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Production Cross–Section Calculations of Medical ^{125}I Radionuclide Using α, d and γ Induced Reactions

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Abstract: Iodine radioisotopes are the most important radioisotopes used in the medicine, especially ^{125}I. ^{125}I is used in radiation therapy as brachytherapy source to treat prostate cancer and brain tumors. In this study, production cross–section calculations of ^{125}Iradionuclide used in medicine produced by ^{123}Sb (α,2n)^{125}I, ^{124}Te(d,n)^{125}I, and ^{127} I(γ,2n)^{125}I reactions have been investigated in the different incident energy range up to 40 MeV. Two–Component Exciton and Generalized Superfluid models of the TALYS 1.6 code and Exciton and Generalized Superfluid models of the EMPIRE 3.1 code have been used to perform calculations. The calculated results have been compared with the experimental results taken fromthe Experimental Nuclear Reaction Data Library (EXFOR). EMPIRE 3.1 Exciton and Generalized Superfluid models are recommended, if experimental production cross–section of ^{125}Iradionuclide data are not available to produce because of the experimental difficulties.

Key words: ^{125}I, Cross–section, TALYS 1.6, EMPIRE 3.1

Tıbbi ^{125}I Radyonüklidininα, d ve γ Girişli Reaksiyonlar Kullanılarak Üretim Tesir Kesitlerinin Hesaplanması

Özet: Özellikle ^{125}I olmak üzere, iyot radyoizotopları tıpta kullanılan en önemli izotoplardır. ^{125}I, prostat kanseri ve beyin tümörlerini tedavi etmek için radyasyon tedavisinde brakterapi kaynağı olarak kullanılır. Bu çalışmada, 40 MeV'e kadar farklı gelme enerjilerinde ^{23}Sb (α,2n)^{125}I, ^{124}Te(d,n)^{125}I, ve ^{127} I(γ,2n)^{125}I reaksiyonları ile ^{125}I radyonüklidin üretim tesir kesiti hesaplamaları araştırılmıştır. TALYS 1.6 İki Bileşenli Eksiton ve Genelleştirilmiş Süperakışkan modelleri, EMPIRE 3.1 Eksiton ve Genelleştirilmiş Süperakışkan modelleri teorik hesaplamaları gerçekleştirmek için kullanılmıştır. Hesaplanan sonuçlar, Deneysel Nükleer Veri Kütüphanesi (EXFOR)'dan alınan deneysel sonuçlar ile karşılaştırılmıştır. ^{125}I radyoizotopunun deneysel üretim tesir kesiti değerleri, deneysel zorluklardan dolayı üretilemiyorsa EMPIRE 3.1Eksiton ve Genelleştirilmiş Süperakışkan modelleri kullanılması önerilmiştir.

Anahtar kelimeler: ^{125}I, Tesir kesiti, TALYS 1.6, EMPIRE 3.1

1. Introduction

One of the most popular radioisotopes used in the brachytherapy is Iodine-125 (^{125}I) [1]. It is chosen for brachytherapy because of the low energy photons of 28.5 keV. Thus, it is possible to minimize doses to normal structures thanks to their low energy with rapid dose fall-off. On the other hand their half-life's (59.4 days) are very suitable for the brachytherapy. In the prostate cancer treatment, ^{125}I seeds are placed directly into the prostate gland by an after loading needle system with a special gun or preloaded needles. The seeds are permanently placed to the prostate gland. Many seeds have to be placed throughout the prostate to cover the entire gland and the cancer site because each seed irradiates a small volume of prostate tissue. The number of seeds used can range from 50 to 150, depending on the size of the prostate gland [2]. Similarly, choroidalmelanoma can be treated using radioactive ^{125}I. Radioactive ^{125}I is produced in the form of seed. ^{125}I seeds are placed into a non-radioactive metallic plaque to apply the choroidalmelanoma. The radioactive plaque is sewn onto the eye as to cover the intraocular tumor shadow with a 2-3 mm margin. These plaques are temporary and radiation is continuously delivered over 5 to 7 days. At the end of treatment, the plaque is removed from eye [3].

