Nuclear Instruments and Methods in Physics Research B 345 (2015) 1–8

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Calculation of excitation functions of proton, alpha and deuteron induced reactions for production of medical radioisotopes $^{122-125}I$

Ozan Artun *, Hüseyin Aytekin

Bülent Ecevit University, Department of Physics, 67100 Zonguldak, Turkey

ARTICLE INFO

Article history:
Received 23 August 2014
Received in revised form 1 December 2014
Accepted 12 December 2014
Available online 2 January 2015

Keywords:
Iodine
Nuclear reaction
Excitation function
Radioisotope
Nuclear model

ABSTRACT

In this work, the excitation functions for production of medical radioisotopes $^{122-125}I$ with proton, alpha, and deuteron induced reactions were calculated by two different level density models. For the nuclear model calculations, the Talys 1.6 code were used, which is the latest version of Talys code series. Calculations of excitation functions for production of the $^{122-125}I$ isotopes were carried out by using the generalized superfluid model (GSM) and Fermi-gas model (FGM). The results have shown that generalized superfluid model is more successful than Fermi-gas model in explaining the experimental results.

1. Introduction

Nuclear reactions in the intermediate-energy region are a matter of interest in some fields of technology and science such as reactor technology, gas production in structural materials, radiation therapy in nuclear medicine, medical radionuclide production, diagnostic and therapeutic studies, astrophysics, accelerator driven systems, environmental sciences, fusion and fission reactors [1]. At the present day, radioisotope production for nuclear medicine is important because of its common use in tomography devices. Both single photon emissions computed tomography (SPECT) and positron emission tomography (PET) are used for diagnosis in nuclear medicine. In particular, the radionuclides $^{122-125}I$ are used for these purposes. Therefore, these radionuclides play an important role in medical applications and researches. Gamma-emitted short-lived ^{123}I ($T_{1/2}$ = 13.2 h, E_γ = 159 keV) and long-lived ^{124}I ($T_{1/2}$ = 4.18 d, E_{β^+} = 2.13 MeV (22%), E_γ = 603 keV) [2] isotopes can be used as diagnostic image in SPECT and PET [3,4]. Besides, the ^{124}I allows for studying of important organs such as brain and heart [5]. The longer-lived ^{125}I ($T_{1/2}$ = 59.4 d, E_γ = 35.5 keV) isotope is used as a source for internal radiotherapy, bone dosimetry and a biological tracer [6]. Another iodine radionuclide ^{122}I ($T_{1/2}$ = 3.6 min, E_{β^+} = 3.1 MeV (77%) is a very short-lived isotope and used in PET for brain blood-flow studies [7].

In the present work, we have investigated the excitation functions of alpha, proton, deuteron induced reactions for production of medical radioisotopes $^{122-125}I$. In order to calculate the excitation functions, the generalized superfluid model (GSM) and the Fermi gas model (FGM), which includes the default density parameter, were used in the Talys 1.6 code. Investigation of the excitation functions has shown that the generalized superfluid model has some advantages in explaining the experimental data.

2. Theoretical framework

The Talys 1.6 code [8], which can simulate the nuclear reactions with light particle-induced reaction, is useful to explain the pre-equilibrium (PEQ) reaction processes through two-component exciton model [9–11].

The GSM takes into account the superconductive pairing correlations established by including the phase transition between the superfluid behaviour of the nucleus at low energy and the high-energy region that is assessed by Fermi gas model. Level density as the thermodynamic function can be defined for the critical energy U_c [11–13]:

$$U_c = a_c T_c^2 + E_{\mathrm{cond.}} \tag{1}$$

Here, $T_c = 0.567\Delta_0$ is the critical temperature, Δ_0 is the pairing correlation function given by $\Delta_0 = \frac{12}{\sqrt{A}}$, and, E_{cond} is the condensation energy given as,

* Corresponding author.
E-mail addresses: ozanartun@yahoo.com (O. Artun), huseyinaytekin@gmail.com (H. Aytekin).

http://dx.doi.org/10.1016/j.nimb.2014.12.029
0168-583X/

$$\mathrm{E}_{\mathrm{cond}} = \frac{3}{2\pi^2} a_c \Delta_0^2, \tag{2}$$

where, a_c is the critical level density parameter. Effective excitation energies (U') for the level density below U_c can be written by means of superfluid Equation of State (EOS) [12,13]

$$U' = E_x + \chi\Delta_0 + \delta. \tag{3}$$

Here, the values of χ are 2, 1 and 0 for odd–odd, odd–even and even–even nuclei, respectively. The level density for GSM is given by,

$$\rho_{\mathrm{GSM}}(E_x, J, \Pi) = \frac{1}{2} \mathrm{R_F}(E_x, J) \rho^{tot}_{\mathrm{GSM}}(E_x), \tag{4}$$

where $\mathrm{R_F}(E_x, J)$ is Fermi gas spin distribution can be defined by,

$$\mathrm{R_F}(E_x, J) = \frac{2J+1}{2\sigma^2} \exp\left[-\frac{\left(J+\frac{1}{2}\right)^2}{2\sigma^2}\right]. \tag{5}$$

There are two statements for $\rho^{tot}_{\mathrm{GSM}}(E_x)$ in Eq. (4) [11]:

(i) For $U' \le U_c$, $\rho^{tot}_{\mathrm{GSM}}(E_x)$ is given by,

$$\rho^{tot}_{\mathrm{GSM}}(E_x) = \frac{1}{\sqrt{2\pi\sigma^2}} \frac{e^S}{\sqrt{D}} \tag{6}$$

where, S, σ^2 and D are entropy, spin cut-off parameter and determinant, respectively. Those terms were explained in detail in Refs. [11–13].

