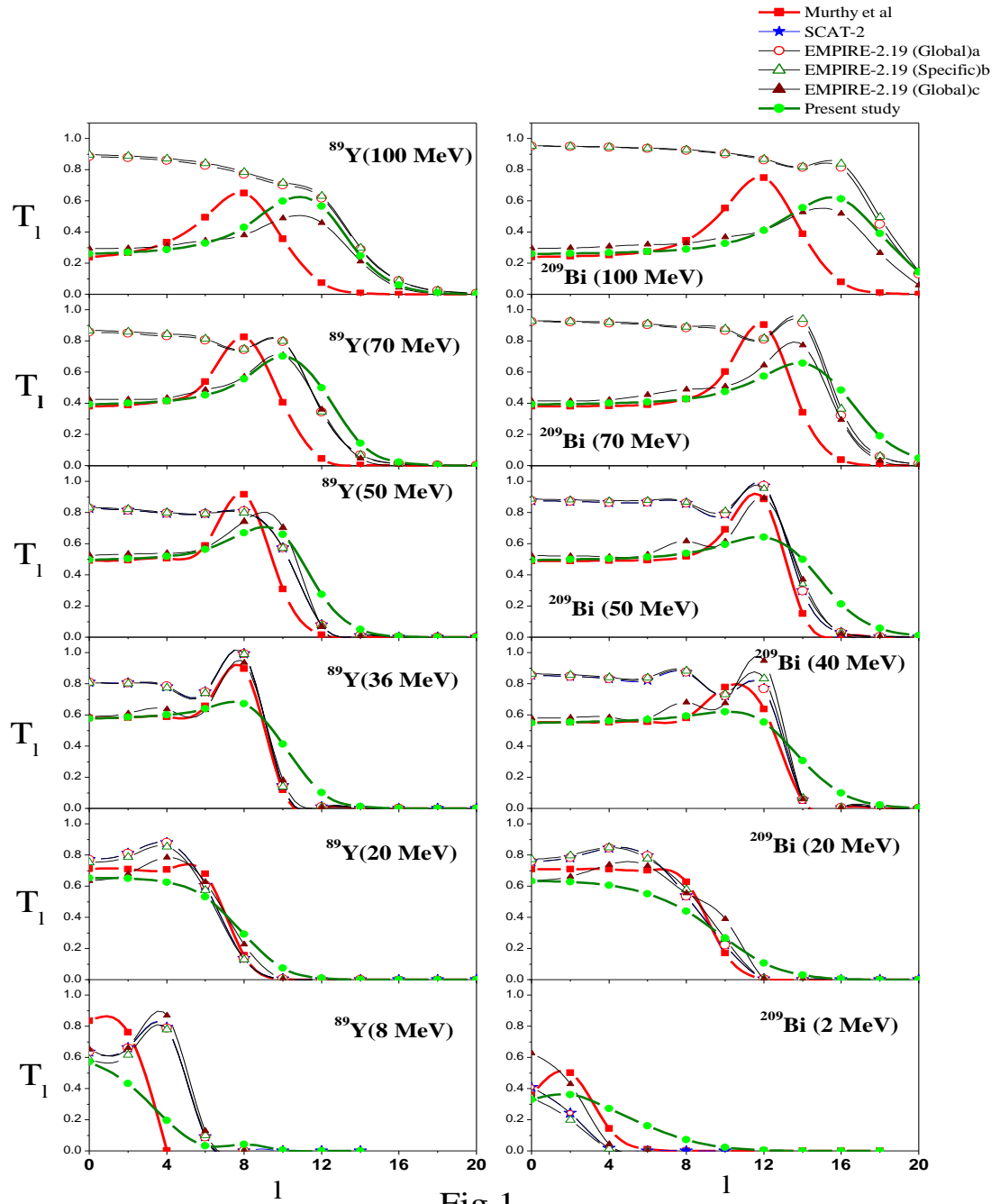


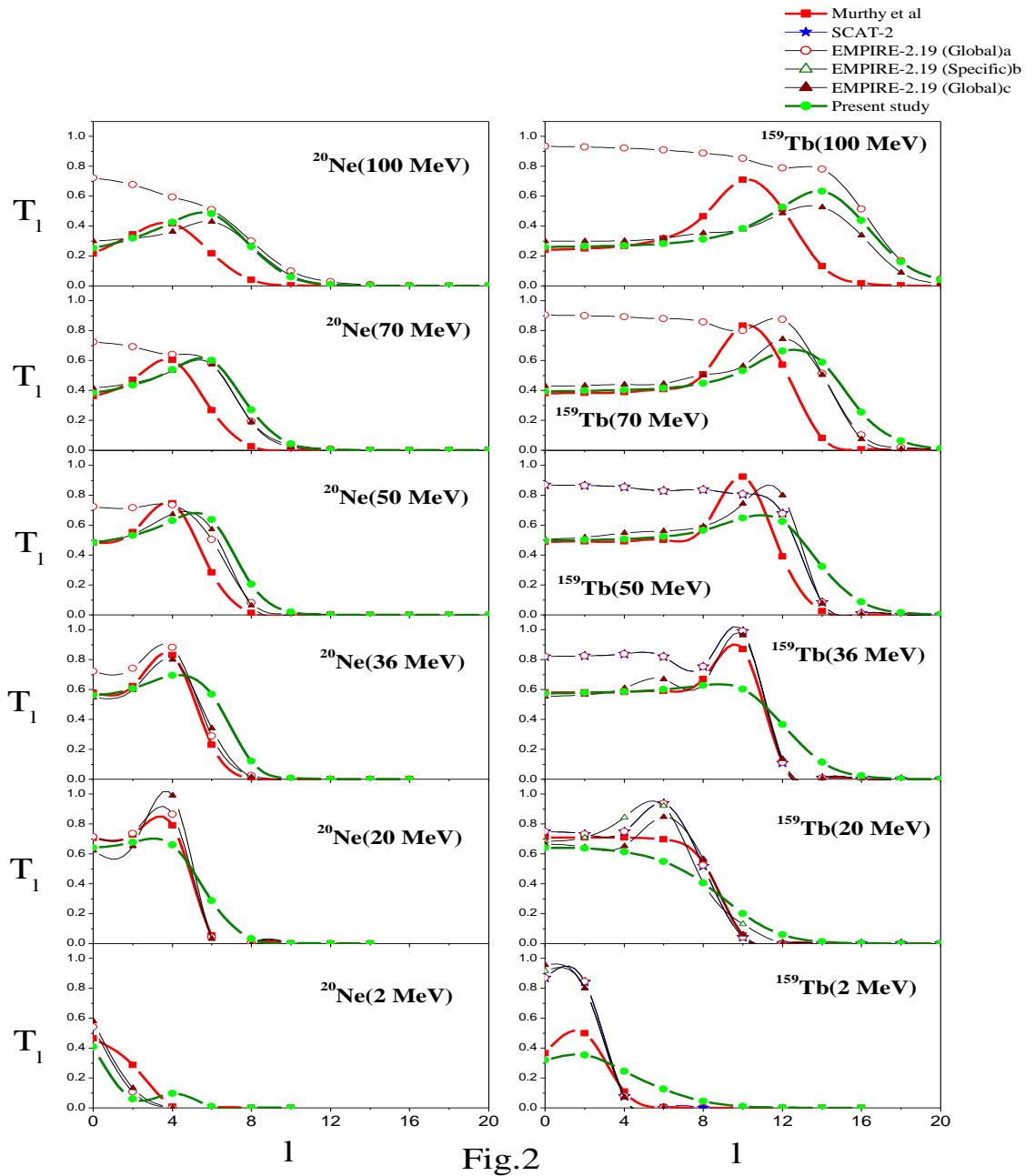
Fig.1

Transmission Coefficients (T_1) for Neutron

a: Koning and Delaroche (2003)

b: Koning and Delaroche (2003) for ^{89}Y and ^{209}Bi

c: Wilmore and Hodgson (1964)



Transmission Coefficients (T_1) for Neutron

a: Koning and Delaroche (2003)

b: Japan At. Ener. Res. Insti., JNDC FP Nucl. Data WG. for ^{159}Tb

c: Wilmore and Hodgson (1964)

