

Final Report

on

NAG1-1789

**RADIATION TRANSPORT AND SHIELDING
FOR
SPACE EXPLORATION AND HIGH SPEED FLIGHT
TRANSPORTATION**

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**Title: Radiation Transport and ~~High Speed Flight Transportation~~ for Space
Exploration and High Speed Flight Transportation**

Principal Investigator: Dr. Khin Maung Maung

Senior Scientist: Dr. R. K. Trapathi

**Institution: Department of Physics
Hampton University**

Transportation of ions and neutrons in matter is of direct interest in several technologically important and scientific areas, including space radiation, cosmic ray propagation studies in galactic medium, nuclear power plants and radiological effects that impact industrial and public health. For the proper assessment of radiation exposure, both reliable transport codes and accurate data are needed. Nuclear cross section data is one of the essential inputs into the transport codes. In order to obtain an accurate parametrization of cross section data, theoretical input is indispensable especially for processes where there is little or no experimental data available.

In this grant period work has been done on the studies of the use of relativistic equations and their one-body limits. The results will be useful in choosing appropriate effective one-body equation for reaction calculations. Work has also been done to improve upon the data base needed for the transport codes used in the studies of radiation transport and shielding for space exploration and high speed flight transportation. A phenomenological model was developed for the total absorption cross sections valid for any system of charged and/or uncharged collision pairs for the entire energy range. The success of the model is gratifying. It is being used by other federal agencies, national labs and universities. A list of publications based on the work during the grant period is given below and copies are enclosed with this report.

- (1). One-Body Limits of Two-Body Relativistic Equations, in "Quark Confinement and the Hadron Spectrum II", page 380, World Scientific, Edt. N. Brambilla and G. M. Prosperini. 1996
- (2). Universal parametrization of absorption cross sections, NASA TP 3621
- (3). Accurate universal parametrization of absorption cross section, Nucl. Instr. Meth. Phys. Res. B 117 (1996)347.
- (4). Accurate universal parametrization of absorption cross section II, Nucl. Instr. Meth. Phys. Res. B 129 (1997) 11.

Quark Confinement and the Hadron Spectrum II

Como, Italy

26 – 29 June 1996

Editors

N. Brambilla & G. M. Prosperi

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ONE-BODY LIMITS OF TWO-BODY RELATIVISTIC EQUATIONS

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The bound state spectra of the Blankenbecler- Sugar, Kadyshevsky and Gross equations with a linearly confining interaction are studied. As a result of the lack of retardation in the interaction, all of these equations approach the same one-body limit, but the rates of approach are different. Numerical results show that the one-body limit is reached when $m_2/m_1 = 10$ for this particular interaction.

In a two particle system of masses m_1 and m_2 , in the limit that m_1 or m_2 goes to infinity the relativistic equation for this system should be one which describes the motion of the lighter particle in the instantaneous field of the heavier particle; the relative energy between the particles is zero. This is known as the one-body limit. The Blankenbecler-Sugar¹, Kadyshevsky², and Gross³ equations are studied to determine how the one-body limit is approached as m_2 is increased with m_1 fixed. The momentum space two-body relativistic bound state equations are solved with a confining potential without retardation.⁴

A wide class of relativistic two-body propagators can be written as

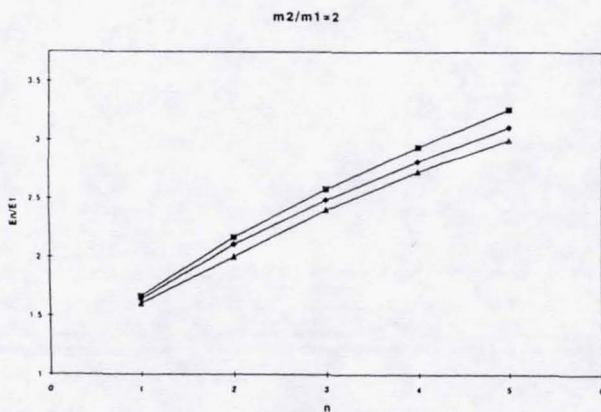
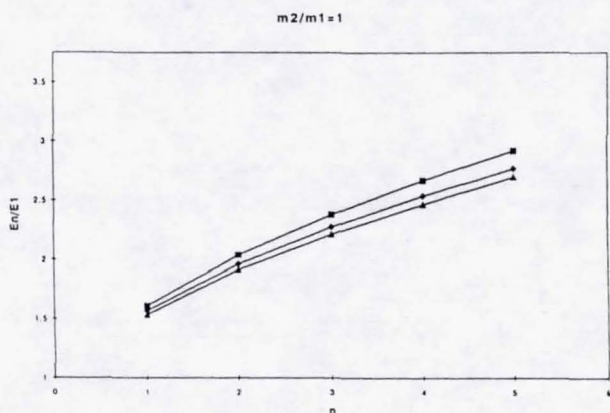
$$g(s', s) = -2\pi i \int \frac{f(s', s)}{s' - s + i\eta} \delta^{(+)}(A) \delta^{(+)}(B) ds'$$

