Implementation of GDH model in TALYS-1.7 code

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Abstract

The geometry dependent hybrid model proposed by M.Blann and supplied with models for the non-equilibrium cluster emission was implemented in the TALYS-1.74 code. A number of subprograms of ALICE and ALICE/ASH codes after an appropriate modification were added to TALYS. The value of the TALYS input variable \textit{preeqmode} equal to five is reserved for the use of new approach. The calculated nucleon and light cluster energy distributions are compared with measured data.
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1. Introduction

More than forty years the geometry dependent hybrid model (GDH) proposed by M.Blann [1] is used successfully for the simulation of non-equilibrium emission of nucleon and light clusters in nuclear reactions at intermediate energies. An advance of the use of the GDH model with a combination with the Hauser-Feshbach model was clearly demonstrated [2,3].

The TALYS code [4] represents a new generation of nuclear model codes combining a number of well justified models and approaches for the simulation of particle interaction with nuclei. In practice the use of various alternative methods of calculations available by user’s choice gives a unique possibility to understand a real uncertainty of theoretical predictions of calculated cross-sections and particle distributions.

The goal of the present work is an extension of the current version of the TALYS code by the implementation of the GDH model and performing test calculations.

A brief description of implemented models, changes in the TALYS text, and results of test calculations are given below.

2. Brief description of models implemented in TALYS

2.1 Pre-compound nucleon emission

In the GDH model the pre-equilibrium energy distribution of nucleons is calculated as follows [5]:

\[
\frac{d\sigma}{d\varepsilon_x} = \pi l \sum_{l=0}^{\infty} T_l \left( \frac{\omega(p-1,h,U)}{\omega(p,h,E)} \right) \frac{\lambda_x^e}{\lambda_x^e + \lambda_x^\nu} g D_n, \tag{1}
\]

where \( T_l \) is the transmission coefficient for \( l \)-th partial wave; \( nX_x \) is the number of nucleons of type “x” in the \( n \)-exciton state; \( \varepsilon_x \) is the channel energy of the nucleon; \( \omega(p,h,E) \) is the density of exciton states with “p” particles and “h” holes (\( p+h=n \)) at the excitation energy \( E \); \( U \) is the final excitation energy, \( U=E-Q_x-\varepsilon_x \) and \( Q_x \) is the nucleon separation energy; \( D_n \) is the factor [6], which takes into account a “depletion” of the \( n \)-exciton state due to the nucleon emission; \( n_0 \) is the initial exciton number.
The nucleon emission rate $\lambda^e_x$ is equal to

$$\lambda^e_x = \frac{(2S_x + 1) \mu_x \varepsilon_x \sigma^\text{inv}_x (\varepsilon_x)}{\pi^2 \hbar g_x}, \quad (2)$$

where $S_x$ and $\mu_x$ are the spin and reduced mass of the outgoing nucleon of type "x", $\sigma^\text{inv}_x$ is the inverse reaction cross-section and $g_x$ is the single-nucleon state density.

The intranuclear transition rate $\lambda^+\!_x$ is defined as follows

$$\lambda^+\!_x = V \sigma_0(\varepsilon_x) \rho_l, \quad (3)$$

where $V$ is a velocity of a nucleon inside the nucleus, $\sigma_0$ is the nucleon-nucleon scattering cross-section corrected for the Pauli principle [5], $\rho_l$ is the average nuclear matter density at the distance from $l \hbar \kappa$ to $(l+1) \hbar \kappa$.

For nucleon induced reactions the density of excited states with the number of excitons $n=2$ and 3 is calculated considering the finite depth of the nuclear potential well [7]

$$\omega(1,1,E) = \frac{g(gE)}{2}, \quad \text{if } E > E_F \quad (5)$$

$$\omega(1,1,E) = \frac{g(gE)}{2}, \quad \text{if } E \leq E_F \quad (6)$$

$$\omega(2,1,E) = \frac{g^3[V(2E - E_F)]}{4}, \quad \text{if } E > E_F \quad (7)$$

$$\omega(2,1,E) = \frac{g^3 E^2}{4}, \quad \text{if } E \leq E_F \quad (8)$$

where $E_F$ is the Fermi energy, and the finite potential depth is equal to $V + Q$, and $Q$ is the nucleon binding energy.