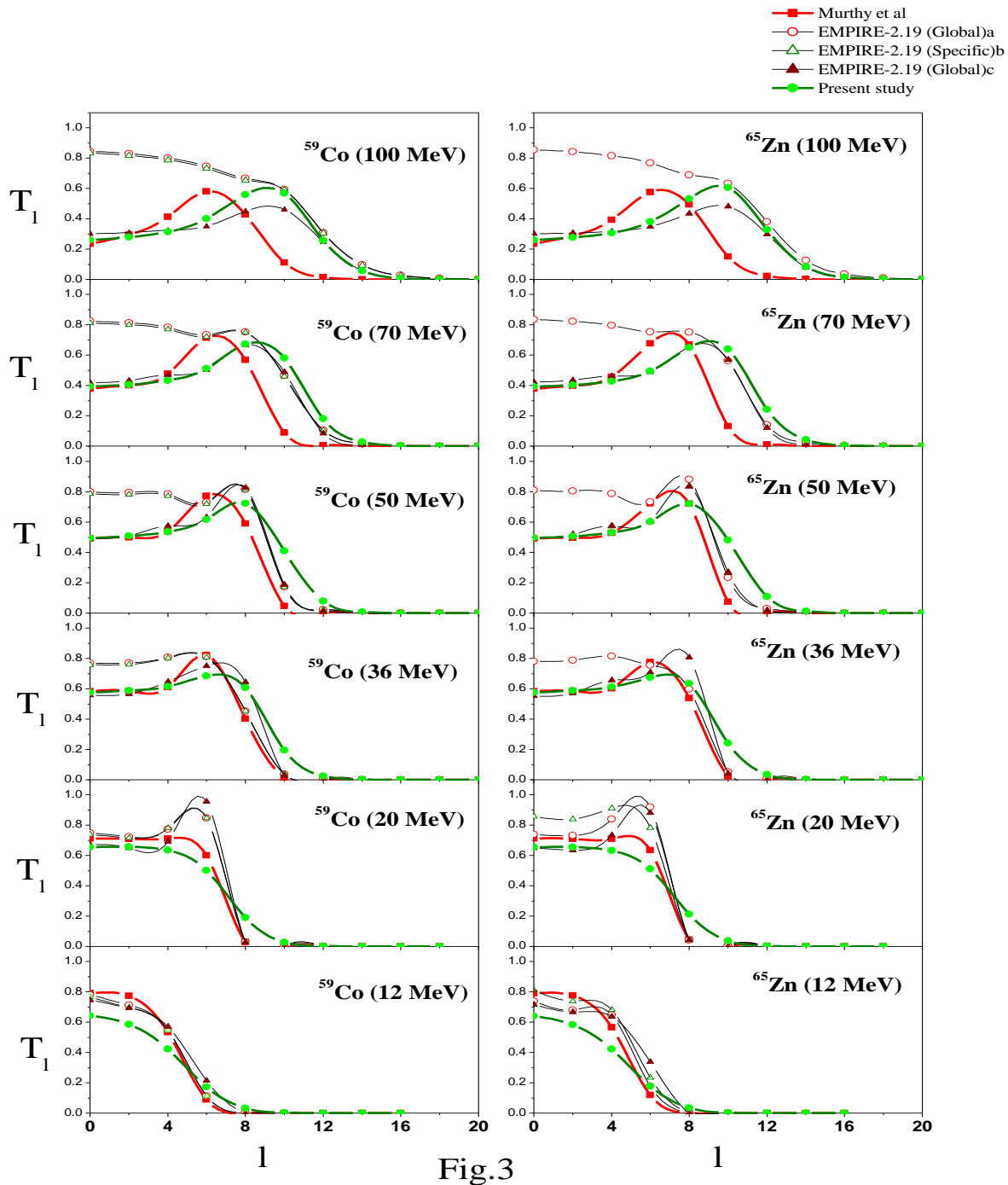


Fig.3

Transmission Coefficients (T_1) for Neutron

- a: Koning and Delaroche (2003)
- b: Koning and Delaroche (2003) for ^{59}Co ;
Young and Rutherford (1988) for ^{65}Zn
- c: Wilmore and Hodgson (1964)

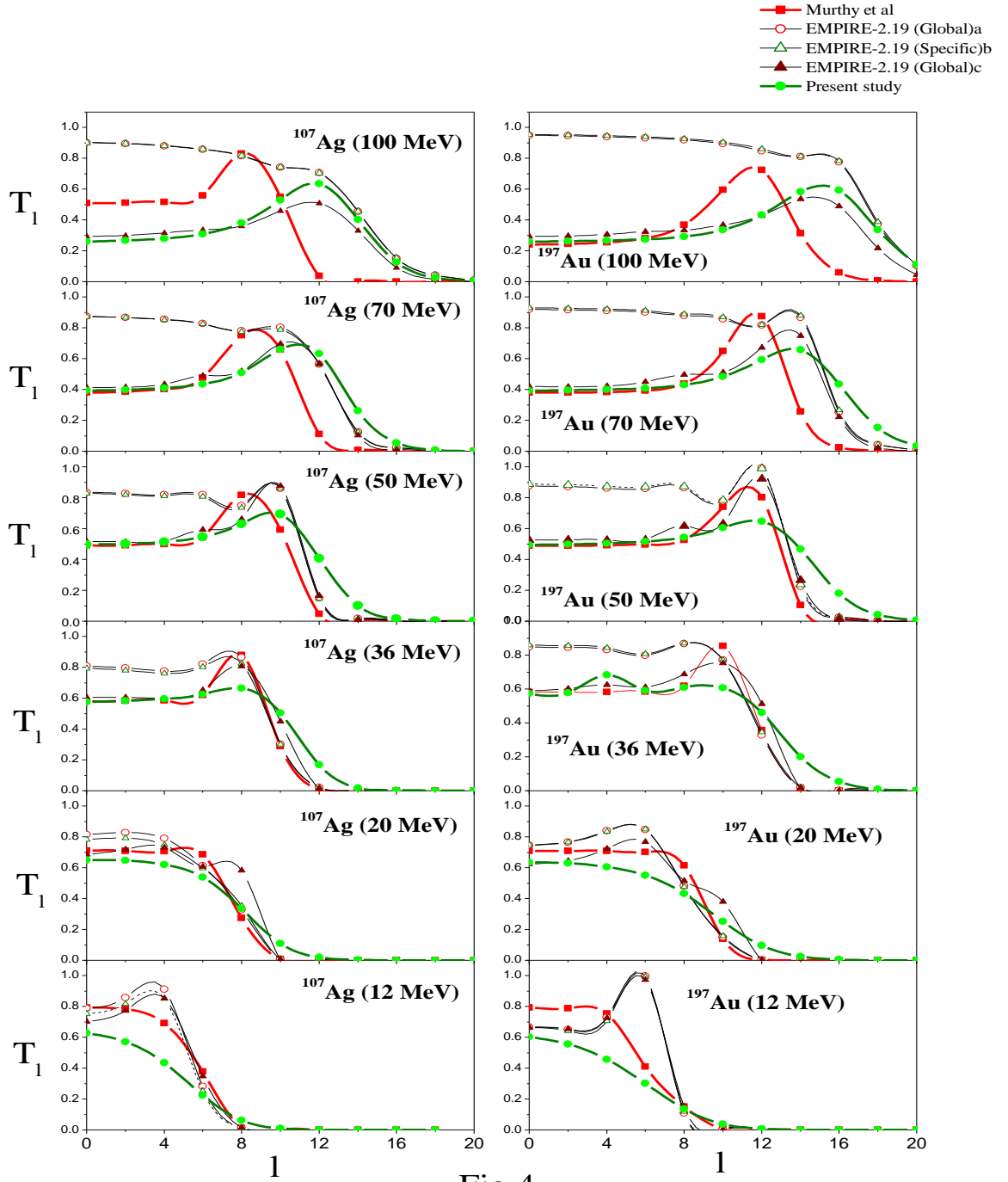


Fig.4

Transmission Coefficients (T_1) for Neutron

a: Koning and Delaroche (2003)

b: Koning and Delaroche (2003) for ^{107}Ag and ^{197}Au

c: Wilmore and Hodgson (1964)

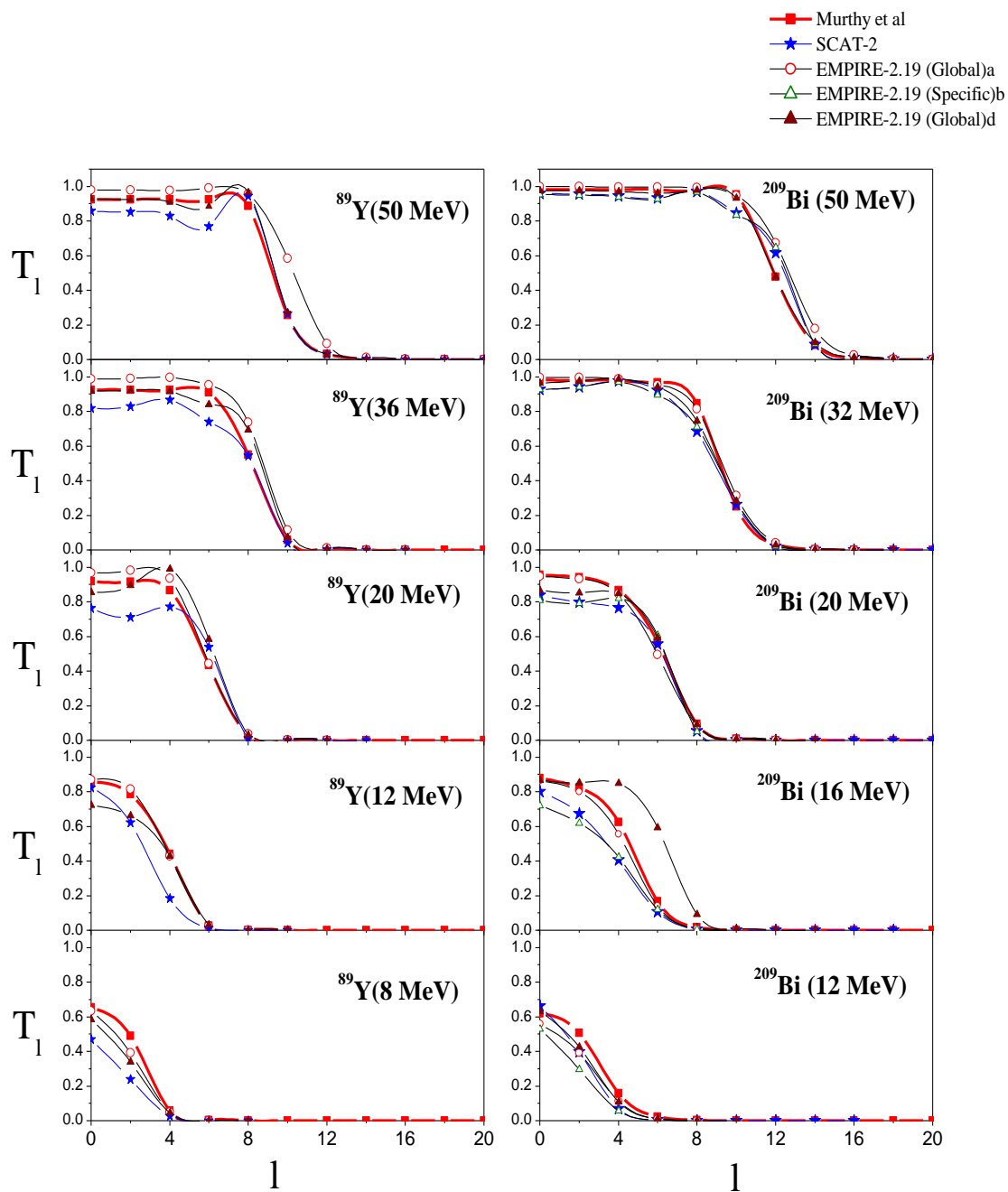


Fig. 5

Transmission Coefficients (T_l) for Proton

- a: Koning and Delaroche (2003)
- b: Johnson et al., (1977, 1979) for ^{89}Y ;
Koning and Delaroche (2003) for ^{209}Bi
- d: Becchetti and Greenlees (1969b)