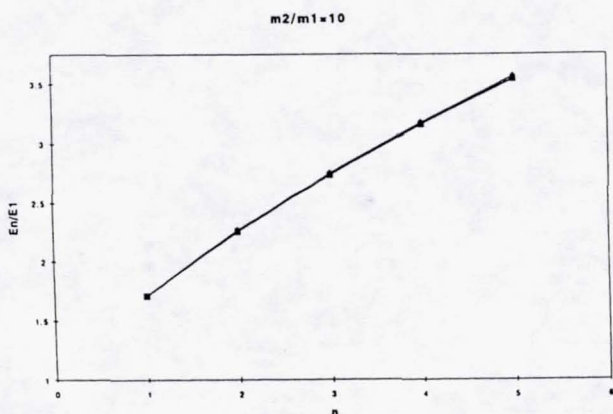
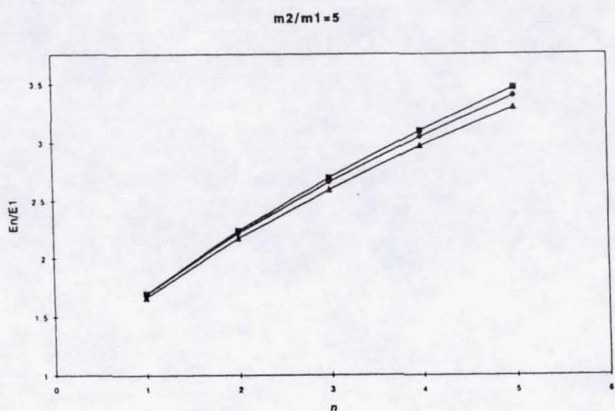
where k and P are the relative and total four-momenta and $f(s', s)$ is any function that satisfies the constraint $f(s, s) = 1$. Therefore in principle there exist an infinite number of three-dimensional equations.⁵ The choices for A and B in the arguments of the delta functions are chosen to distinguish between one particle on-mass-shell systems and both particles equally off-mass-shell.

For one particle on-mass-shell systems, Type I, $A = (aP + k)^2 - m_1^2$ and $B = (P' - aP - k)^2 - m_2^2$ and $A = (aP' + k)^2 - m_1^2$ and $B = (bP' - k)^2 - m_2^2$ for Type II, both particles equally off-mass-shell. In order to have a one-body limit in three-dimensional equations, we use the Wightman-Garding variables^{6, 7}, a and b ; $a = (s + m_1^2 - m_2^2)/2s$ and $b = (s + m_2^2 - m_1^2)/2s$ where s is the total

four-momentum squared. Explicit forms of propagators in the center-of-mass frame have been tabulated.⁸ The Blankenbecler-Sugar propagator is Type II, while the Kadyshevsky and Gross propagators are Type I.

In these preliminary calculations, we study the bound state spectrum of these equations with a linear confining interaction without retardation. The figures represent each of the three equations evaluated with increasing m_2 . In figures (1) to (4) the mass ratios are 1, 2, 5 and 10 respectively. In each figure, squares, diamonds and triangles represent the Kadyshevsky, Blankenbecler-Sugar and Gross results.





The curves display important revelations: for this particular interaction, the various equations approach the same one-body limit at different rates, and a mass ratio is determined for a two particle bound state system to reach the one-body limit at m_2 to m_1 equal 10.

The results can be understood in the following way. As m_1 or m_2 goes to infinity the choice of type becomes insignificant. The function $f(s', s)$ goes to unity as well if one particle mass goes to infinity. Therefore for any nonretarded interaction, they all have the same one-body limit. Although a one-body limit

was reached, the Klein-Gordon result was not obtained. This shortcoming is attributed to additional multiplicative terms that vary from one propagator to the next but nevertheless prevent the Klein-Gordon limit from being reached.⁹ However, $f(s', s)$ does not equal one in general. This accounts for the difference in the rates of approach to the one-body limit for the different equations.

In conclusion, it is shown that the same one-body limit is reached for Type I and Type II equations without retardation in the interaction. This can be helpful when evaluating a two particle system; the results suggest that a one-body equation should not be used if the mass ratios of the particles are not consistent with the results obtained above, at least for this particular interaction. This type of study should also be considered for scattering problems where the use of a one-body equation is very common.

Acknowledgements

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Beam Interactions with Materials & Atoms

Nuclear Instruments and Methods in Physics Research B 117 (1996) 347-349

Accurate universal parameterization of absorption cross sections

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Accurate universal parameterization of absorption cross sections

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Abstract

We present a simple universal parameterization of total reaction cross sections for any system of colliding nuclei valid for the entire energy range from a few A MeV to a few A GeV. The universal picture presented here treats the proton-nucleus collision as a special case of the nucleus-nucleus collision, where the projectile has charge and mass number one. The parameters are associated with the physics of the collision system. In general terms Coulomb interaction modifies cross sections at lower energies and the effects of Pauli blocking are important at higher energies. The agreement between the calculated and experimental data is better than all earlier published results.