The number of nucleons of x-type in the n-exciton state $nX_x$ for incident neutrons is calculated as

$$3X_n = 2 \frac{(\sigma_{np} / \sigma_{nn})Z + 2N}{2(\sigma_{np} / \sigma_{nn})Z + 2N}, \quad (9)$$

$$3X_p = 2 - 3X_n, \quad (10)$$

and for incident proton

$$3X_p = 2 \frac{(\sigma_{pn} / \sigma_{pp})N + 2Z}{2(\sigma_{pn} / \sigma_{pp})N + 2Z}, \quad (11)$$
where $\sigma_{xy}$ is the nucleon-nucleon interaction cross-section in the nucleus.

The ratio of the nucleon-nucleon cross-sections calculated taking into account the Pauli principle and the nucleon motion is parameterized in the present work as

$$\frac{\sigma_{pn}}{\sigma_{pp}} = \frac{\sigma_{np}}{\sigma_{nn}} = 1.375 \times 10^{-5} T^2 - 8.734 \times 10^{-3} T + 2.776,$$

where $T$ is the kinetic energy of the projectile outside the nucleus in MeV.

A correction has been made for the high energy tails of (p,xn) and (n,xp) reaction spectra calculated by the GDH model [8]. The details are given in Ref.[9].

Fig.1 shows an example of neutron energy distribution for the p+$^{90}$Zr reaction calculated using the GDH model implemented in TALYS and the common pre-equilibrium exciton model of TALYS.
2.2 Pre-compound $\alpha$-particle emission

The pre-equilibrium $\alpha$-particle emission spectrum for nucleon induced reaction is calculated as a sum of components corresponding to the mechanism of pick-up and knock-out

$$\frac{d\sigma}{d\varepsilon_\alpha} = \frac{d\sigma^{PU}}{d\varepsilon_\alpha} + \frac{d\sigma^{KO}}{d\varepsilon_\alpha} \quad (14)$$

The contribution of the pick-up mechanism is calculated with the help of the coalescence pick-up model \([10,11]\) combined with the hybrid exciton model

$$\frac{d\sigma^{PU}}{d\varepsilon_\alpha} = \sigma_{non}(E_p) \sum_{n=n_0} \sum_{k+m=4} F_{k,m}(\varepsilon_\alpha) \frac{\omega(p-k,h,U)}{\omega(p,h,E)} \frac{\lambda_\alpha^e(\varepsilon_\alpha)}{\lambda_\alpha^e(\varepsilon_\alpha) + \lambda_\alpha^+(\varepsilon_\alpha)} g_\alpha D_n, \quad (15)$$

where $\sigma_{non}$ is the nonelastic interaction cross-section of the primary particle with a nucleus at kinetic energy $E_p$, $F_{k,m}(\varepsilon_\alpha)$ is the $\alpha$-formation factor \([10]\) equal to the probability that the $\alpha$-particle is composed of “$k$” particles above Fermi level and “$m$” particles below, the residual excitation energy $U$ is equal to $E - Q_\alpha - \varepsilon_\alpha$, $\lambda_\alpha^e$ is the emission rate of the $\alpha$-particle; $\lambda_\alpha^+$ is the intranuclear transition rate corresponding to the absorption of the $\alpha$-particle in a nucleus; $g_\alpha$ is the intranuclear density of single particle states for the $\alpha$-particle. The emission rate of $\alpha$-particles is calculated as

$$\lambda_\alpha^e = \frac{(2S_\alpha + 1) \mu_\alpha \varepsilon_\alpha \sigma_{inv}^{\alpha}(\varepsilon_\alpha)}{\pi^2 \hbar g_\alpha}, \quad (16)$$

where $S_\alpha$ and $\mu_\alpha$ are the spin and reduced mass of the outgoing $\alpha$-particle, and the inverse reaction cross-section for $\alpha$-particles, $\sigma_{inv}^{\alpha}(\varepsilon_\alpha)$ is calculated by the optical model with parameters discussed in Ref. \([6]\). The absorption rate of $\alpha$-particles is defined as follows

$$\lambda_\alpha^+ = 2W_{\alpha}^{opt} / \hbar, \quad (17)$$

where $W_{\alpha}^{opt}$ is the imaginary part of the optical potential for $\alpha$-particles.