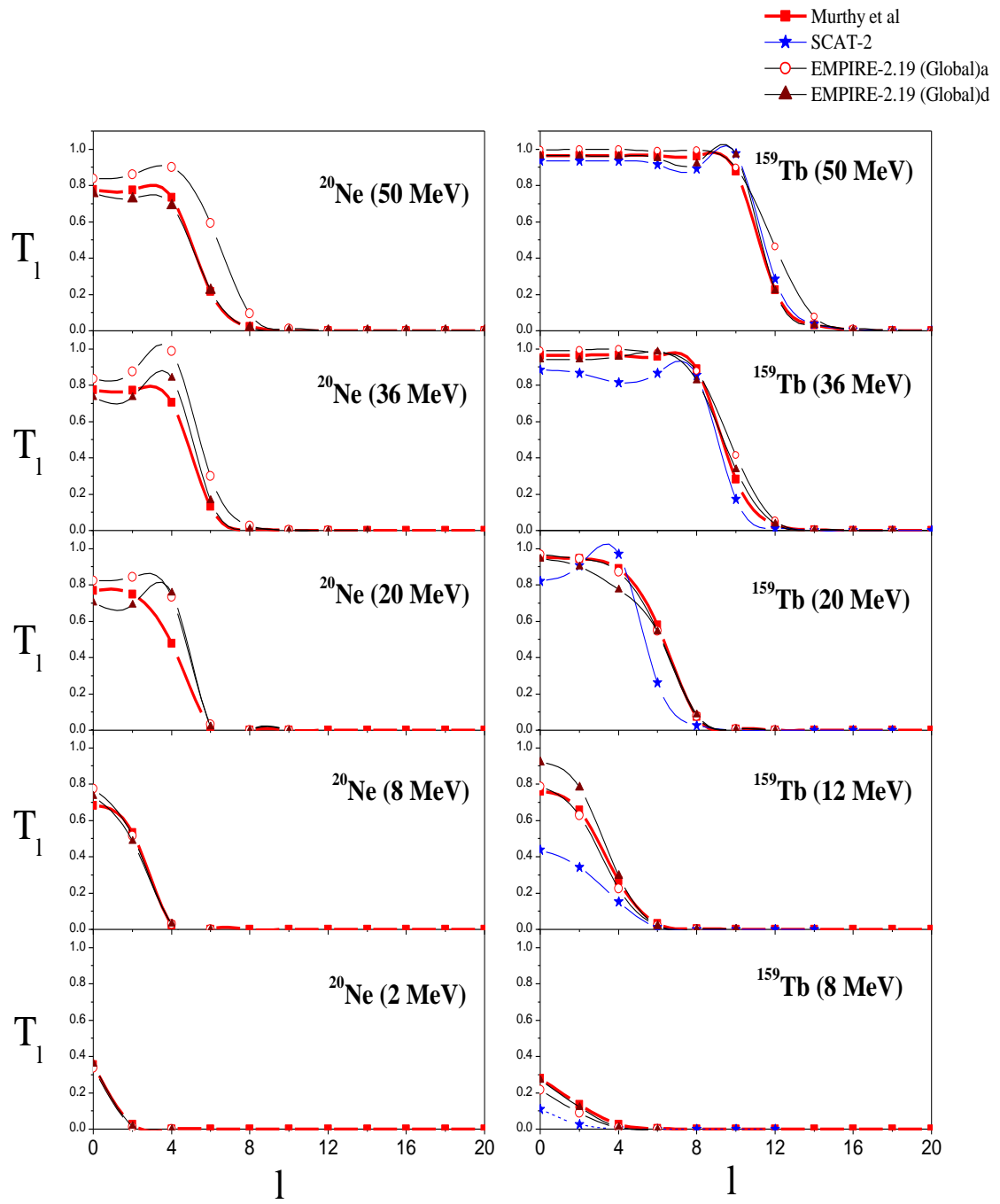
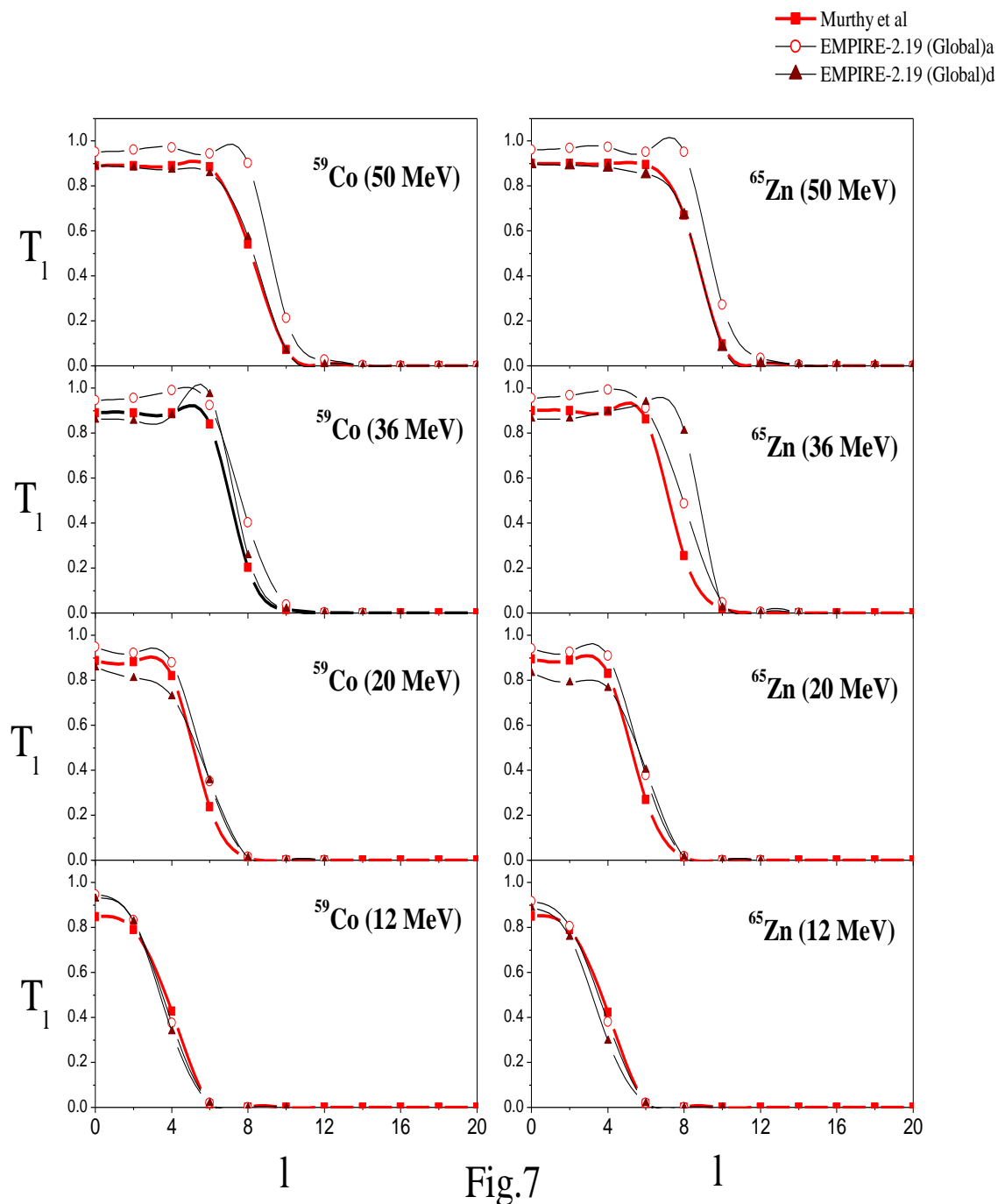