Production of medical isotope is an important and constantly evolving issue. Cyclotrons and reactors are used for radionuclide production purposes [4,5]. The cross–section data for nuclear reactor production are generally well-known and can be satisfactorily reproduced by nuclear model calculations. Theoretical models of nuclear reactions are generally needed to get the prediction of the reaction cross–sections, in a specific manner if the experimental measurements are unobtainable or are improbably to be produced because of the experimental difficulties. In this study, production cross–section calculations of ^{125}Iradionuclide used in brachytherapy produced by ^{123}Sb (α,2n)^{125}I, ^{124}Te(d,n)^{125}I, and ^{127} I(γ,2n)^{125}I reactions have been investigated in the different incident energy range up to 40 MeV**.** Two–Component Exciton and Generalized Superfluid models of the TALYS 1.6 [6] code and Exciton and Generalized Superfluid models of the EMPIRE 3.1 [7] code were used to perform calculations and calculated results were compared with the experimental results reported in the literature.

2. Calculation Methods

The production cross–sections of ^{125}I radionuclide used in prostate and uveal melanoma treatments have been calculated using Two–Component Exciton and Generalized Superfluid models of the TALYS 1.6 code and Exciton and Generalized Superfluid models of the EMPIRE 3.1 code.

Two versions of the exciton model are implemented in TALYS 1.6. The default is the Two–Component model in which the neutron or proton types of particles and holes are followed throughout the reaction. In the following reaction equations, we use a notation in which $p_\pi(p_\nu)$ is the proton (neutron) particle number and $h_\pi(h_\nu)$ the proton (neutron) hole number. From this, we define the proton exciton number $n_\pi = p_\pi + h_\pi$ and the neutron exciton number $n_\nu = p_\nu + h_\nu$. From this, we can construct the charge independent particle number $p = p_\pi + p_\nu$, the hole number $h = h_\pi + h_\nu$ and the exciton number $n = n_\pi + n_\nu$.

The primary pre–equilibrium differential cross–section for the emission of a particle k with emission energy E_k can then be expressed in terms of τ, the composite–nucleus formation cross–section σ^{CF}, and an emission rate W_k,

$$\frac{d\sigma_k^{PE}}{dE_k} = \sigma^{CF} \sum_{p_\pi=p_\pi^0}^{P_\pi^{max}} \sum_{p_\nu=p_\nu^0}^{P_\nu^{max}} W_k(p_\pi,h_\pi,p_\nu,h_\nu,E_k)\,\tau(p_\pi,h_\pi,p_\nu,h_\nu) \times P(p_\pi,h_\pi,p_\nu,h_\nu) \tag{1}$$

where the factor P represents the part of the pre–equilibrium population that has survived emission from the previous states and now passes through the $(p_\pi, h_\pi, p_\nu, h_\nu)$ configurations, averaged over time. The basic feeding term for pre–equilibrium emission is the compound formation cross–section σ^{CF}, which is given by

$$\sigma^{CF} = \sigma_{reac} - \sigma_{direct} \tag{2}$$

where the reaction cross–section σ_{reac} is directly obtained from the optical model and σ_{direct} is the sum of the cross–sections for direct reactions to discrete states $\sigma^{disc,direct}$ as defined in Eq. (3) [6].

$$\sigma^{disc,direct} = \sum_i \sum_{k=n,p,d,t,h,\alpha} \sigma^{i,direct}_{n,k} \tag{3}$$

EMPIRE permits the calculation of pre–equilibrium emission in reactions using either the exciton model PCROSSmodule. The module PCROSS includes the pre–equilibrium mechanism as defined in the exciton model, as based on the solution of the master equation in the form proposed by Cline [8] and Ribansky [9].

The formula described below may suggest a nuclide-specific constant value for the level density parameter a, and the first level density analyses spanning an entire range of nuclides indeed treated a as a parameter independent of energy. We argued that a more realistic level density is obtained by assuming that the Fermi gas formula outlined above are still valid, but that energy-dependent shell effects should be effectively included through an energy dependent expression for a.

$$a = a(E_x) = \tilde{a}\left(1 + \delta W \frac{1-exp[-\gamma U]}{U}\right) \tag{4}$$

The asymptotic value $\tilde{a}$ is given by the smooth form

$$\tilde{a} = \alpha A + \beta A^{2/3} \tag{5}$$

where A is the mass number, while the following systematical formula for the damping parameter is used,

$$\gamma = \frac{\gamma_1}{A^{1/3}} + \gamma_2 \tag{6}$$

α, β and $\gamma_{1,2}$ are global parameters that have been determined to give the best average level density description over a whole range of nuclides. They are given in Table 1 [6].

