# $\gamma +^9 Be$ Reactions Below 30 MeV

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# 1 Reaction Mechanism of $\gamma +^9 Be$ Reaction

At low energies below 30 MeV, the Giant-Dipole Resonance (GDR) is the dominant excitation mechanism, in this energy region a simple approximation of isotropy is used to the angular distributions for outgoing particle. Semiclassical pre-equilibrium exciton model has been proved to be powerful tool for predicting particle emission spectra. For the light nucleus, like $^9Be$ the recoil effect in multi-stage emission processes are included. The pre-equilibrium exciton model is implemented using a master equation approach, and generalized to include angular momentum and parity conservation, which allows a unified treatment of pre-equilibrium and equilibrium emission. The pick-up mechanism for cluster emissions are also included.

In view of $\gamma +^9 Be$ reactions for $E_\gamma \leq 30\ MeV$ the reaction channels are listed as the follows

$$\gamma +^9 Be = \begin{cases} \gamma +^9 Be & \text{Q= 0.0 MeV} \\ n' +^8 Be & \text{Q=-1.665 MeV} \\ p +^8 Li & \text{Q=-16.886 MeV} \\ \alpha +^5 He & \text{Q=-2.467 MeV} \\ ^3He +^6 He & \text{Q=-21.175 MeV} \\ d +^7 Li & \text{Q=-16.695 MeV} \\ t +^6 Li & \text{Q=-17.688 MeV} \\ 2n +^7 Be & \text{Q=-20.563 MeV} \\ n, p +^7 Li & \text{Q=-18.919 MeV} \\ n, \alpha + \alpha & \text{Q=-1.523 MeV} \\ p, n +^7 Li & \text{Q=18,919 MeV} \end{cases}$$

The $(\gamma,^3 He)$ reaction is caused by emitting a $^3He$ to the ground state of $^6He$, while the excited levels of $^6He$ will decay into $n + n + \alpha$ by three body break-up process. Reaction mechanism in the $\gamma +^9 Be$ system leading to decay into one neutron and two $\alpha$ particles may proceed via a number of different reaction channels, as two body break-up process or three body break-up process, the different approach strongly differs each other in their respective neutron and $\alpha$ particle energy spectra. The reaction channels to $^9Be(\gamma, n)2\alpha$ channel involved in the calculation are as follows:

(a) $\gamma +^9 Be \rightarrow n +^8 Be^* \ (\alpha + \alpha)$
(b) $\gamma +^9 Be \rightarrow \alpha +^5 He^* \ \ (n + \alpha)$
(c) $\gamma +^9 Be \rightarrow n, \alpha$

The discrete level scheme of every reaction channels at $E_\gamma \leq 30$ MeV are taken from the "Table of Isotopes" 1996[1].

The neutron production reaction channels include $\gamma +^9 Be$ at $E_\gamma \leq 30$ MeV include $(\gamma, n2\alpha)$, $(\gamma, 2n\alpha)^3He$, $(\gamma, 2np)^6Li$, $(\gamma, nd)^6Li$ channels and output in ENDF-BVI format.

The reaction situation from the compound nucleus $^9Be^*$ to the discrete levels of the residual nuclei up to $E_\gamma = 30\ MeV$ is presented In Table I. $E_{th}$ refers to the threshold energy to open the $k_2$ level of the residual nucleus via $k_1$ level.

From Table I one can see that all of the excited levels of $^9Be$ can emit secondary particles, therefore $(\gamma, n\gamma)$ reaction channel is always small enough to be omitted.

Following the first proton emission the residual nucleus is $^8Li$. The ground state of $^8Li$ becomes into $^8Be$ through $\beta^-$ decay, while the excited states of $^8Li$ can emit neutron and becomes into $^7Li$. The $^3He$ emission results the residual nucleus $^6He$, the ground state of which becomes to be $^6Li$ through $\beta^-$ decay, while the excited state of $^6He$ undergoes the three-body breakup process to $n + n + \alpha$. The residual nucleus of $(\gamma, 2n)$ reaction channel is $^7Be$, which becomes $^7Li$ through EC with $T_{\frac{1}{2}} = 53.29\ d$. The residual nucleus $^5He$ of $(\gamma, \alpha)$ reaction channel is separated spontaneously into $n + \alpha$.

Table I. The reaction situation from the compound nucleus $^9Be^*$ to the discrete levels of the residual nuclei from $(\gamma, 2n)$, $(\gamma, np)$, $(\gamma, n\alpha)$, and $(\gamma, pn)$ reactions up to $E_\gamma = 30\ MeV$