1. Introduction

The transportation of energetic ions in bulk matter is of direct interest in several areas [1] including shielding against ions originating from either space radiations or terrestrial accelerators, cosmic ray propagation studies in galactic medium or radiobiological effects resulting from the work place or clinical exposures. For carcinogenesis, terrestrial radiation therapy, and radiobiological research, knowledge of the beam composition and interactions is necessary to properly evaluate the effects on human and animal tissues. For the proper assessment of radiation exposures both reliable transport codes and accurate input parameters are needed.

One such important input is the total reaction cross section, defined as the total minus the elastic cross sections for two colliding ions:

$$\sigma_R = \sigma_T - \sigma_{el}. \quad (1)$$

In view of its importance the total reaction cross section has been extensively studied both theoretically [1-14] and experimentally [15-20] for the past five decades. A detailed list of references is given in Refs. [1,13,16]. Empirical prescriptions have been developed [2-4,10,11,13] for the total reaction cross sections working in various energy ranges and combination of interacting ions. The present model works in all energy ranges for any combination of interacting ions including proton-nucleus collisions and is more accurate than earlier reported empirical models.

2. Model description

The present model is an updated and revised version of the empirical model developed at NASA Langley Research Center and reported earlier [10]. Most of the empirical models approximate the total reaction cross section of the Bradt-Peters form:

$$\sigma_{abs} = \pi r_0^2 (A_P^{1/3} + A_T^{1/3} - \delta)^2, \quad (2)$$

where r_0 is energy independent and δ is either an energy-independent or energy dependent parameter, and A_P and A_T are the projectile and target mass numbers, respectively. This form of parameterization works nicely for higher energies. However, for lower energies Coulomb interaction becomes important and modifies the reaction cross sections significantly. In addition, strong absorption models suggest an energy dependence of the interaction radius. Incorporating these effects, and other effects discussed later in the text, we propose the following form for the reaction cross section:

$$\sigma_R = \pi r_0^2 (A_P^{1/3} + A_T^{1/3} + \delta_E)^2 (1 - B/E_{cm}). \quad (3)$$

We notice that the Coulomb interaction, where $r_0 = 1.1$ fm, and E_{cm} is in MeV, modifies the cross sections at lower energies and gets less important as the energy increases (typically after several tens of A MeV). In Eq. (3) B is the energy dependent Coulomb interaction barrier (right hand factor in Eq. (3)), and is given by

$$B = 1.44 Z_P Z_T / R, \quad (4)$$

where

$$R = r_P + r_T + 1.2 (A_P^{1/3} + A_T^{1/3}) / E_{cm}^{1/3}, \quad (5)$$

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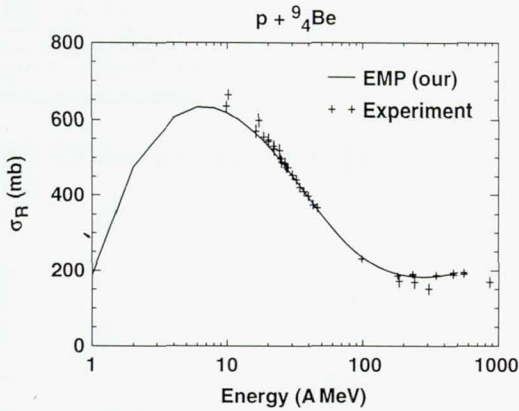


Fig. 1. Absorption cross sections for the proton-beryllium collision as a function of proton kinetic energy. The solid line represents present model and the experimental data are from Ref. [15].

with ($i = P, T$)

$$r_i = 1.29(r_i)_{\text{rms}}. \quad (6)$$

There is an energy dependence in the reaction cross section at intermediate and higher energies mainly due to two effects – transparency and Pauli blocking. This is taken into account in δ_E , which is given by

$$\delta_E = 1.85S + 0.16 \frac{S}{E_{\text{cm}}^{1/3}} - C_E + 0.91 \frac{(A_T - 2Z_T)Z_P}{A_T A_P}, \quad (7)$$

where S is the mass asymmetry term and is given by

$$S = A_P^{1/3} A_T^{1/3} / (A_P^{1/3} + A_T^{1/3}) \quad (8)$$

and is related to the volume overlap of the collision system. The last term on the right hand side of Eq. (7) accounts for the isotope dependence of the reaction cross section. The term C_E is related to the transparency and Pauli blocking and is given by

$$C_E = D(1 - \exp(-E/40)) - 0.292 \exp(-E/792) \times \cos(0.229E^{0.453}). \quad (9)$$

Here D is related to the density dependence of the colliding system scaled with respect to the density of the C+C system, i.e.:

$$D = 1.75(\rho_{A_P} + \rho_{A_T}) / (\rho_{A_C} + \rho_{A_C}). \quad (10)$$

The density of a nucleus is calculated in the hard sphere model [24], and for a nucleus of mass number A_i is given by

$$\rho_{A_i} = A_i / \frac{4}{3} \pi r_i^3, \quad (11)$$

where the radius of the nucleus r_i is defined in Eq. (6) with the root-mean-square radius, $(r_i)_{\text{rms}}$, obtained directly from experiment [25]. There is interesting physics associated with the constant D . This in effect simulates the modifications of the reaction cross sections due to Pauli blocking.