Table 1. Global level density parameters [6]

Model	α	β	γ_1	δ_{global}
GSM effective	0.110575	0.0313662	0.648723	1.13208
GSM collective	0.0357750	0.135307	0.699663	-0.149106

EMPIRE 3.1 Generalised Superfluid model is characterized by a phase transition from superfluid behaviour at low energy where pairing correlations strongly influence the level density, to a high energy region which is described by the Fermi Gas model. Thus, the Generalised Superfluid model resembles the Gilbert–Cameron to the extent that the model distinguishes between a low energy and a high energy region, although for the Generalised Superfluid model this distinction follows naturally from the theory and does not depend on specific discrete levels that determine a matching energy [7].

The details of model parameters and options of TALYS 1.6 and EMPIRE 3.1 codes can be found in Refs. [6,7,10].

3.Results and Discussion

The production cross–sections of ^{125}I radionuclide were calculated as a function of different incident energies up to 40 MeV by using the pre–equilibrium models of TALYS 1.6 and EMPIRE 3.1 codes. The calculated and experimental cross–sections of ^{123}Sb $(\alpha,2n)^{125}$I,

^{124}Te(d, n)^{125}I, and ^{127} I(γ,2n)^{125}I reactions have been plotted in Figs. 1–3. All experimental results used in this present study were taken from the EXFOR [11] library.

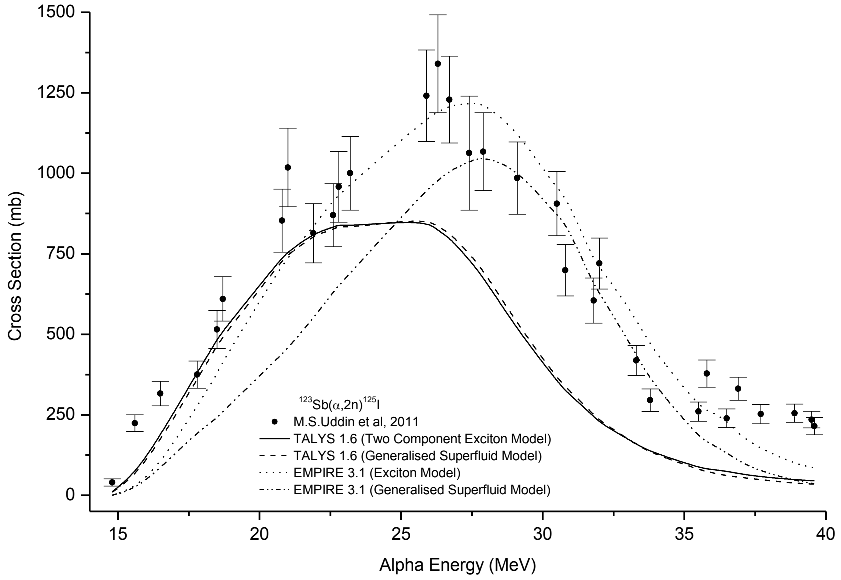

Figure 1. The comparison of calculated cross–sections of ^{123}Sb(α,2n)^{125}I reaction with the experimental values reported in the literature

The calculated cross–sections of ^{123}Sb (α,2n)^{125}I reaction was compared with the experimental results in Fig. 1. The energy range of α particle was selected between 15 and 40 MeV to make a comparison with the results reported in the literature. TALYS 1.6 Two–Component Exciton and Generalised Superfluid models and EMPIRE 3.1 Exciton model calculations are in good agreement with the experimental data up to 24 MeV α incident energy. EMPIRE 3.1 Exciton model and Generalised Superfluid model calculations are in good agreement with experimental data from 27 MeV to 38 MeV α incident energy.