(ii) For $U' \ge U_c$, $\rho^{tot}_{\mathrm{GSM}}(E_x)$ is given by,

$$\rho^{tot}_{\mathrm{GSM}}(E_x) = \frac{1}{\sqrt{2\pi\sigma^2}} \frac{\sqrt{\pi}}{12} \frac{\exp[2\sqrt{aU}]}{a^{1/4}U^{5/4}}, \tag{7}$$

where U is the effective excitation energy and given by,

$$U = E_x - \Delta^{\mathrm{GSM}} \tag{8}$$

and Δ^{GSM} is defined as,

$$\Delta^{\mathrm{GSM}} = \mathrm{E}_{\mathrm{cond}} - \chi\Delta_0 - \delta. \tag{9}$$

In Eqs. (7) and (9), a and δ are regulatable parameters for GSM [11].

3. Result and discussion

In this paper, excitation functions of alpha, proton, and deuteron-induced reactions for production of $^{122-125}$I isotopes are investigated by the generalized superfluid model (GSM) and Fermi-gas model (FGM) and the present calculated results are compared with the existing literature. Additionally, we calculated the Q-value and the threshold energy (E-threshold) of 23 reactions with the Talys code and decay data of radionuclides $^{122-125}$I, which are shown in Table 1.

3.1. Production of radioisotope ^{122}I

The calculated excitation functions of (p,n), (p,2n), (p,4n), (d,2n) reactions for production of radionuclide ^{122}I and all the experimental data reported, which was taken from EXFOR [14], are given in Figs. 1–4. The results of the level density calculations, namely FGM and GSM, and the experimental data of ^{123}Te(p,2n)^{122}I reaction (Fig. 1) closes to the results of GSM more compared to FGM, but considering the experimental error rate, model calculations agree with the data reported by Scholten et al. [16] in maximum of excitation function about 19 MeV. The excitation function deduced from the reported data of Scholten et al. for this reaction is lower as compared to the theoretical results. The calculation for GSM shows agreement with only two data points in the 12 and 19 MeV. The results of theoretical calculations along with the data reported by Hohn et al. [3] for ^{122}Te(p,n)^{122}I reaction are shown in Fig. 2. The trend of the experimental data is described well by all the two model calculations. The results of the models were found to be in very good agreement with one another. However, except for only two data points, there existed discrepancies between theoretical values and experimental data. In the case of the ^{122}Te(d,2n)^{122}I reaction (Fig. 3), the data reported by Zaidi et al. [17] is too far from the theoretical results and peak amplitude of experimental results is not comparable to the calculated results. The remarkable discrepancy becomes obvious between the model calculations and literature experimental data. The results of theoretical calculations along with the measurement by Hohn et al. for ^{125}Te(p,4n)^{122}I reaction are shown in Fig. 4. The experimental data for this reaction are rather scanty (only six data points up to 70 MeV). Excitation function of this reaction obtained with GSM approach closes to the experimental data points of Hohn et al. [18] when the error rate is included. Although there existed the measurement beyond 38 MeV, only two data points approach the theoretical results beyond 60 MeV.

3.2. Production of radioisotope ^{123}I

The excitation functions for the radionuclide ^{123}I are produced by nine different reactions given in Table 1. The excitation functions for production of radioisotope ^{123}I derived by FGM and GSM along with the experimental data are shown in Figs. 5–13. The data reported by Scholten et al. [19] for ^{126}Te(p,4n)^{123}I reaction is shown together with the results of calculations in Fig. 5. Except for one point near the threshold of the reaction, there are dispersed experimental data and very few data points. Especially, the experimental data are rather scanty before maximum of the excitation function and higher than the model calculations in the energy region above 41 MeV. The theoretical excitation functions and recommended data reported by Aslam et al. [20] along with the experimental measurements for ^{121}Sb(α,2n)^{123}I reaction are shown in Fig. 6. The agreement between the experimental data and theoretically calculated data in the energy range above 16 MeV and below 21 MeV is good, but calculated results are lower around maximum of the excitation function. The data reported by Singh et al. [21] are described well by the models. The recommended excitation function curve for this reaction agrees with the measurement by Ismail [22] in the energy range between 16 and 41 MeV. The excitation function data for ^{123}Te(d,2n)^{123}I reaction were reported in one experiment measured by Scholten et al. [25] and the results are shown in Fig. 7. Although the results of calculations using the density models (GSM and FGM) are in good agreement with each other, the experimental data have the discrepancies. For ^{123}Te(p,n)^{123}I reaction, the results of density model calculations and the experimental data are shown in Fig. 8. The calculated results are consistent with each other up to 14 MeV. The data reported by Mahunka et al. [26] agree with the theoretical results below 10 MeV but when it comes to the results beyond 13 MeV, while the calculated result with GSM is consistent with the measurements by Takacs et al. [27], the measurements by Mahunka et al. [26] are in good agreement with calculated result with FGM. The calculated excitation functions of the ^{123}Sb(α,4n)^{123}I reaction together with the measurement by Singh et al. [21] and by Ismail [22] are shown in Fig. 9. The results of the measurements by Singh et al. are low but the theoretical calculations show good agreement with the data reported by Ismail up to 43 MeV. Especially beyond 45 MeV, the theoretical results for this reaction are discrepant. For ^{121}Sb(α,2n)^{123}I, ^{123}Te(d,2n)^{123}I, ^{123}Te(p,n)^{123}I, and ^{123}Sb(α,4n)^{123}I reactions, the accordance between the experimental data and the theoretical results is