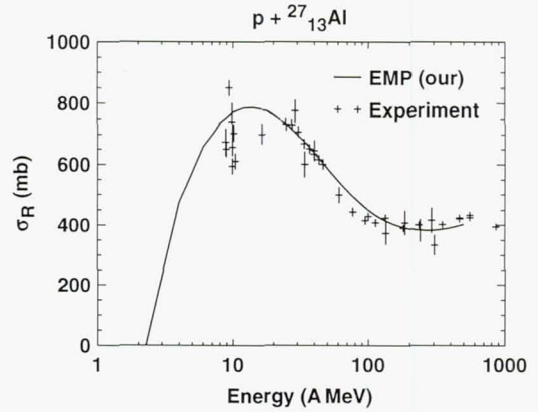


Fig. 2. Absorption cross sections for the proton-aluminum collision as a function of proton kinetic energy. The solid line represents the present model and the experimental data are from Ref. [15].

This effect is new and has not been taken into account in other empirical calculations. This helps present a universal picture of the reaction cross sections.

At lower energies (below several tens of A MeV) where the overlap of interacting nuclei is small (and where Coulomb interaction modifies the reaction cross sections significantly) the modifications of the cross sections due to Pauli blocking are small, and gradually play an increasing role as the energy increases, since this leads to higher densities where Pauli blocking gets increasingly important. Interestingly enough for the proton-nucleus case, since there is not much compression effect, a single constant value of $D = 2.05$ gives very good results for all proton-nucleus collisions. For alpha-nucleus collisions, where there is a little compression, the best value of D is given by

$$D = 2.77 - 8.0 \times 10^{-3} A_T + 1.8 \times 10^{-5} A_T^2 - 0.8 / (1 + \exp(250 - E)/75). \quad (12)$$

For lithium nuclei because of the “halos”, compression is less and hence the Pauli blocking effect is less important and a reduced value of $D/3$ gives better results for the reaction cross sections at the intermediate and higher energies.

There are no adjustable parameters in the model except that for proton-nucleus collisions this method of calculating the Coulomb energy underestimates its value for the very light closed shell nuclei of alpha and carbon, and these should be increased by a factor of 27 and 3.5 respectively for a better fit.

3. Results/conclusions

Typical results obtained from the model are shown in Figs. 1 through 5. Agreement with experimental data is excellent and is better than all other empirical models reported earlier. This is particularly important in view of the fact that the agreement is excellent throughout the whole energy

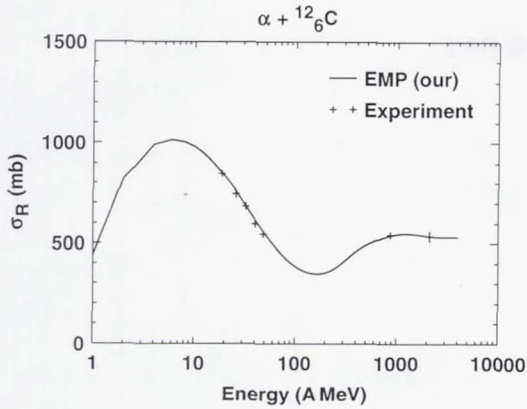


Fig. 3. Absorption cross sections for the alpha-carbon collision as a function of incident ion kinetic energy. The solid line represents present model and the experimental data are from Refs. [21,22].

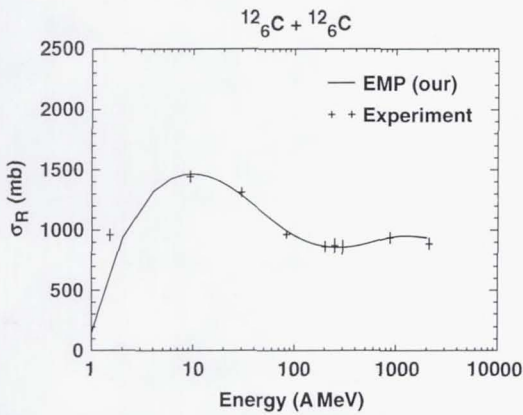


Fig. 4. Absorption cross sections for the carbon-carbon collision as a function of incident ion kinetic energy. The solid line represents the present model and the experimental data are from Refs. [1,9,13,16].

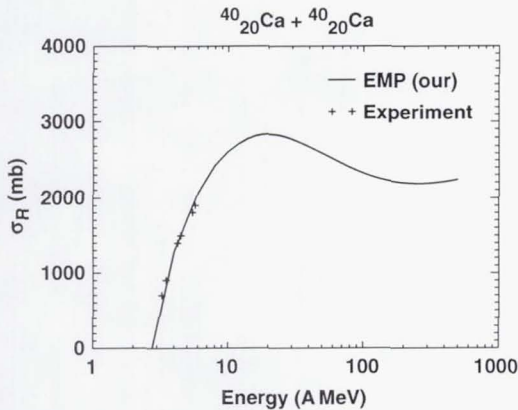


Fig. 5. Absorption cross sections for the calcium-calcium collision as a function of incident ion kinetic energy. The solid line represents the present model and the experimental data are from Refs. [1,9,13,16].

range – up to a few A GeV. The model has been tested with all the available data for projectiles proton through krypton and targets alpha through bismuth for the energy range from a few A MeV up to a few A GeV and is found to give excellent results for all the systems throughout the energy range. In view of the simplicity and accuracy of the model it is a welcome improvement for transport calculations.