The knock-out contribution to the $\alpha$-particle energy distribution \([12]\) is equal to

$$\frac{d\sigma^{\text{knock-out}}}{d\varepsilon_\alpha} = \sigma_{non}(E_p) \sum_{n=n_0} \phi_\alpha \frac{g_\alpha}{g_\alpha p} \frac{\omega(p-1,h,U)}{\omega(p,h,E)} \frac{\lambda_\alpha^e(\varepsilon_\alpha)}{\lambda_\alpha^e(\varepsilon_\alpha) + \lambda_\alpha^+(\varepsilon_\alpha)} g_\alpha D_n, \quad (18)$$
where the factor $g/(g_{\alpha}p)$ justifies the substitution of the level density $\omega(\pi,\pi)$ for the three-component system (neutron, proton, $\alpha$-particle) [13,12] by the one-component state density $\omega(p,h,E)$ in Eq.(18), and $\varphi_{\alpha}$ is the probability of interaction of the incident particle with a “pre-formed” $\alpha$-cluster resulting in its excitation in the nucleus [13].

The imaginary part of the optical potential for $\alpha$-particles is calculated as follows: $W_{\alpha}^{\text{opt}} = (\varepsilon_{\alpha}/\varepsilon_{0})W'$ at $\varepsilon_{\alpha} \leq \varepsilon_{0}$, $W_{\alpha}^{\text{opt}} = W'$ at $\varepsilon_{0} < \varepsilon_{\alpha} < 72$ MeV, and $W_{\alpha}^{\text{opt}} = W'\exp(0.06\varepsilon_{\alpha} - 4.32)$ at $\varepsilon_{\alpha} \geq 72$ MeV, where $W' = \beta W_{0}$ and $\varepsilon_{0}=0.228A$, $\beta=0.25$. The value of $W_{0}$ is taken from Refs.[14,15] $W_{0}=10 +0.345(A−2Z)$ MeV. The value adopted for $g_{\alpha}$ is equal to $A/13$ [16].

2.3 Pre-compound deuteron emission

It is supposed that a non-equilibrium deuteron emission in nucleon induced reactions results from: i) the pick-up of nucleons with energy below the Fermi energy after the formation of the (2p,1h) initial exciton state, ii) coalescence of two excited nucleons with energies above $E_{F}$, iii) knock-out of a “pre-formed” deuteron, and iv) a direct process resulting in deuteron formation and escape. The non-equilibrium deuteron spectrum is calculated as a sum of different components

$$\frac{d\sigma}{d\varepsilon_{d}} = \frac{d\sigma_{\text{PU}}^{D}}{d\varepsilon_{d}} + \frac{d\sigma_{\text{KO}}^{D}}{d\varepsilon_{d}} + \frac{d\sigma_{\text{D}}^{D}}{d\varepsilon_{d}},$$

where the first term relates to pick-up and coalescence after the formation of the (2p,1h) exciton state, the second component describes the contribution of the deuteron knock-out and the last term relates to the direct process.

The exciton level density is calculated following Bĕták, Dobeš [17] taking into account the finite depth of the nuclear potential well

$$\omega(p,h,E) = g_{p}^{p} \sum_{k=0}^{n} (-1)^{k} \Theta(E-kE_{F}) \frac{(E-kE_{F})^{n-k}}{p!h!(n-k)!}$$

where $E$ is the excitation energy, $E_{F}$ is the Fermi energy, $g$ and $\tilde{\omega}$ are the single particle level densities for particles and holes, respectively, $\Theta(x)$ is the Heaviside function, $\Theta = 0$ for $x < 0$ and $\Theta = 1$ for $x > 0$.

The exciton coalescence pick-up model [11] is used for the calculation of the
\[ \frac{d\sigma_{PU}}{d\varepsilon_d} = \sigma_{\text{non}} \sum_{n=n_0} \sum_{k+m=2} F_{k,m}(\varepsilon_d + Q_d) \frac{\omega(p-k,h,U)}{\omega(p,h,E)} \frac{\lambda_d^e(\varepsilon_d)}{\lambda_d^e(\varepsilon_d) + \lambda_d^+ (\varepsilon_d)} g_d D_n, \]  

where \( F_{k,m} \) is the deuteron formation factor equal to the probability that the deuteron is composed of \( \text{“}k\text{”} \) particles above the Fermi level and \( \text{“}m\text{”} \) particles below; \( \varepsilon_d \) is the channel emission energy corresponding to the deuteron emission; \( \lambda_d^e \) is the deuteron emission rate; \( \lambda_d^+ \) is the intranuclear transition rate for the absorption of the deuteron in the nucleus; \( g_d \) is the density of single particle states for the deuteron.