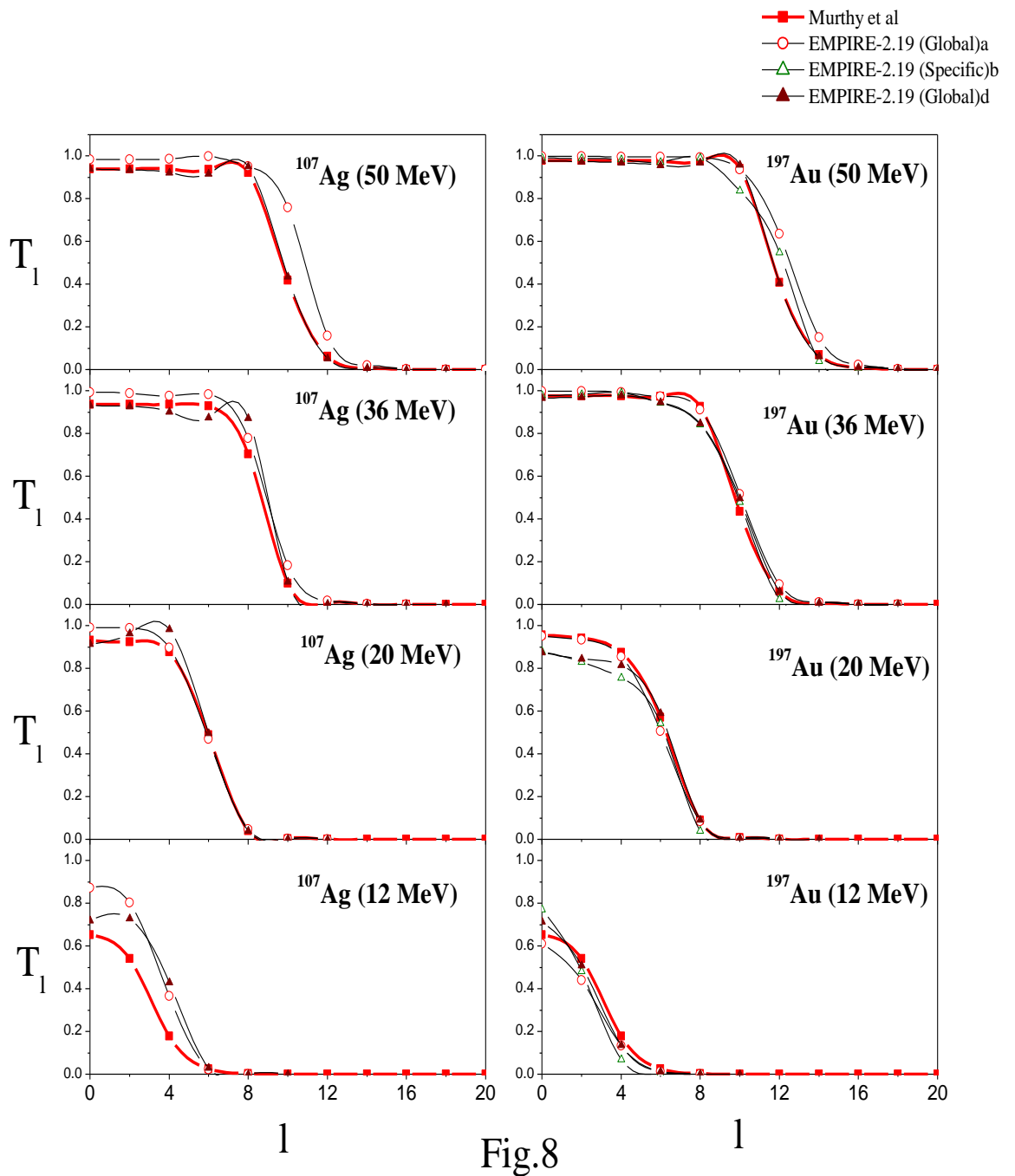
Fig. 6
Transmission Coefficients (T_l) for Proton
 a: Koning and Delaroche (2003)
 d: Becchetti and Greenlees (1969b)



Transmission Coefficients (T_l) for Proton

a: Koning and Delaroche (2003)

d: Becchetti and Greenlees (1969b)



Transmission Coefficients (T_l) for Proton

- a: Koning and Delaroche (2003)
- b: Young and Arthur (1984, 1994) for ^{197}Au ;
- d: Becchetti and Greenlees (1969b)

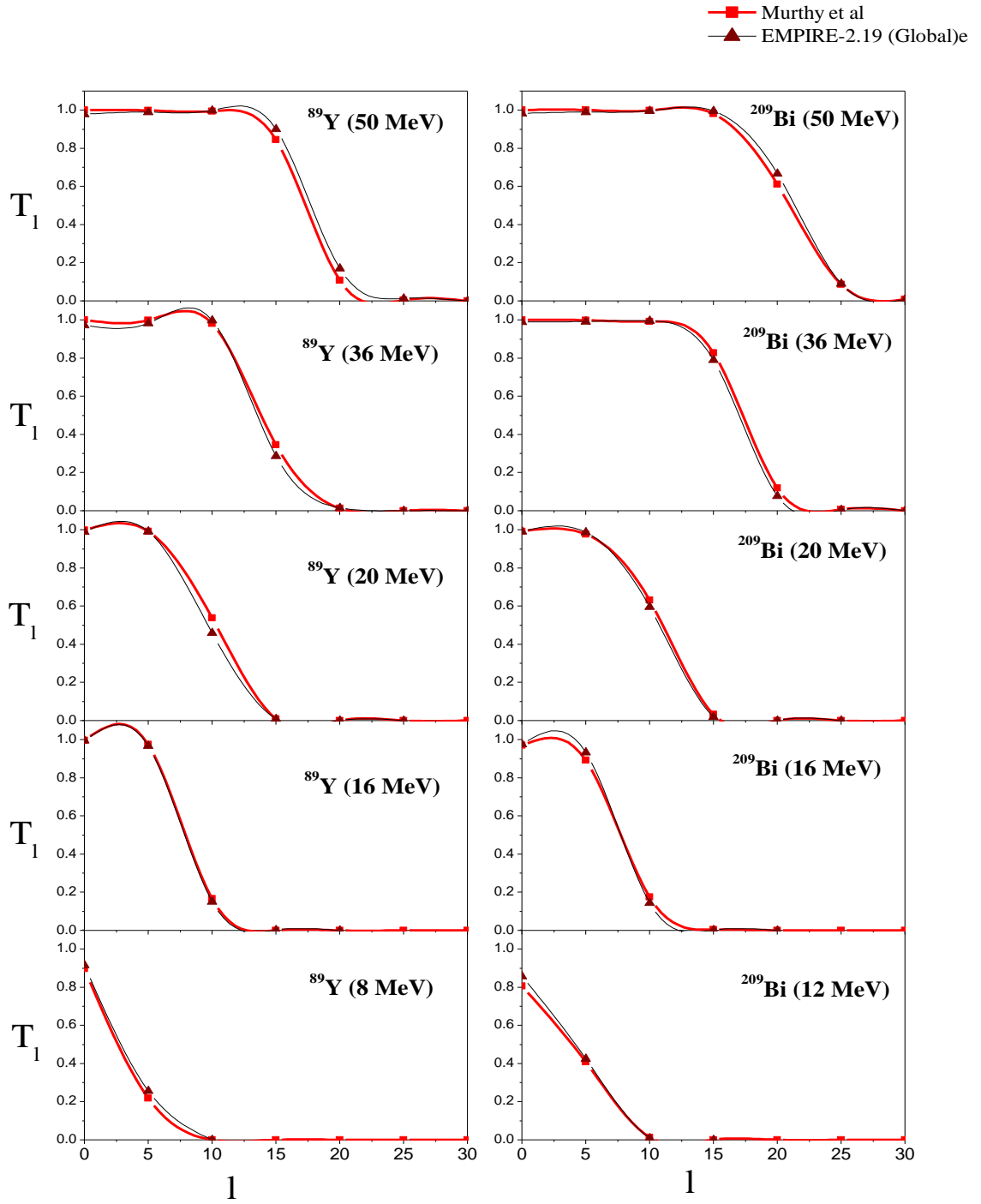


Fig.9

Transmission Coefficients (T_1) for Deuteron

e: Lohr and Haerberli (1974)