It will be interesting to see how the model compares with the new experimental data as and when these become available.

Acknowledgements

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Accurate universal parameterization of absorption cross sections II
— neutron absorption cross sections

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Accurate universal parameterization of absorption cross sections II — neutron absorption cross sections

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Abstract

A recent parameterization (here after referred as paper I, Ref. [4]) of absorption cross sections for any system of charged ions collisions including proton–nucleus collisions, is extended for neutron–nucleus collisions valid from ~ 1 MeV to a few GeV, thus providing a comprehensive picture of absorption cross sections for any system of collision pair (charged and/or uncharged). The parameters are associated with the physics of the problem. At lower energies, the optical potential at the surface is important and the Pauli operator plays an increasingly important role at intermediate energies. The agreement between the calculated and experimental data is better than earlier published results.

1. Introduction

The transport of neutrons in matter is of direct interest in several technologically important and scientific areas [1–3] including space radiations, cosmic ray propagation studies in galactic medium, nuclear power plants, radiobiological effects impacting on industrial and public health. For the proper assessment to radiation exposures both reliable transport codes and accurate input data are needed.

An important ingredient of the input data is the total absorption (reaction) cross section, defined as the total minus the elastic cross sections for two colliding ions:

$$\sigma_R = \sigma_T - \sigma_{el}. \quad (1)$$

Recently, we have developed a simple accurate formalism (paper I and Ref. [5]) for the total absorption cross sections for any system of charged colliding ions including protons. The present work extends the formalism to neutron–nucleus collisions, thus presenting a simple accurate comprehensive formalism for the absorption cross sections for any combination of colliding ions (charged and/or uncharged) valid for the entire energy range. We have retained the high energy features of the model [6] developed here at NASA Langley Research Center (LaRC) where it is accurate, and improved on its behavior at lower energies within the universal formalism recently developed (paper I and Ref. [5]). The other commonly used model [7] gives good

results for higher energies but shows increasingly larger deviations from experiment for lower energies.

2. Model description

Most of the empirical models approximate total reaction cross section for charged ion collisions of Bradt–Peters form [8], but have very different form for the neutron–nucleus collisions. We have maintained the uniform consistent picture for all the systems proton–nucleus, nucleus–nucleus, and now for the neutron–nucleus collisions, and have written total reaction cross sections for neutron–nucleus collisions also of the Bradt–Peters form:

$$\sigma_R = \pi r_0^2 (A_P^{1/3} + A_T^{1/3} - \delta)^2, \quad (2)$$

where r_0 is energy independent and δ is either energy-independent or dependent parameter, and A_P and A_T are the projectile and target mass numbers respectively.

It is well known that this type of parameterization is suited for higher energies and is modified through Coulomb interaction at lower energies (paper I and Ref. [5]) for the charged ion collisions. For the neutron–nucleus collisions there is no Coulomb interaction, but the total reaction cross section, in this case, is modified by the strength of the imaginary part of the optical potential at the surface. Since we are using this form of parameterization for the neutron–nucleus case for the first time (which helps to provide the unified consistent and accurate picture for the total reaction cross sections for any system of colliding nuclei for the entire energy range), we introduce a low

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energy multiplier (X_m) accounting for the strength of the optical model interaction. In addition, the effects of the transparency and Pauli blocking are taken into account through the energy dependent parameter, δ_E , defined latter in the text. We, therefore, propose the following similar form for the reaction cross sections for the neutron–nucleus:

$$\sigma_R = \pi r_0^2 (A_P^{1/3} + A_T^{1/3} + \delta_E)^2 X_m, \quad (3)$$

where $r_0 = 1.1$ fm. The low energy multiplier X_m is given by

(i) For $A_T < 200$

$$X_m = 1 - X_1 \exp\left(-\frac{E}{X_1 S_L}\right), \quad (4)$$

where $S_L = 0.6$ for $A_T < 12$, $S_L = 1.6$ for $A_T = 12$, $S_L = 1$ otherwise with

$$X_1 = 2.83 - 3.1 \times 10^{-2} A_T + 1.7 \times 10^{-4} A_T^2. \quad (5)$$

For the low energy, shell effects play an important role in light nuclei and the optical potential at the surface varies differently with these effects showing variation in S_L .