| | $E^a_{th}$ | $k_1$ | $k_2$ | | $E_{th}$ | $k_1$ | $k_2$ |
|---|---|---|---|---|---|---|---|
| $(\gamma, 2n)$ | 20.58 | 7 | gs[b] | $(\gamma, 2n)$ | 20.74 | 8 | gs |
| $(\gamma, 2n)$ | 20.91 | 9 | gs | $(\gamma, 2n)$ | 21.07 | 10 | gs |
| $(\gamma, 2n)$ | 21.53 | 11 | gs | $(\gamma, 2n)$ | 21.77 | 12 | gs |
| $(\gamma, 2n)$ | 21.87 | 13 | gs | $(\gamma, 2n)$ | 22.57 | 14 | gs |
| $(\gamma, 2n)$ | 23.37 | 15 | gs | $(\gamma, 2n)$ | 23.67 | 16 | gs |
| $(\gamma, 2n)$ | 23.72 | 17 | gs | | | | |
| $(\gamma, np)$ | 19.31 | 5 | gs | $(\gamma, np)$ | 19.82 | 6 | gs - 1 |
| $(\gamma, np)$ | 20.58 | 7 | gs - 1 | $(\gamma, np)$ | 20.74 | 8 | gs - 1 |
| $(\gamma, np)$ | 20.91 | 9 | gs - 1 | $(\gamma, np)$ | 21.07 | 10 | gs - 1 |
| $(\gamma, np)$ | 21.53 | 11 | gs - 1 | $(\gamma, np)$ | 21.77 | 12 | gs - 1 |
| $(\gamma, np)$ | 21.87 | 13 | gs - 1 | $(\gamma, np)$ | 22.57 | 14 | gs - 1 |
| $(\gamma, np)$ | 23.37 | 15 | gs - 1 | $(\gamma, np)$ | 23.67 | 16 | gs - 2 |
| $(\gamma, np)$ | 23.72 | 17 | gs - 2 | | | | |
| $(\gamma, n\alpha)$ | 4.705 | 1 | gs | $(\gamma, n\alpha)$ | 13.07 | 2 | gs |
| $(\gamma, n\alpha)$ | 13.07 | 3 | gs | $(\gamma, n\alpha)$ | 18.29 | 4 | gs |
| $(\gamma, n\alpha)$ | 19.31 | 5 | gs | $(\gamma, n\alpha)$ | 19.82 | 6 | gs |
| $(\gamma, n\alpha)$ | 20.58 | 7 | gs | $(\gamma, n\alpha)$ | 20.74 | 8 | gs |
| $(\gamma, n\alpha)$ | 20.91 | 9 | gs | $(\gamma, n\alpha)$ | 21.07 | 10 | gs |
| $(\gamma, n\alpha)$ | 21.53 | 11 | gs | $(\gamma, n\alpha)$ | 21.77 | 12 | gs |
| $(\gamma, n\alpha)$ | 21.87 | 13 | gs | $(\gamma, n\alpha)$ | 22.57 | 14 | gs |
| $(\gamma, n\alpha)$ | 23.37 | 15 | gs | $(\gamma, n\alpha)$ | 23.67 | 16 | gs |
| $(\gamma, n\alpha)$ | 23.72 | 17 | gs | | | | |
| $(\gamma, pn)$ | 19.16 | 2 | gs | $(\gamma, pn)$ | 20.12 | 3 | gs - 1 |
| $(\gamma, pn)$ | 22.31 | 4 | gs - 1 | $(\gamma, pn)$ | 23.01 | 5 | gs - 1 |
| $(\gamma, pn)$ | 23.45 | 6 | gs - 1 | $(\gamma, pn)$ | 24.91 | 7 | gs - 1 |

[a] The term $E_{th}$ refers to the threshold energy needed to open the $k_2$ level of the residual nucleus via $k_1$ level.

[b] The acronym *gs* refers to ground state.

The formulation of the double differential cross sections from discrete levels to discrete levels of sequential two-body reactions, three-body breakup process and the double differential cross section of cluster separation can be found in Refs 2 and 3.

The residual nuclei $^8Be$ and $^5He$ are unstable and separated into two clusters spontaneously. For instance $^8Be \rightarrow \alpha + \alpha$, with $Q$=0.092 $MeV$, $^5He \rightarrow \gamma + \alpha$, with $Q$=0.894 $MeV$, respectively.

## 2 Results and Summary

The GLUNF code is developed for calculating the interrelated data below 30 MeV. The physical quantities calculated numerically by GLUNF code contain:

1. photoabsorption cross sections;

2. all kinds of reaction cross sections with different reaction mechanism and energy spectra of outgoing particles, like neutron, proton, $\alpha$ particle, triton and deuteron;

3. the energy spectra of outgoing particles from each reaction channel.

4. the total neutron spectrum of the emitted neutron.

5. outputting the data in ENDF/B-VI format.

The model has been used for calculating the cross sections of $\gamma +^9 Be$ reactions. The plotting of the $(\gamma, abs)$, $(\gamma, 2n)$ and $(\gamma, n + np + 2n)$ evaluated cross sections are shown through Fig.1 to 4, the experimental data are taken from Refs. 4 through 9. All of the comparisons between the experimental data and the calculated results are in good fitting. The plotting of every reaction channels is shown in Fig.5.

Lack of the experimental data on energy spectrum, so that this kind of plotting is not given.

In this model the sequential two-body emisions, two-body separation reactions and three-body breakup process are included, from which the different respective energy spectra are obtained as the components of the total energy spectrum of the outgoing particles.

The $E_1$, $M_1$ and $E_2$ mechanism are taken into account for $\gamma$ emission in pre-equilibrium and equilibrium processes. For light nucleus the direct emissions are not included, due to very small contribution at low energies.

The equilibrium mechanism and pre-equilibrium mechanism are involved in the model calculations. The prè-equilibrium mechanism plays important role in $\gamma +^9 Be$ reactions.

The new model for photonuclear light nucleus reactions has been proposed. The initial nuclear excitation can be understood in terms of particle-hole excitations (1p1h) for GDR. The key point in this model is the description of the particle emissions between discrete levels in both equilibrium state and pre-equilibrium state. The pre-equilibrium emission mechanism dominates the reaction processes.

## 3 Reference

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