The form factors for deuteron formation, \( F_{k,m} \) were calculated in Ref.[11] for the effective nuclear radius with a \( dR \) parameter value equal to 1 fm. The original values [11] are approximated and used as follows

\[ F_{1,1}(\varepsilon) = \begin{cases} -1.409 \cdot 10^{-2} \varepsilon + 0.6 & \text{for } \varepsilon \leq 30 \text{ MeV} \\ 1.377 \cdot 10^{-4} \varepsilon^2 - 1.807 \cdot 10^{-2} \varepsilon + 0.5946 & \text{for } 30 < \varepsilon \leq 65 \text{ MeV} \\ 0 & \text{for } \varepsilon > 65 \text{ MeV} \end{cases} \]  

\[ F_{2,0}(\varepsilon) = 0.6 - F_{1,1}(\varepsilon) \]  

In analogy with \( \alpha \)-particle emission the knock-out component of the precompound deuteron emission spectrum is written as follows

\[ \frac{d\sigma^{KO}}{d\varepsilon_d} = \sigma_{\text{non}} \sum_{n=n_0} \Phi_d(E_0) \frac{g}{g_d p} \frac{\omega(p-1,h,U)}{\omega(p,h,E)} \frac{\lambda_d^e(\varepsilon_d)}{\lambda_d^e(\varepsilon_d) + \lambda_d^+ (\varepsilon_d)} g_d D(n), \]  

where the factor \( \Phi_d \) describes the initial number of excited deuteron clusters in the nucleus

\[ \Phi_d = 2 F_d(E_0), \]  

where \( F_d \) is the probability of interaction of the incident particle with the “pre-formed” deuteron resulting in its excitation in the nucleus; and the factor of two reflects the normalization on the number of particles in the initial exciton state \( n_0 \).

The general expression for \( F_d \) [19] is

\[ F_d = \frac{Z}{A'} \frac{\phi \sigma_{sd}(E_0)}{\sigma_{sp}(E_0) + \left( \frac{A'-Z'}{A'} \right) \sigma_{xn}(E_0) + \phi \sigma_{sd}(E_0)}, \]
where “x” refers to the initial proton or neutron, $\sigma_{xd}$, $\sigma_{xp}$ and $\sigma_{xn}$ are the cross-sections of the elastic interaction of projectile with deuteron, proton and neutron, respectively, corrected for a Pauli principle, $\varphi$ is the number of “pre-formed” deuterons in the nucleus, $Z'$ and $A'$ are the number of protons and nucleons in the nucleus corrected for a number of clustered deuterons.

The direct pick-up process corresponds to the pick-up of a nucleon without formation of a (2p,1h) exciton configuration. A rigorous description of this process can be done only outside of pre-equilibrium models. However, mathematical expressions obtained formally using the pre-compound exciton model [19,20] are useful for the phenomenological and qualitative description of direct nucleon pick-up.

According to Ref.[18], the direct component of the deuteron spectrum is

$$\frac{d\sigma^D}{dE_d} = \sigma_{non} \frac{\omega^*(U)}{\omega(1p,0h,E)} \frac{\lambda_d^*(\varepsilon_d)}{\lambda_d^*(\varepsilon_d) + \lambda_d^*(\varepsilon_d)} g_d,$$  \hspace{1cm} (33)

where the final level density $\omega^*(U)$ is approximated by $\omega(0p,1h,U) \gamma g_d$ [18]. See details in Ref.[9] or in the code text.