(ii) For $A_T \geq 200$

$$X_m = \left[1 - 0.3 \exp\left(-\frac{E-1}{15}\right)\right] [1 - \exp(0.9 - E)]. \quad (6)$$

The effects of the energy dependence at intermediate and higher energies due to Pauli blocking and transparency are taken into account in δ_E , which is defined as,

$$\delta_E = 1.85S + 0.16S/E_{CM}^{1/3} - C_E + 0.91(A_T - 2Z_T)Z_P/(A_T A_P), \quad (7)$$

where S is the mass asymmetry term and is given by

$$S = \frac{A_P^{1/3} A_T^{1/3}}{A_P^{1/3} + A_T^{1/3}} \quad (8)$$

and is related to the volume overlap of the collision system. For the results reported here $A_P = 1$. The last term on the right hand side of Eq. (7) accounts for the isotope dependence of the reaction cross section. The term C_E is related to the transparency and Pauli blocking and is given by

$$C_E = D[1 - \exp(-E/T_1)] - 0.292 \exp(-E/792) \times \cos(0.229E^{0.453}), \quad (9)$$

where $T_1 = 40$ (except for $11 \leq A_T \leq 40$ a value of $T_1 = 30$ is recommended for a better fit). Here D is related to the density dependence of the colliding system and the global value is given by

$$D_g = \frac{0.538}{\rho_{A_P} + \rho_{A_T}}. \quad (10)$$

The density of a nucleus is calculated in the hard sphere model, and for a nucleus A_i is given by

$$\rho_{A_i} = A_i / \frac{4\pi}{3} r_i^3, \quad (11)$$

where r_i is the equivalent sphere radius and is related to the $r_{rms,i}$ radius by

$$r_i = 1.29 r_{rms,i}, \quad (12)$$

where $r_{rms,i}$ values are taken from the experiment [9].

There is interesting physics associated with the constant D . This in effect simulates the modifications of the reaction cross sections due to Pauli blocking. This effect is new and was introduced in our charged particles reaction cross section work (paper I), and is being used for the first time in neutron–nucleus work. This is an important physical ingredient of the model and helps present a unified picture of the reaction cross sections for any system of colliding particles.

Let us elaborate on the choice of D in Eq. (9). This has contributions from the global characteristics of nuclei and also takes into account the specific characteristics related to their stability. The density of a nucleus is a very useful global property. We, therefore, associate the global value D_g to the nuclear densities (Eq. (11)) of the colliding system. Consequently, for *most systems*, we have:

$$D = D_g, \quad (13)$$

where D_g has been defined in Eq. (10). This value of D is modified in certain groups of nuclei to account for their special features in the following way:

The shell structure plays an important role in the size of a light nucleus and hence its cross sections. These effects are more prevalent upto double closed sd shell nuclei ($A \leq 40$) and manifest themselves as a tightly bound nucleus and also as isotopic effects. Hence for this group of nuclei, by taking into account these special characteristics, the best value of D is given by:

For $A_T \leq 40$

$$D = D_g - 1.5(A_T - 2Z_T)/A_T + 0.25/\{1 + \exp[(E - 170)/100]\}. \quad (14)$$

The second term on the RHS of Eq. (14) accounts for the isotopic effects and the last energy dependent term accounts for the shell effects upto doubly closed sd shell nuclei. For still heavier nuclei shell effects start becoming less important but the isotopic effects persist on. We, therefore, found better agreement using the following expression:

For $40 < A_T < 60$

$$D = D_g - 1.5(A_T - 2Z_T)/A_T. \quad (15)$$

For even higher nuclei ($A \geq 60$) special characteristics do not dominate the stability of a nucleus and the global value of D defined in Eq. (13) works well. However, for

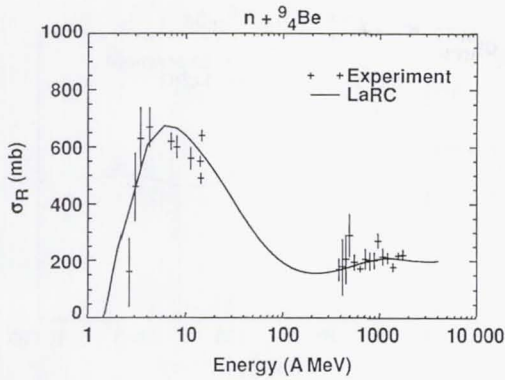


Fig. 1. Total absorption cross sections for $n + {}^9_4\text{Be}$ as a function of neutron energy.

very heavy systems the Coulomb force becomes an important effect and manifests itself as neutron excess (or proton deficiency) for the stability of a nucleus. We found that it is necessary to modify the global value of D (Eq. 13) for nuclei heavier than lead to account for this effect. We determine that the best value of D for, $Z_T > 82$ is given by

$$D = D_g - Z_T / (A_T - Z_T). \quad (16)$$

For any regions not covered by these special effects the global value of D (Eq. (13)) gives good results.

3. Results/conclusions

Figs. 1–12 show the plot of the total absorption cross sections for the neutron–nucleus collisions. We observe that cross sections are never negative and are always positive quantities. For a particular system the energy at which the cross section drops down to zero is the lowest energy to which our model should be used. The data for

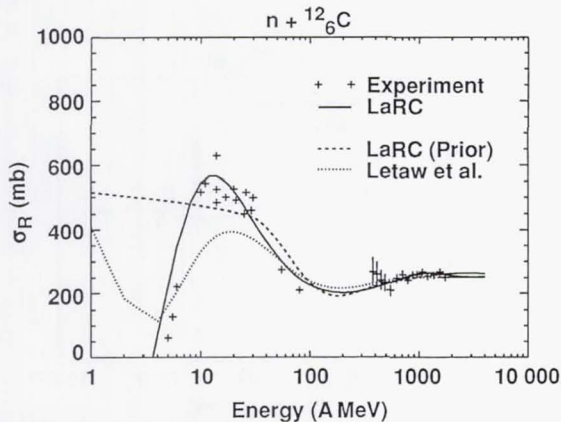


Fig. 2. Total absorption cross sections for $n + {}^{12}_6\text{C}$ as a function of neutron energy.