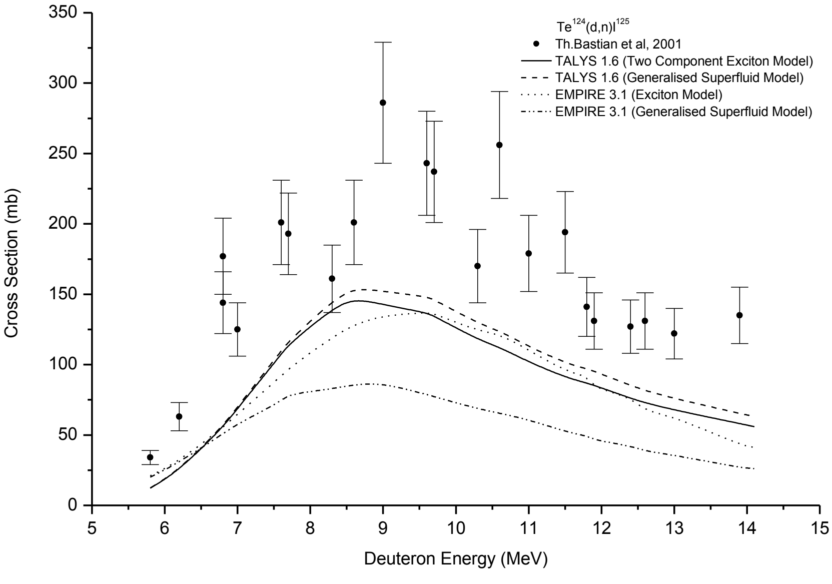

Figure 2. The comparison of calculated cross–sections of ^{124}Te (d,n)^{125}I reaction with the experimental values reported in the literature.

The comparison of experimental and theoretical results of ^{124}Te (d, n)^{125}I reaction was given in Fig. 2. The energy range of deuteron particle was selected between 6 and 14 MeV to make a comparison with the results reported in the literature. All model calculations are significantly disagree with the experimental data. On the other hand, the EMPIRE 3.1 Generalised Superfluid model calculations extremely differs from other model results as shown in the Fig 2.

The experimental and theoretical results on the production cross–sections of ^{125}I radionuclide via ^{127} I (γ, 2n)^{125}I reaction was given in Fig. 3. The energy range of γ was selected between 16 and 31 MeV to make a comparison with the results reported in the literature. All model calculations are in agreement with the experimental values including error bars.

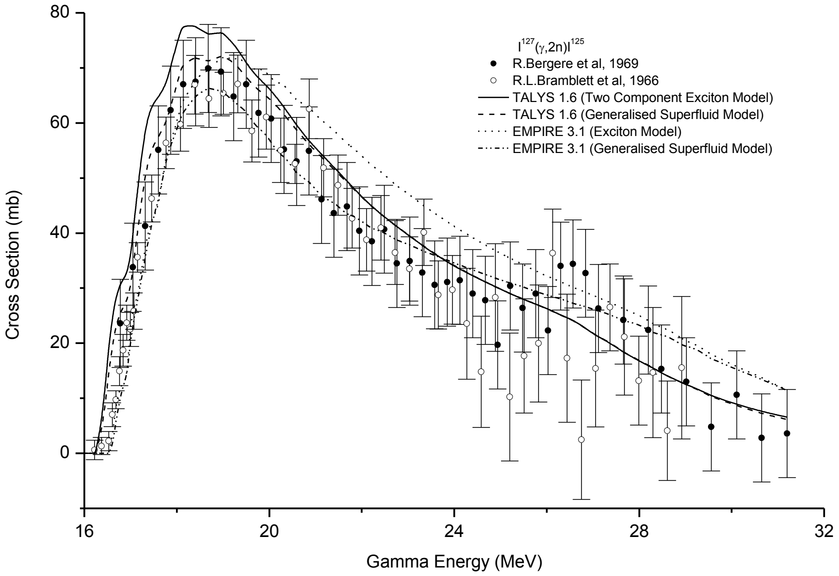

Figure 3. The comparison of calculated cross–sections ^{127}I (γ,2n)^{125}I reaction with the experimental values reported in the literature

4. Summary and Conclusions

The results can be summarized and concluded as follows:

1. The cross–section results calculated with EMPIRE 3.1 and TALYS 1.6 computer codes for all reactions are mostly in agreement with the experimental data except for ^{124}Te (d, n)^{125}I reaction.
2. The EMPIRE 3.1 Exciton model option for the production cross–section calculations of ^{125}Iradionuclide can be chosen, if the experimental data are not available or are improbable to be produced due to the experimental difficulty.

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