Formal consideration of the finite depth of the nuclear potential well shows that Eq.(33) can contribute only in the highest energy part of the deuteron emission spectrum, as has been mentioned above. In this case the calculated part of the spectrum is a rectangular step with width equal to $E_F$. To improve the agreement of calculations and the measured deuteron spectra, the direct component of the spectrum was rewritten in the following form [19]

$$\frac{d\sigma^D}{dE_d} = \sigma_{non} \alpha_1 \exp \left(-\frac{(E - \alpha_2 E_F)^2}{2(\alpha_3 E_F)^2}\right) \frac{\lambda_d^*(\varepsilon_d)}{\lambda_d^*(\varepsilon_d) + \lambda_d^*(\varepsilon_d)} g_d,$$  \hspace{1cm} (34)

where $\alpha_1$, $\alpha_2$, and $\alpha_3$ are parameters and $E_F$ is the effective value of the Fermi energy.

The values of $\alpha_i$ are obtained from analysis of experimental deuteron spectra. The global parameterization of $\alpha_i$ parameters is hardly possible.

Model parameters were obtained from the comparison of calculations with available experimental data. The change in values of different parameters results to different energetic dependencies of calculated deuteron spectrum. In most cases such change cannot be represented by a simple redefinition of other model parameters.
3. Changes in the program text

A module providing calculations of pre-equilibrium nucleon and light cluster distributions using GDH was implemented in the TALYS-1.74 code. The module consists of a number of primary subprograms of ALICE/ASH code [9], the ALICE/ASH subprograms modified for an appropriate integration in TALYS, and subroutines written to provide an interface between TALYS and modified ALICE/ASH modules.

The value of the TALYS input variable \textit{preeqmode} equal to five is reserved for GDH calculations. A brief description of changes of TAYLS and ALICE/ASH subprograms and the list of modified and new routines is given below.

3.1 Changes in TALYS subprograms

The following TALYS-1.74 subroutines were modified in the present work:

\begin{itemize}
  \item \texttt{checkvalue}
  \item \texttt{exciton}
  \item \texttt{exciton2}
  \item \texttt{input3}
  \item \texttt{preeq}
  \item \texttt{preeqcomplex}
\end{itemize}

The modification concerns an addition of a number of instructions allowing the calculations with the new value of the \textit{preeqmode} parameter equal to five. The main GDH module \texttt{gdh0} is called in the subroutine \texttt{preeq}.

3.2 Changes in ALICE/ASH subprograms

The list of modified ALICE/ASH subroutines is follows:

\begin{itemize}
  \item \texttt{gdhadist}
  \item \texttt{gdhangel}
  \item \texttt{gdhangl}
  \item \texttt{gdhbinde}
  \item \texttt{gdhex1ex2}
\end{itemize}
The modification of subprograms, which name begins with “gdh” and original name follows the abbreviation, concerns mainly their formal integration in TALYS. The subroutines *alph05, ddirec, deut05, iwamo*, and *iwamod* were altered to provide an agreement of experimental data and GDH-TALYS calculations.

An increase of memory load after the implementation of the GDH model in TALYS is about 0.15 %.

4. Example of the input file

A typical example of the input file for calculations applying GDH is given below

```
# GDH model
projectile n
element Fe
mass 56
energy 96.0
preeqmode 5
outspectra y
```
Calculated energy distributions for emitted proton, deuteron, and $\alpha$-particles for this task are shown in Figs. 2-4. The experimental data are discussed in the next Section.

Fig. 2 Calculated and measured proton energy distribution for the $n^{56}\text{Fe}$ reaction.

Fig. 3 Calculated and measured deuteron energy distribution for the $n^{56}\text{Fe}$ reaction.
Fig. 4  Calculated and measured $\alpha$-particle energy distribution for the n$^+$$^{56}$Fe reaction.

5. Comparison of calculations with measured data

Measured energy distributions for emitted neutrons, protons, deuterons, and $\alpha$-particles in nucleon induced reactions [21-51] were compared with results of calculations using the GDH model and “default” TALYS models.

The figures are given in Appendices A-C.

When comparing the results, it should be borne in mind that “default” calculations use general parameterizations of pre-compound model parameters, while GDH calculations are performed using specific parameters for different targets.

For some neutron induced reactions there is a large discrepancy of calculated and measured values at the high energy tail of spectra. The same disagreement is observed for calculations using the “default” pre-compound model of TALYS. While the TALYS computation of reaction energies is usually correct, the discrepancy is
apparently due to the lack of measurements; the short discussion can be found in Ref.[19].