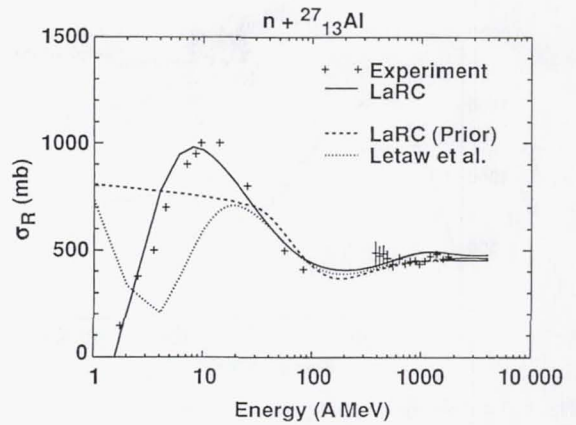


Fig. 3. Total absorption cross sections for $n + {}^{27}_{13}\text{Al}$ as a function of neutron energy.

higher energies (379–1731 MeV) has been taken from Ref. [10], and for lower energies has been taken from the compilations of ENDF/B-VI, and Refs. [11,12]. The agreement with experiment is excellent for all nuclei for the

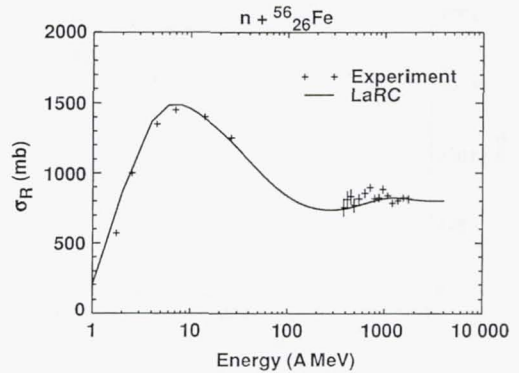


Fig. 4. Total absorption cross sections for $n + {}^{56}_{26}\text{Fe}$ as a function of neutron energy.

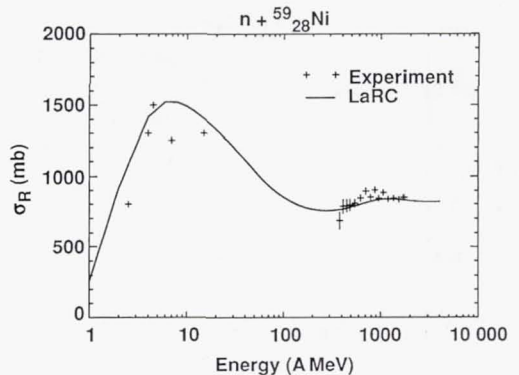


Fig. 5. Total absorption cross sections for $n + {}^{59}_{28}\text{Ni}$ as a function of neutron energy.

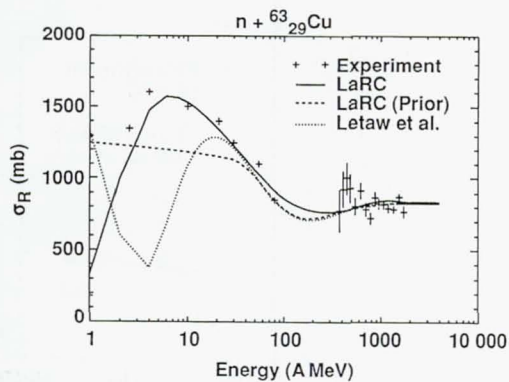


Fig. 6. Total absorption cross sections for $n + {}^{63}_{29}\text{Cu}$ as a function of neutron energy.

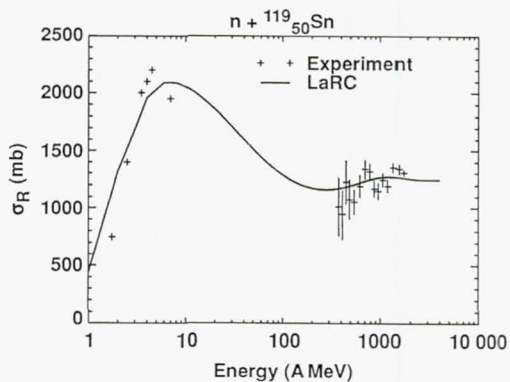


Fig. 9. Total absorption cross sections for $n + {}^{119}_{50}\text{Sn}$ as a function of neutron energy.

entire energy range. We have also compared (Figs. 2, 3, 6, 8, 10) present results with the two popular models: model developed by Wilson et al. [6] here at the NASA Langley Research Center (LaRC (Prior)), and that of Letaw et al.