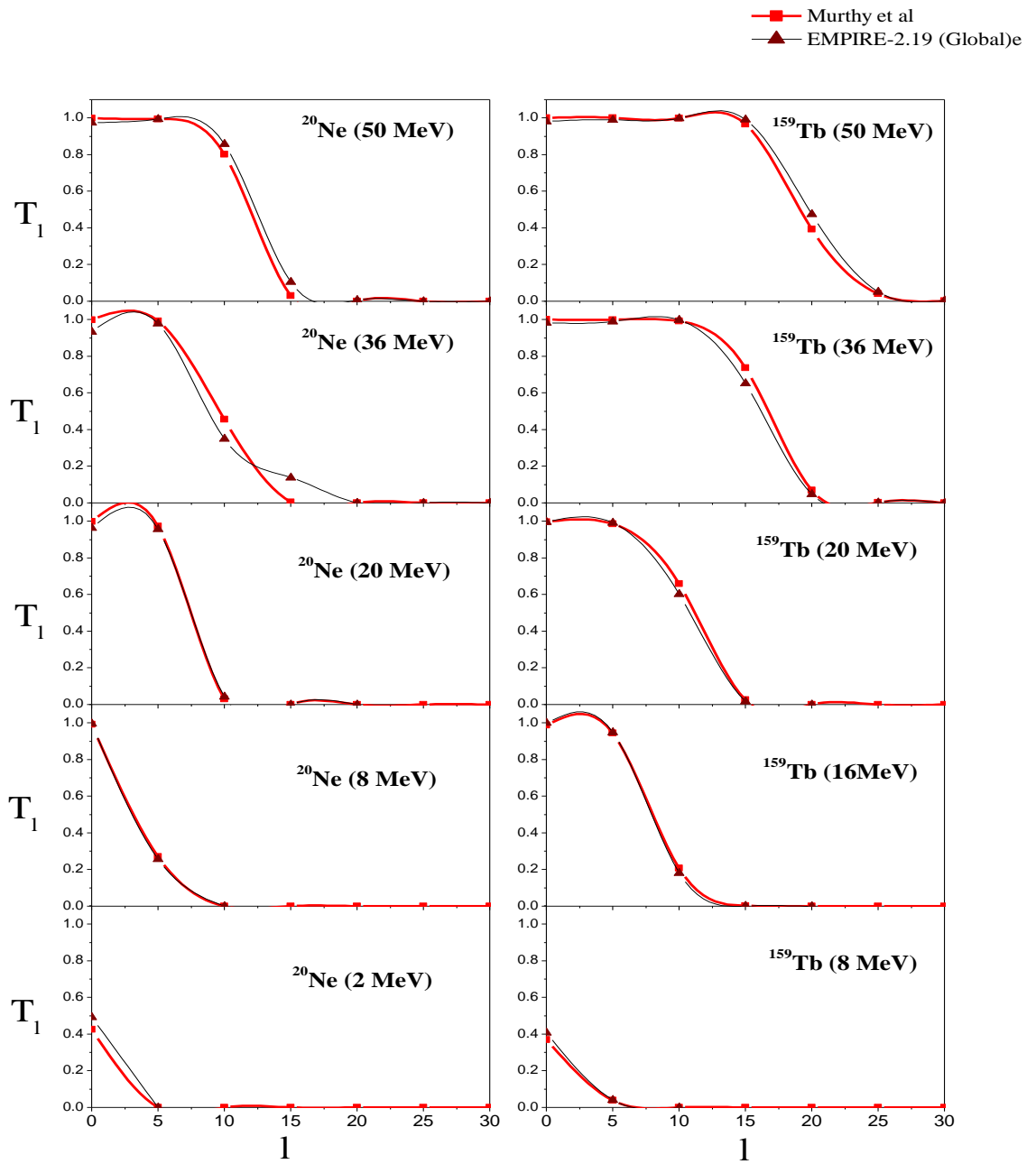


Fig.10

Transmission Coefficients (T₁) for Deuteron

e: Lohr and Haerberli (1974)

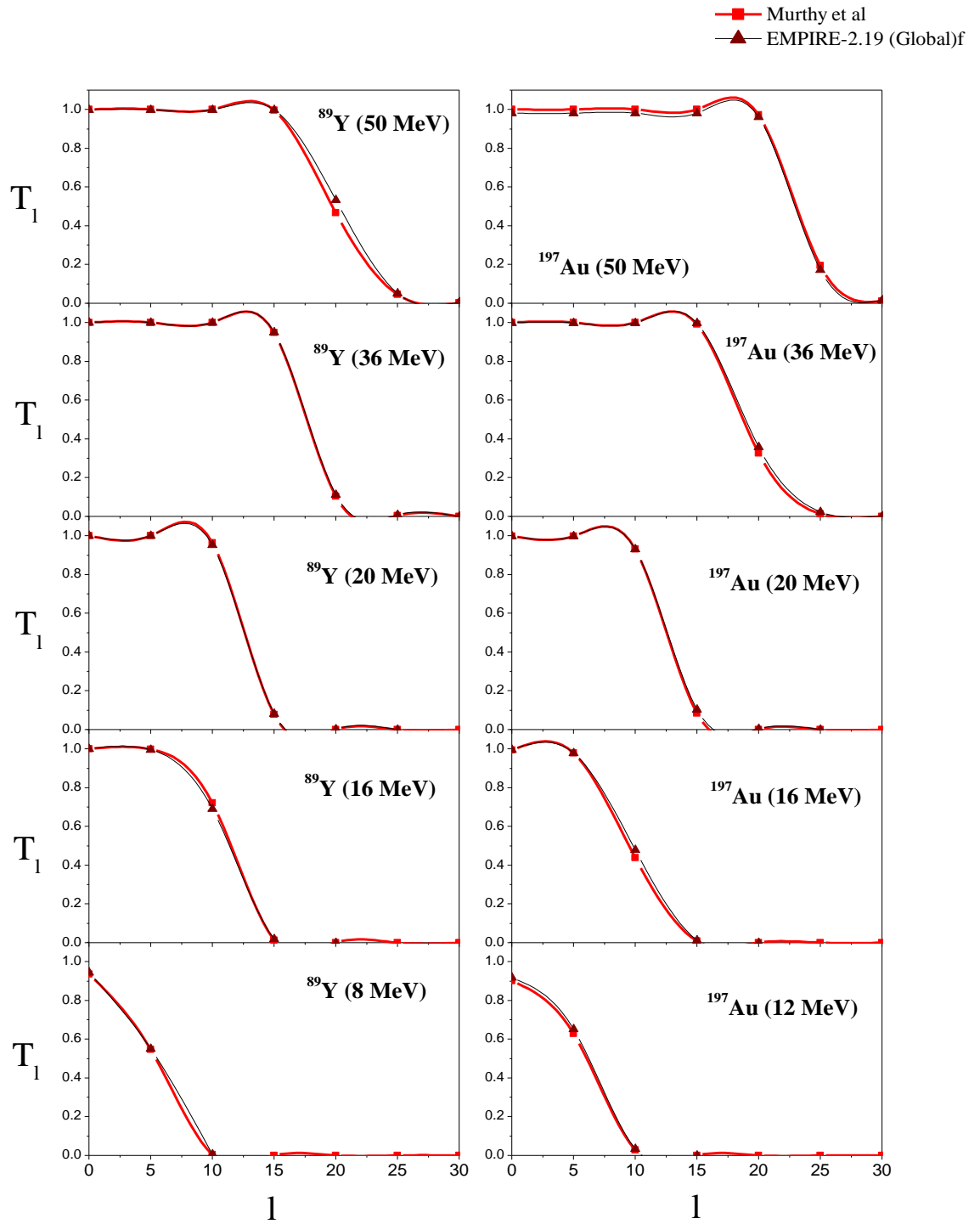


Fig.11

Transmission Coefficients (T_1) for Triton

f: Becchetti and Greenlees (1969a)

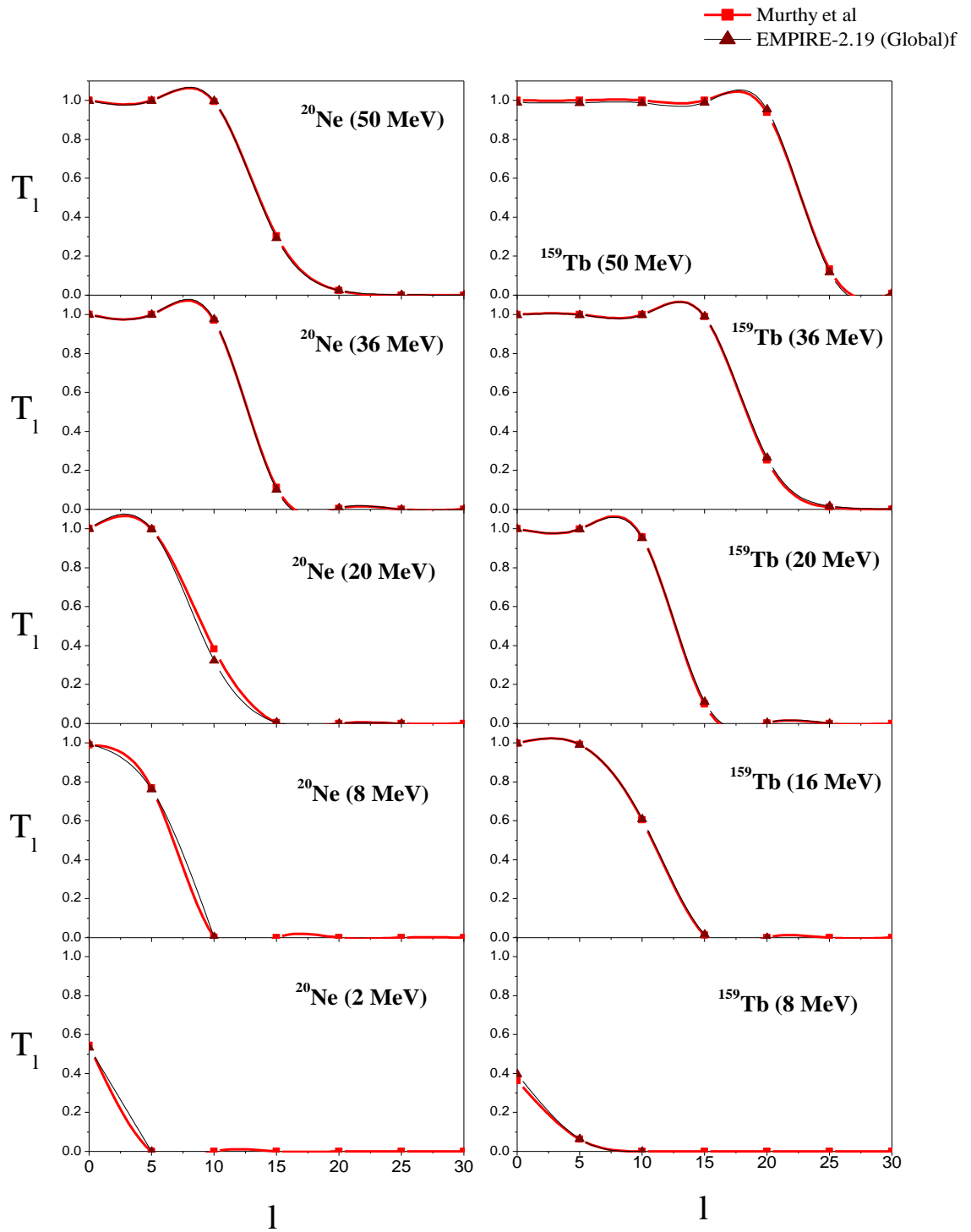


Fig.12

Transmission Coefficients (T_1) for Triton
 f: Becchetti and Greenlees (1969a)