6. Conclusion

The geometry dependent hybrid model supplemented by phenomenological models for the simulation of non-equilibrium emission of deuterons and \( \alpha \)-particles was implemented in the TALYS-1.74 code. Models discussed present an alternative to the pre-compound exciton model of TALYS and can be used for the prediction of cross-sections and secondary particle distribution in nuclear reactions induced by intermediate energy nucleons.

The results of calculations were compared with experimental energy distributions (Appendices A-C).
References


Appendix A

Calculated and experimental nucleon energy distributions
$^{12}\text{C}(n,\text{p})$, $E_n=26.5$ MeV

$^{12}\text{C}(n,\text{p})$, $E_n=29.5$ MeV
$^{12}\text{C}(n,xp), \ E_n=32.5 \text{ MeV}$

$^{12}\text{C}(n,xp), \ E_n=35.5 \text{ MeV}$
$^{12}\text{C}(n,\alpha)$, $E_n=55.3$ MeV

$^{12}\text{C}(n,\alpha)$, $E_n=62.7$ MeV
$^{12}\text{C}(n,\alpha)$, $E_n=72.8$ MeV

$^{12}\text{C}(n,\alpha)$, $E_n=95.6$ MeV
\(^{16}\text{O}(n,\text{xp}), \; E_n=41 \text{ MeV}\)

\(\text{Energy distribution (mb/MeV)}\)

\(\text{Outgoing energy (MeV)}\)

\(^{16}\text{O}(n,\text{xp}), \; E_n=45 \text{ MeV}\)

\(\text{Energy distribution (mb/MeV)}\)

\(\text{Outgoing energy (MeV)}\)
\(^{16}\text{O}(n,xp), \ E_n=49 \ \text{MeV}\)

\[
\begin{array}{c}
\text{Energy distribution (mb/MeV)} \\
\log_{10} \text{Energy distribution (mb/MeV)}
\end{array}
\]

\[
\begin{array}{c}
0 \quad 5 \quad 10 \quad 15 \quad 20 \quad 25 \quad 30 \quad 35 \quad 40 \quad 45
\end{array}
\]

\(\text{Outgoing energy (MeV)}\)

\(^{16}\text{O}(n,xp), \ E_n=53.5 \ \text{MeV}\)

\[
\begin{array}{c}
\text{Energy distribution (mb/MeV)} \\
\log_{10} \text{Energy distribution (mb/MeV)}
\end{array}
\]

\[
\begin{array}{c}
0 \quad 5 \quad 10 \quad 15 \quad 20 \quad 25 \quad 30 \quad 35 \quad 40 \quad 45
\end{array}
\]

\(\text{Outgoing energy (MeV)}\)
$^{16}\text{O}(n,\text{p}), \ E_n=62.7$ MeV

$^{16}\text{O}(n,\text{p}), \ E_n=95.6$ MeV
$^{27}\text{Al}(n,xp), \ E_n=41 \ MeV$

$^{27}\text{Al}(n,xp), \ E_n=45 \ MeV$
$^{27}\text{Al}(n,xp)$, $E_n=62.7$ MeV

$^{27}\text{Al}(p,xn)$, $E_p=90$ MeV
$^{27}\text{Al}(p,\text{xp}), \ E_p=61.7 \text{ MeV}$

$^{27}\text{Al}(p,\text{xp}), \ E_p=90 \text{ MeV}$
$^{54}\text{Fe}(p,xp), \ E_p=61.5 \text{ MeV}$

$^{56}\text{Fe}(n,xp), \ E_n=25.5 \text{ MeV}$
$^{56}\text{Fe}(p,xp)$, $E_p=61.5$ MeV

$^{59}\text{Co}(n,xp)$, $E_n=25.5$ MeV
$^{89}\text{Y}(p,xp), \ E_p=61.5 \text{ MeV}$

$^{90}\text{Zr}(p,xn), \ E_p=35 \text{ MeV}$
$^{90}\text{Zr}(p,xp),\ E_p=30.3\ \text{MeV}$