[7] at the Naval Research Laboratory (NRL). We see from the plots that both these models agree very well with experiment at higher energies, however, there are departures

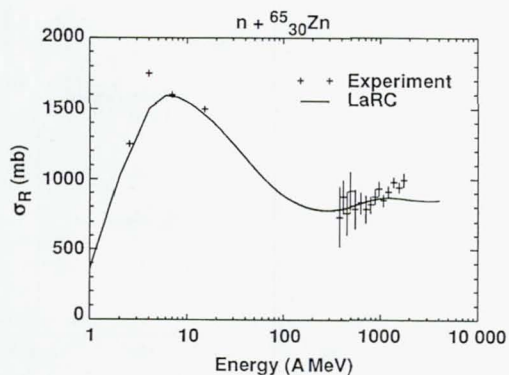


Fig. 7. Total absorption cross sections for $n + {}^{65}_{30}\text{Zn}$ as a function of neutron energy.

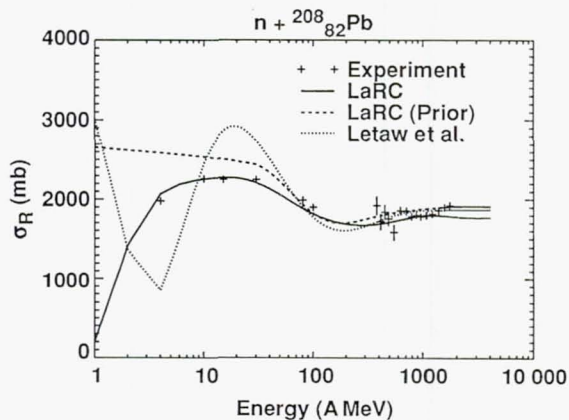


Fig. 10. Total absorption cross sections for $n + {}^{208}_{82}\text{Pb}$ as a function of neutron energy.

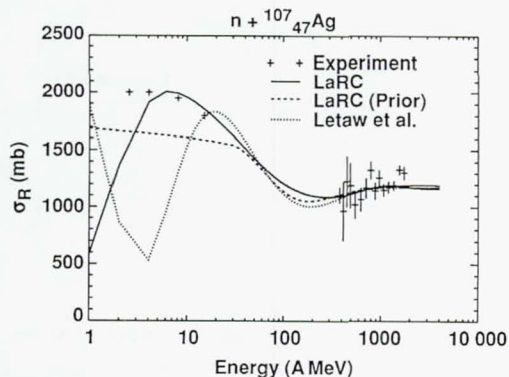


Fig. 8. Total absorption cross sections for $n + {}^{107}_{47}\text{Ag}$ as a function of neutron energy.

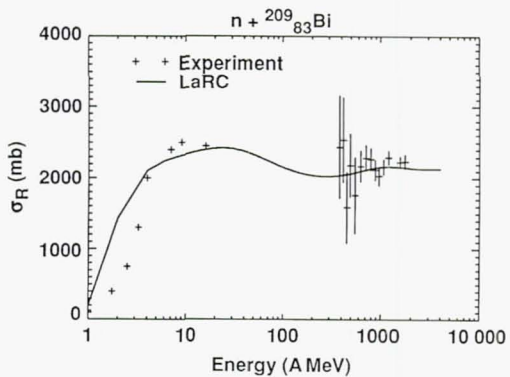


Fig. 11. Total absorption cross sections for $n + {}^{209}_{83}\text{Bi}$ as a function of neutron energy.

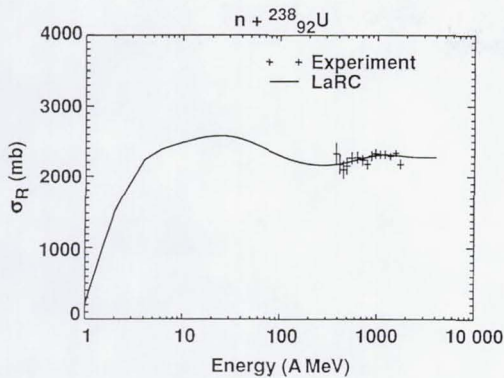


Fig. 12. Total absorption cross sections for $n + {}^{238}\text{U}$ as a function of neutron energy.

tures at lower energies. In general LaRC gives better results than NRL model at lower energies.

Clearly present model (LaRC) improves on earlier models and gives accurate results to much lower energies, and is a welcome improvement for the transport model data base. Neutrons are the dominant component of the radiation environment for the High Speed Civil Transport (HSCT) mission where the data base proposed here is of immense importance.

We have successfully presented simple accurate and unified model for the total absorption cross sections for any system of charged and/or uncharged collision systems valid for the entire energy range, which are important ingredients for several data bases including transport. The model will also be useful where analytical forms of the cross sections are needed.

In view of its utility the computer program calculating the comprehensive accurate absorption cross sections of paper I and present paper will be placed in the COSMIC program library for the public use.

Note added in proof

There is an error in Eq. (12) of paper I (Ref. [4]). A pair of parentheses is missing. The correct equation should read as follows:

$$D = 2.77 - 8.0 \times 10^{-3} A_T + 1.8 \times 10^{-5} A_T^2 - 0.8 / (1 + \exp((250 - E)/75)). \quad (12)$$

Acknowledgements

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