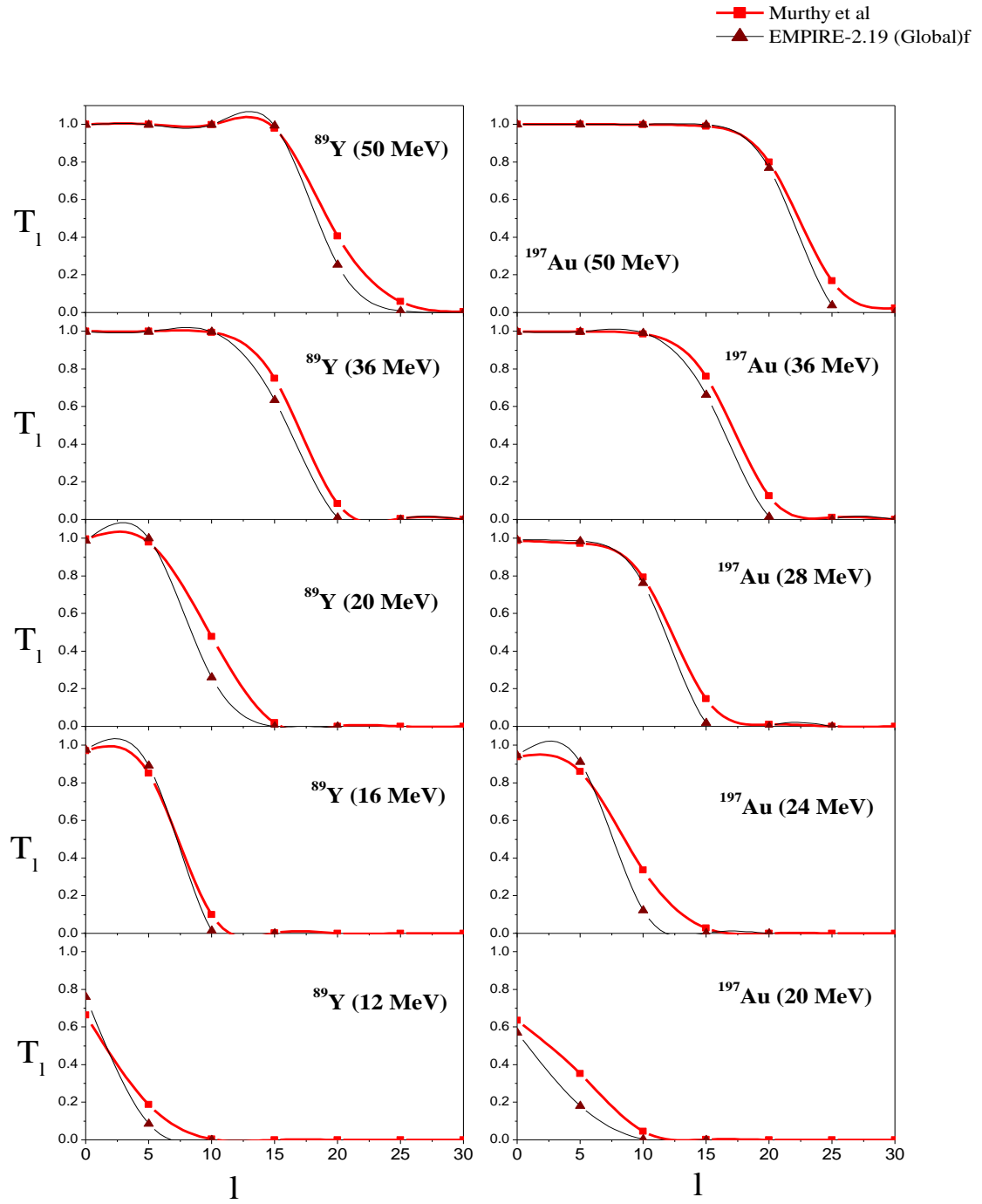


Fig.13

Transmission Coefficients (T_1) for Helium-3

f: Becchetti and Greenlees (1969a)

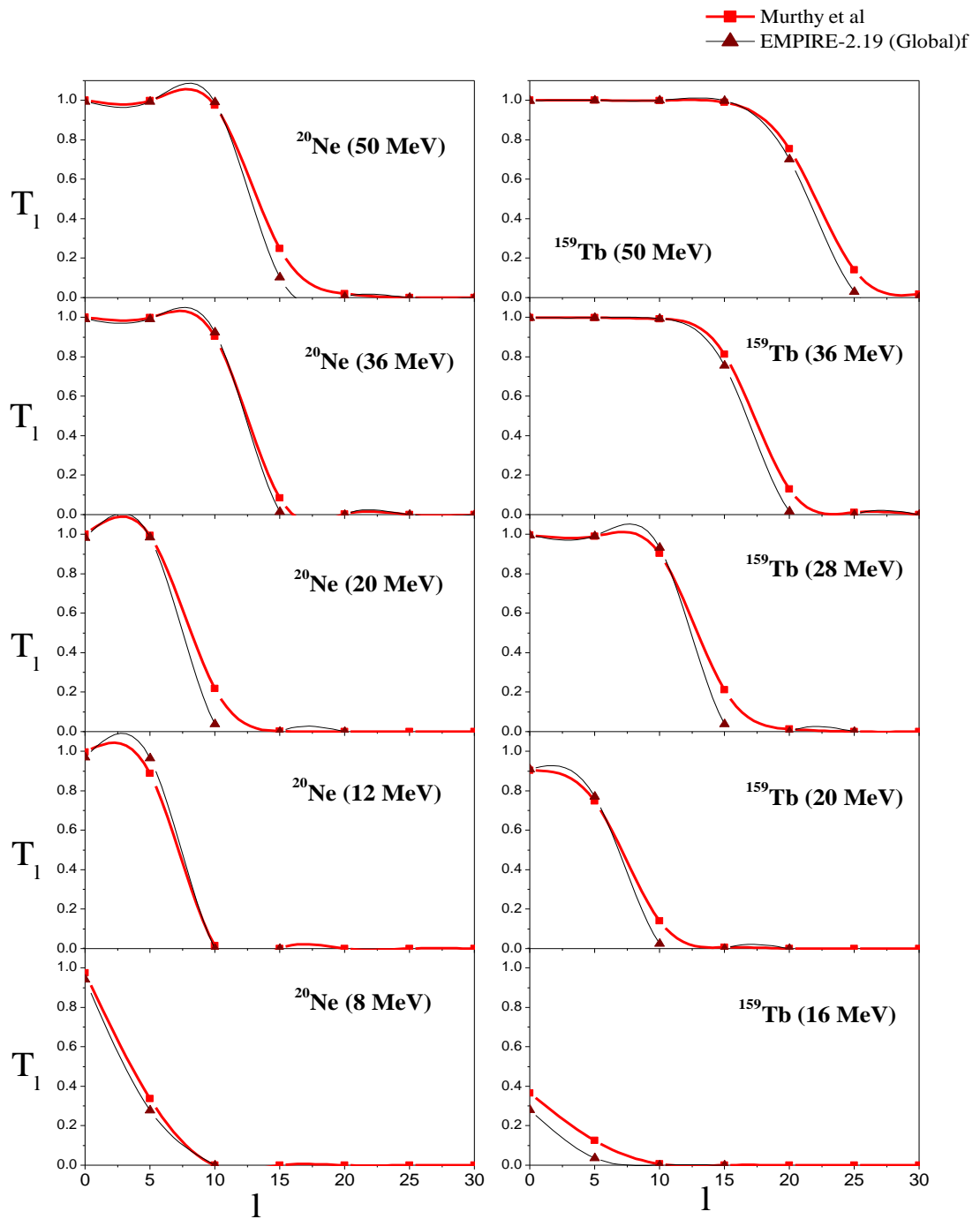


Fig.14

Transmission Coefficients (T_1) for Helium-3
 f: Becchetti and Greenlees (1969a)