$^{90}\text{Zr}(p,xp),\ E_p=90\ \text{MeV}$
$^{120}$Sn(p,xp), $E_p=61.5$ MeV

$^{197}$Au(p,xp), $E_p=28.8$ MeV
\[ ^{209}\text{Bi}(p,xn), \ E_p=90 \text{ MeV} \]

\[ ^{209}\text{Bi}(p,xp), \ E_p=38.7 \text{ MeV} \]
Appendix B

Calculated and experimental deuteron energy distributions
$^{12}\text{C}(n,xd), \ E_n=72.8 \text{ MeV}$

$^{12}\text{C}(n,xd), \ E_n=95.6 \text{ MeV}$
$^{16}$O$(p,xd)$, $E_p=61$ MeV

$^{27}$Al$(n,xd)$, $E_n=28.5$ MeV
$^{27}\text{Al}(n,xd), \ E_n=45 \text{ MeV}$

$^{27}\text{Al}(n,xd), \ E_n=49 \text{ MeV}$
$^{28}\text{Si}(n,\text{xd}), \ E_n=21 \text{ MeV}$

Energy distribution (mb/MeV)

Outgoing energy (MeV)

$^{28}\text{Si}(n,\text{xd}), \ E_n=23 \text{ MeV}$

Energy distribution (mb/MeV)

Outgoing energy (MeV)
$^\text{28}\text{Si}(n,\text{xd}), \ E_n=25 \text{ MeV}$

Energy distribution (mb/MeV)

Outgoing energy (MeV)

$^\text{28}\text{Si}(n,\text{xd}), \ E_n=27 \text{ MeV}$

Energy distribution (mb/MeV)

Outgoing energy (MeV)
\[ ^{28}\text{Si}(n,xd), \quad E_n=28.5\text{ MeV} \]

\[ ^{28}\text{Si}(n,xd), \quad E_n=29\text{ MeV} \]
$^{28}\text{Si}(n,\text{xd}),\ E_n=31\ \text{MeV}$

$^{28}\text{Si}(n,\text{xd}),\ E_n=31.5\ \text{MeV}$
$^{28}$Si(p,xd), $E_p=48.5$ MeV

$^{28}$Si(p,xd), $E_p=62.9$ MeV
$^{54}\text{Fe}(p,xd), \ E_p=28.8 \text{ MeV}$

Energy distribution (mb/MeV)

$^{54}\text{Fe}(p,xd), \ E_p=38.8 \text{ MeV}$

Energy distribution (mb/MeV)
$^{56}\text{Fe}(n,\alpha d)$, $E_n=34.5$ MeV

$^{56}\text{Fe}(n,\alpha d)$, $E_n=37.5$ MeV
$^{56}$Fe(n,xd), $E_n=41$ MeV

$^{56}$Fe(n,xd), $E_n=45$ MeV
\(^{89}\text{Y}(p, xd), \quad E_p=61.5 \text{ MeV}\)

\(^{90}\text{Zr}(p, xd), \quad E_p=30.3 \text{ MeV}\)
$^{120}\text{Sn(p,xd), } E_p=61.5 \text{ MeV}$

$^{197}\text{Au(p,xd), } E_p=28.8 \text{ MeV}$
$^{208}\text{Pb}(n,\text{xd}), \ E_n=96\ \text{MeV}$

$^{208}\text{Pb}(p,\text{xd}), \ E_p=62.9\ \text{MeV}$
$^{209}\text{Bi}(n,xd), \ E_n=34.5 \text{ MeV}$

$^{209}\text{Bi}(n,xd), \ E_n=37.5 \text{ MeV}$
$^{209}\text{Bi}(\text{n,xd}), \ E_n=41 \text{ MeV}$

Raeymackers(03)  default  GDH

Energy distribution (mb/MeV)

Outgoing energy (MeV)

$^{209}\text{Bi}(\text{n,xd}), \ E_n=45 \text{ MeV}$

Raeymackers(03)  default  GDH

Energy distribution (mb/MeV)

Outgoing energy (MeV)
Appendix C

Calculated and experimental $\alpha$-particle energy distributions
$^{16}\text{O}(n,x^{4}\text{He}), \ E_{n}=49 \text{ MeV}$

$^{16}\text{O}(n,x^{4}\text{He}), \ E_{n}=53.5 \text{ MeV}$
$^{16}\text{O}(n,^{4}\text{He}), \ E_n=62.7 \ \text{MeV}$

$^{16}\text{O}(n,^{4}\text{He}), \ E_n=95.6 \ \text{MeV}$
$^{27}$Al(n,$x^4$He), $E_n = 37.5$ MeV

$^{27}$Al(n,$x^4$He), $E_n = 41$ MeV
\( ^{27}\text{Al}(n,x^{4}\text{He}), \ E_{n}=53.5 \text{ MeV} \)

\( ^{27}\text{Al}(n,x^{4}\text{He}), \ E_{n}=62.7 \text{ MeV} \)
$^{27}\text{Al}(p,x^4\text{He})$, $E_p=90$ MeV

$n_{\text{atSi}}(n,x^4\text{He})$, $E_n=15$ MeV
natSi(n,x^4He), E_n=25 MeV

Outgoing energy (MeV)

Energy distribution (mb/MeV)

Bateman(99) default GDH

Outgoing energy (MeV)

natSi(n,x^4He), E_n=27 MeV

Energy distribution (mb/MeV)

Bateman(99) default GDH
$^{nat}Si(n,x^4He), \ E_n=42 \ MeV$

$^{nat}Si(n,x^4He), \ E_n=46 \ MeV$
$^{\text{nat}}\text{Si}(n,x^4\text{He}), \ E_n=95.6 \text{ MeV}$

$^{\text{nat}}\text{Si}(p,x^4\text{He}), \ E_p=26.5 \text{ MeV}$
\[ \text{n}_\text{at} \text{Si(p,x}^4\text{He)}, \ E_p=48.5 \ \text{MeV} \]

\[ \text{n}_\text{at} \text{Si(p,x}^4\text{He)}, \ E_p=62.9 \ \text{MeV} \]
$^{56}$Fe(n,x$^4$He), $E_n=96$ MeV

$^{56}$Fe(p,x$^4$He), $E_p=61.5$ MeV
$^{89}$Y(p,x$^4$He), $E_p=61.5$ MeV

$^{90}$Zr(p,x$^4$He), $E_p=72.3$ MeV
$^{90}\text{Zr}(p,x^4\text{He})$, $E_p=90\text{ MeV}$

$^{93}\text{Nb}(p,x^4\text{He})$, $E_p=19.9\text{ MeV}$
$^{93}\text{Nb}(p,x^4\text{He}), \quad E_p=24.6 \text{ MeV}$

Outgoing energy (MeV)

Energy distribution (mb/MeV)

- Ferrero(79)
- default
- GDH

$^{93}\text{Nb}(p,x^4\text{He}), \quad E_p=29.7 \text{ MeV}$

Outgoing energy (MeV)

Energy distribution (mb/MeV)

- Ferrero(79)
- default
- GDH
$^{118}\text{Sn}(p,x^4\text{He}), \ E_p=30.4 \text{ MeV}$

$^{118}\text{Sn}(p,x^4\text{He}), \ E_p=36.5 \text{ MeV}$
$^{118}\text{Sn}(p,x^4\text{He}), \ E_p=44.3 \text{ MeV}$

$^{120}\text{Sn}(p,x^4\text{He}), \ E_p=28.8 \text{ MeV}$
$^{120}\text{Sn}(p,x^4\text{He}), \ E_p=61.5 \text{ MeV}$

$^{165}\text{Ho}(p,x^4\text{He}), \ E_p=19.9 \text{ MeV}$
\[ {^{165}} \text{Ho}(p, x^{4}\text{He}), \ E_p = 44.3 \text{ MeV} \]

\[ {^{169}} \text{Tm}(p, x^{4}\text{He}), \ E_p = 29.7 \text{ MeV} \]
$^{197}$Au($p,x^4$He), $E_p=28.8$ MeV

$^{197}$Au($p,x^4$He), $E_p=61.5$ MeV
$^{209}\text{Bi}(n,x^4\text{He}),\ E_n=49\ \text{MeV}$

Energy distribution (mb/MeV)

Outgoing energy (MeV)

$^{209}\text{Bi}(n,x^4\text{He}),\ E_n=53.5\ \text{MeV}$

Energy distribution (mb/MeV)

Outgoing energy (MeV)
\[ ^{209}\text{Bi}(n,x^4\text{He}), \ E_n=62.7 \text{ MeV} \]

\[ ^{209}\text{Bi}(p,x^4\text{He}), \ E_p=38.7 \text{ MeV} \]