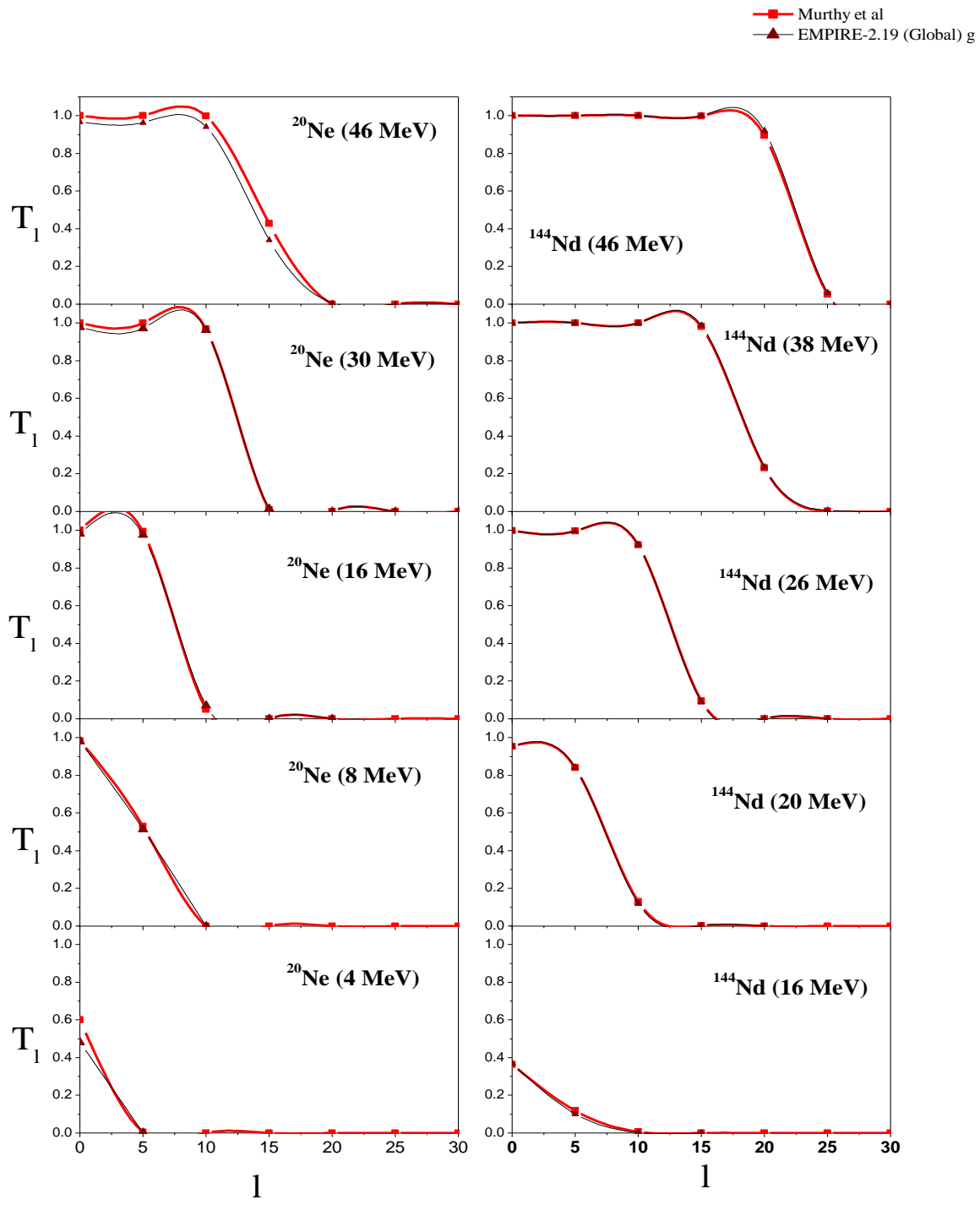


Fig.15

Transmission Coefficients (T_l) for Helium-4
 g: Huizenga and Igo (1961a)

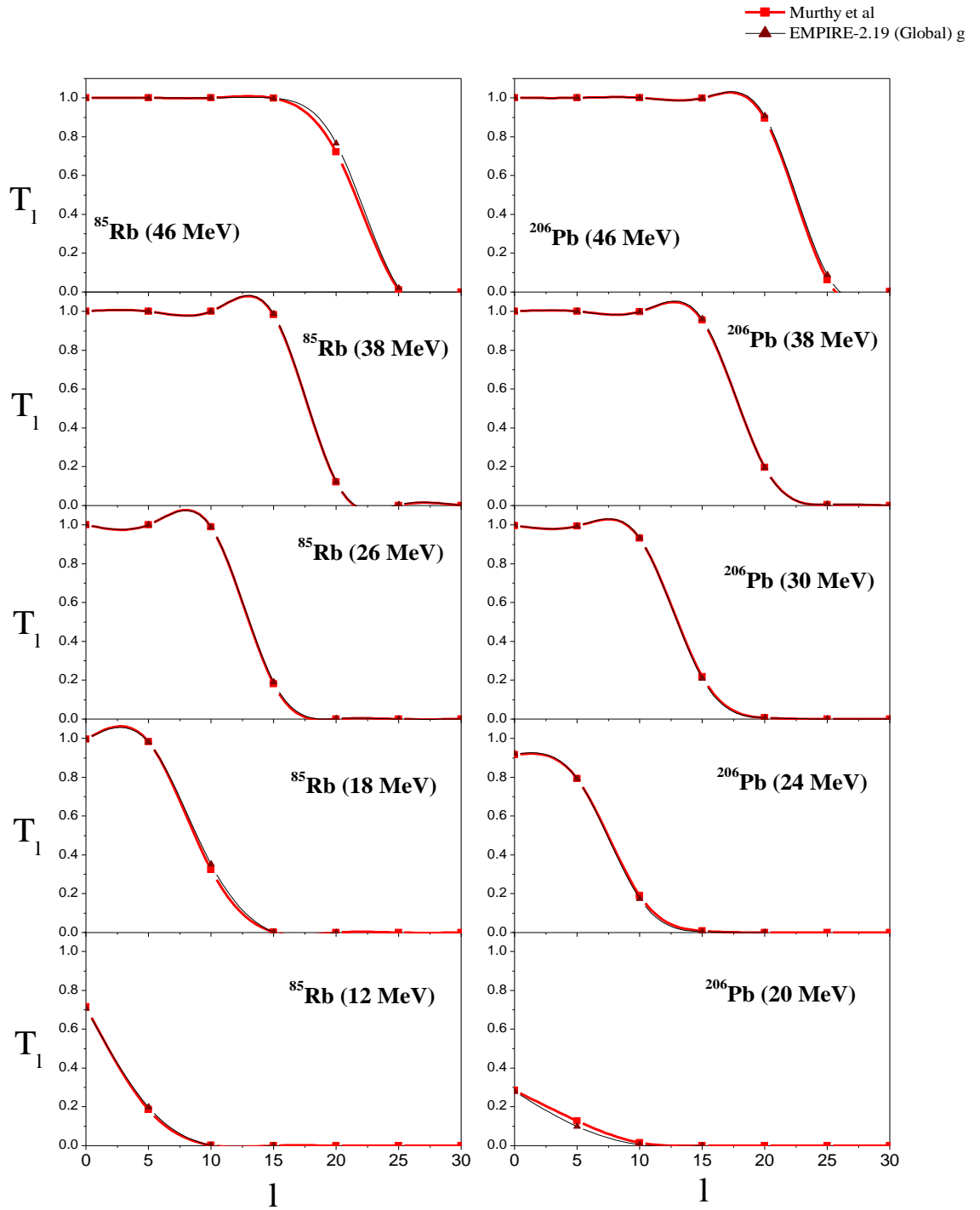


Fig.16

Transmission Coefficients (T_l) for Helium-4

g: Huizenga and Igo (1961a)

Transmission Coefficients (T_l) For Neutron

Table 4.1 Target: ^{20}Ne , Energy (Lab):100 MeV

Orbital angular momentum (l)	Wilmore and Hodgson (1964)	Murthy <i>et al.</i> , (1982)	Present work	Koning and Delaroche (2003)
0	2.99E-1	2.15E-1	2.51E-1	7.22E-1
2	3.19E-1	3.44E-1	3.20E-1	6.77E-1
4	3.64E-1	4.17E-1	4.26E-1	5.93E-1
6	4.29E-1	2.19E-1	4.81E-1	5.09E-1
8	2.67E-1	3.97E-2	2.62E-1	3.00E-1
10	6.96E-2	3.32E-3	5.90E-2	9.95E-2
12	1.14E-2	1.49E-4	7.25E-3	2.65E-2
14	1.73E-3	3.70E-6	5.67E-4	6.75E-3
16	2.65E-4	5.11E-8	2.91E-5	1.73E-3
18	4.07E-5	3.95E-10	9.93E-7	4.46E-4
20	6.27E-6	1.71E-12	2.25E-8	1.16E-4

Table 4.2 Target: ^{20}Ne , Energy (Lab):70 MeV

Orbital angular momentum (l)	Wilmore and Hodgson (1964)	Murthy <i>et al.</i> , (1982)	Present work	Koning and Delaroche (2003)
0	4.15E-1	3.60E-1	3.83E-1	7.24E-1
2	4.50E-1	4.70E-1	4.35E-1	6.92E-1
4	5.34E-1	6.02E-1	5.38E-1	6.39E-1
6	5.76E-1	2.67E-1	6.00E-1	5.8E-1
8	1.87E-1	2.55E-2	2.69E-1	1.93E-1
10	2.17E-2	9.33E-4	4.08E-2	3.74E-2
12	2.25E-3	1.56E-5	3.16E-3	6.69E-3
14	2.43E-4	1.22E-7	1.46E-4	1.21E-3
16	2.66E-5	4.46E-10	4.11E-6	2.25E-4
18	2.92E-6	7.70E-13	7.12E-8	4.29E-5
20	3.20E-7	6.28E-16	7.59E-10	8.31E-6

Transmission Coefficients (T_l) For Neutron

Orbital angular momentum (l)	Wilmore and Hodgson (1964)	Murthy <i>et al.</i> , (1982)	Present work	Koning and Delaroche (2003)
0	2.95E-1	5.09E-1	2.60E-1	9.02E-1
2	3.00E-1	5.11E-1	2.67E-1	8.95E-1
4	3.15E-1	5.16E-1	2.80E-1	8.81E-1
6	3.35E-1	5.58E-1	3.08E-1	8.58E-1
8	3.62E-1	8.31E-1	3.80E-1	8.15E-1
10	4.59E-1	5.50E-1	5.29E-1	7.42E-1
12	5.09E-1	3.70E-2	6.35E-1	7.07E-1
14	3.32E-1	9.91E-4	4.03E-1	4.54E-1
16	9.12E-2	1.47E-5	1.27E-1	1.52E-1
18	1.53E-2	1.23E-7	2.57E-2	4.08E-2
20	2.40E-3	5.87E-10	3.97E-3	1.06E-2

Table 4.3 Target: ^{107}Ag , Energy (Lab):100 MeV

Table 4.4 Target: ^{107}Ag , Energy (Lab):70 MeV

Orbital angular momentum (l)	Wilmore and Hodgson (1964)	Murthy <i>et al.</i> , (1982)	Present work	Koning and Delaroche (2003)
0	4.13E-1	3.80E-1	3.93E-1	8.75E-1
2	4.15E-1	3.86E-1	3.99E-1	8.68E-1
4	4.36E-1	4.02E-1	4.09E-1	8.55E-1
6	4.90E-1	4.76E-1	4.36E-1	8.28E-1
8	5.20E-1	7.51E-1	5.10E-1	7.80E-1
10	6.97E-1	6.59E-1	6.60E-1	8.03E-1
12	5.68E-1	1.11E-1	6.32E-1	5.63E-1
14	1.04E-1	7.68E-3	2.63E-1	1.26E-1
16	1.07E-2	3.25E-4	5.45E-2	2.28E-2
18	1.16E-3	8.85E-6	7.72E-3	4.19E-3
20	1.32E-4	1.56E-7	8.32E-4	7.96E-4

Chapter 5 *Summary and Conclusion*

Transmission coefficients for various projectiles are an important input for calculations using the statistical theory **(Hauser and Feshbach, 1952)** of nuclear reactions.

The statistical theory relates the average cross-sections and their fluctuations to the statistics of resonance parameters, and further relates the later to the physical models and to the basic principles.

Transmission coefficients are also related to the magnitude of the scattering matrix which is useful in description of elastic scattering. Usually they are obtained from a numerical solution of Schrödinger equation with an optical potential for each partial wave as has been discussed in Chapter 2.

The numerical solution of the Schrödinger equation involves a large amount of computational time and the use of tabulated values of T_ℓ 's for extensive statistical model calculations is cumbersome. These difficulties could be overcome by prescribing simple empirical expressions based on modified Hill-Wheeler expression.

So far, there is no unique form of optical potential. Various parameters are allowed to vary to fit the experimental data.

In the current study, we have compared transmission coefficients for light projectiles, calculated using empirical expressions of **Murthy *et al.*, (1982)** with those of EMPIRE-2.19 global potentials as well as specific potentials. We have proposed simple relations and parameters to predict the transmission coefficient values over the mass range 20-209 and energy greater than 50 MeV (up to 100 MeV), in case of neutron as projectile.

The present work confirms that parameterized empirical expressions of **Murthy *et al.*, (1982)** produce transmission coefficient values satisfactorily over the target mass range 20-209 and energies up to 50 MeV for light projectiles (n, p, ^2H , ^3H , ^3He and ^4He). Our parameters produce better transmission coefficient values for neutron over the mass range 20-209 and energy greater than 50 MeV (up to 100 MeV) than those for **Murthy *et al.*, (1982)**.

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Appendix A: PROGRAM TO CALCULATE TRANSMISSION COEFFICIENTS FOR NEUTRON

pdt111.for

```
c*****program for transmission coefficients for neutron
open (unit=8,file='pdt111.out',status='new')
write(*,*)'give AT,ELAB'
read(*,*)AT,ELAB
AP=1.0
a=0.66
r1=1.285
r2=-0.38
r3=1.87
r4=-4.93
d1=0.042
d2=0.021
d3=2.80
r0=1.322-(7.6E-4)*AT+(4.E-6)*AT**2-(8.E-9)*AT**3
ECM=AT*ELAB/(AP+AT)
R=r1*AT**(1./3.)+r2*ECM**(1./2.)+r3
x=.0482*AP*AT/(AP+AT)
Vo=47.01-.267*ECM-.0018*ECM**2
Vn=-Vo/(1.+exp((R-ro*AT**(1./3.))/a))
AL=x*(ECM-Vn+r4)*R**2
D=d1*ECM*AT**(1./3.)+d2*AT+d3
do 100 bl=0,20,2
y=exp(((bl*(bl+1.))-AL)/D)
fl=1./(1.+y)
A=((2.*bl+1.)*y)/D
B=(1.+y)**2
dfl=-A/B
AN1=1.09-.085*sqrt(ECM)
C=12.98*AT**(-1./3.)
F=76.38*AT**(-1./3.)*ECM**(-1./2.)
G=37.55*ECM**(-1./2.)
AN2=7.94-C+F-G
if(AN2*dfl.gt.AN1*fl) then
Tl=AN1*fl
else
Tl=AN1*fl-AN2*dfl
endif
write(8,*)'AT,ELAB,bl,Tl'
write(8,*)AT,ELAB,bl,Tl
100 continue
stop
end
```

Appendix B: PROGRAM TO CALCULATE TRANSMISSION COEFFICIENTS FOR CHARGED PARTICLES

Program to Calculate v_0 's and r_0 for Charged Projectiles *real1.for*

```
open(unit=7,file='real1.out',status='new')
write(*,*)'give zt,at,elab'
read(*,*) zt,at,elab
nt=at-zt
Ecm=at*elab/(1+at)
v0n=47.01-0.267*Ecm-0.0018*Ecm**2
r0n=1.322-7.6*10**(-4.0)*at+4*10**(-6.0)*at**2-8*10**(-9.0)*at**3
v0p=54.0-0.32*elab+24.0*(nt-zt)/at+.4*zt/at**(1./3.)
v0d=91.33+2.2*zt/at**(1./3.)
v0t=165.0-.17*elab-6.4*(nt-zt)/at
v0h=151.9-.17*elab+50.0*(nt-zt)/at
r0=1.17+1.77/at**(1./3.)
write(7,*)'Ecm,v0n,r0n,v0p,v0d,v0t,v0h,r0'
write(7,*)Ecm,v0n,r0n,v0p,v0d,v0t,v0h,r0
close(7)
stop
end
```

pdt3.inp

```
1.730,-0.49,2.27,-2.0,0.0,0.041,4.18,0.087,0.0,0.019,1.47
1.580,-0.25,3.29,-5.0,0.153,0.026,1.52,0.133,0.048,-0.050,4.50
1.257,-0.42,5.44,0.0,0.097,,0.022,6.71,0.799,-0.079,0.001,1.26
1.638,-0.38,4.09,0.0,0.154,0.043,3.07,0.593,0.0,-0.168,4.44
1.451,-0.26,3.74,0.0,0.137,0.025,4.53,0.238,0.0,0.031,3.09
57.0359,1.17,0.75
122.1,1.05,0.86
164.66,1.2,0.72
150.54,1.2,0.72
50.0,1.572,0.576
```

pdt3.for

```
c*****program for transmission coefficients of charged particles
dimension a(5,11),b(5,3)
open(unit=7,file='pdt3.inp',status='old')
```

```

        open(unit=8,file='pdt3.out',status='new')
        do 100 i=1,5
100    read(7,*)(a(i,j),j=1,11)
        do 100 i=1,5
110    read(7,*)(b(i,j),j=1,3)
        write(*,*)'give AT,ZT,AP,ZP,ELAB'
        read(*,*)AT,ZT,AP,ZP,ELAB
        do 120 i=1,5
            r1=a(i,1)
            r2=a(i,2)
            r3=a(i,3)
            r4=a(i,4)
            d1=a(i,5)
            d2=a(i,6)
            d3=a(i,7)
            d1p=a(i,8)
            d2p=a(i,9)
            d3p=a(i,10)
            d4p=a(i,11)
            Vo=b(i,1)
            ro=b(i,2)
            apr=b(i,3)
            ECM=(AT*ELAB)/(AT+AP)
            R=r1*AT**(1./3.)+r2*ECM**(1./2.)+r3
            VN=-Vo/(1.+exp((R-ro*AT**(1./3.))/apr))
            VC=1.44*ZP*ZT/R
            D=d1*ECM*(AT**(1./3.))+d2*AT+d3
            Dp=(d1p*AT**(1./3.)+d2p*AT**(2./3.))*ECM+d3p*AT+d4p
            x=0.0482*AP*AT/(AP+AT)
            bL=x*(ECM-VN-VC)*(R**2)+(R4/ECM)
            do 500 al=0,20,2
                ale=al*(al+1.)
                fl=1./(1.+exp((ale-bL)/D))
                if(r1.eq.a(1,1)) then
                    AN=1.153-1.02*AT**(-1./3.)
                else
                    AN=1.0
                endif
                if(ale.le.bL) then
                    Tl=AN*fl
                else
                    Tl=AN*exp(-(ale-bL)/Dp)*0.5
                endif
                write(8,*)'AT,AP,al,ELAB,Tl'
                write(8,*)AT,AP,al,ELAB,Tl
500    continue

```

```
120 continue
    close(7)
    close(8)
    stop
end
```

Vita

Pravesh Dhyani, the author of this manuscript, was born on September 19, 1984 at Kashipur, Udham Singh Nagar, District of Uttranchal. He passed High School Examination in 1998 from G. B. Pant Inter College (Kashipur) and Intermediate Examination in 2001 from U.H. Inter College (Kashipur).

He earned B.Sc. degree from Kumaon University, Nainital in 2004. Same year he joined the M.Sc. (Physics) in historic G. B. Pant University of Agriculture and Technology, Pantnagar, Uttranchal. During his Masters Degree he was a recipient of graduate teaching assistantship. Prior to it, he qualified JEST-2006 with 94.2 percentile.

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ABSTRACT

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**Thesis Title: “Transmission Coefficients For Light Projectiles
Based On Global Optical Potentials”**

Advisor: Dr. H. M. Agrawal

Present Work is motivated to compute transmission-coefficients for light projectiles (n, p, ^2H , ^3H , ^3He and ^4He) with the help of simple empirical expressions together with different global and specific optical potentials available in the literature.

On the basis of parameterized expressions, an empirical fit has been proposed for neutron projectile, which is in better agreement with Wilmore and Hodgson's global potential compared to empirical expressions of Murthy *et al.* over the target mass range 20-209 and energy greater than 50 MeV (up to 100 MeV).

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