Investigation of neutron induced reactions on ^{23}Na by using Talys1.4 *

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Abstract: The neutron induced reactions on ^{23}Na are investigated by using the Talys1.4 program. The calculated results for the ^{23}Na(n, 2n)^{22}Na reaction are found to agree with the experimental results. The cross sections of the residues of the (n, n), (n, γ), (n, p), and (n, np) channels in the reactions are presented, and at the same time, the neutron induced reactions on ^{22}Ne are also investigated.

Key words: neutron activation, ^{23}Na(n, 2n)^{22}Na, ^{23}Na(n, np)^{22}Ne, ^{22}Ne(n, x)

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1 Introduction

The sodium isotopes are important in the neutron activation analysis since they are the most utilized in practical application. For example, the ^{23}Na(n, 2n) is necessary for the radiation protection in a fast reactor using sodium as a coolant. The ^{22}Na nucleus is a positron-emitting isotope with a remarkably long half-life [2.6027(10) yr] and the daughter is ^{22}Ne. It is used to create test-objects and point-sources for positron emission tomography. The ^{24}Na nucleus is one of the most important isotopes of sodium. With a 15 h half life, ^{24}Na decays to ^{24}Mg by the emission of an electron and two γ rays. Exposure of the human body to intense neutron flux creates ^{24}Na in blood plasma. Measurements of its quantity are used to determine the absorbed radiation dose of the patient [1, 2]. From the theoretical side, ^{23}Na is just in the intermediate zone between the region of validity of statistical theory and the region of light nuclei which requires detailed treatment.

In this article, we investigate the neutron induced reactions on ^{23}Na, and its reaction-grid is also studied by considering the related important residues. The tool used is the Talys1.4, which is a computer code system for the analysis and prediction of nuclear reactions [3].

2 Methods

The complete description of the Talys code can be found in the Talys1.4 manual [4]. To deal with the neutron induced reactions, the optical model is adopted. All optical model calculations are performed by ECIS-06 [5], which is implanted as a subroutine in Talys. At low energies, elastic scattering and capture are considered when $E_n < 0.2$ MeV, and inelastic scattering to discrete states will be considered when $0.2 < E_n < 4$ MeV. The pre-equilibrium reactions are considered from $E_n > 4$ MeV, and the multiple compound emission will be considered when $E_n > 8$ MeV. The default values of parameters are adopted in the calculation. The Distorted Wave Born Approximation (DWBA) is used for the (near-)spherical nuclide for direct reactions. The multiple Hauser-Feshbach decay is used to deal with the multiple emission.

3 Results and discussion

The considered reaction grid of the neutron induced reactions on ^{23}Na is plotted in Fig. 1. In the grid, the main reactions and the long-live residues are considered. The natural sodium material includes no other isotopes but ^{23}Na. Furthermore, the ^{23}Ne can be produced through the (n, p) channel from ^{23}Na, and the (n, γ) channel from ^{22}Ne. And ^{23}Ne changes to ^{23}Na again through the β^- emission with a half-life of 37.24(12) s. ^{22}Ne can be produced through the (n, np) channel from ^{23}Na. Thus ^{22,23}Ne are also the nuclei we will consider. The productions of the n+^{23}Na reaction that we will calculate include the (n, n), (n, 2n), (n, np), (n, γ) channels. In these channels, the ^{23}Na(n, 2n)^{22}Na reaction has been experimentally measured by many groups in a large range of incident energy. In the Talys1.4 calculation, the

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default value of parameter is used. First we compare the results between the measured ^{23}Na(n, 2n)^{22}Na and the calculated ones. Then the predicted yields of other residues will be presented.

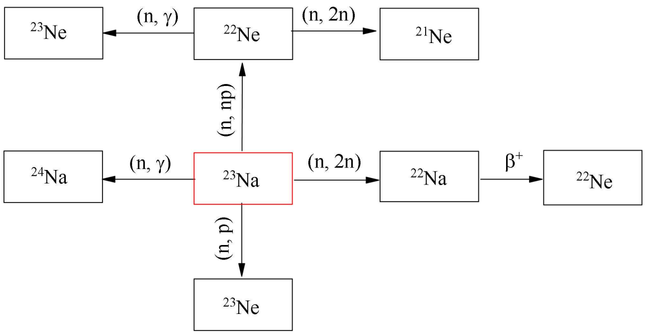

Fig. 1. The grid of neutron induced reactions on ^{23}Na considered in the work.

The measured yields of ^{22}Na in the ^{23}Na(n,2n)^{22}Na reaction are plotted in Fig. 2. The experimental results of ^{22}Na are extracted from the EXFOR library provided by the National Nuclear Data Center (NNDC) [6]. From Fig. 2, it can be seen that the measured cross section of ^{22}Na agrees well with each other when E_n is smaller than about 14 MeV [7–13] (and other data [14–22]), while the cross sections fall into three groups when $E_n > 14$ MeV: (1) the largest group measured by Lisken et al. [7] and Xu et al. [8]; (2) the smallest group measured by Picard et al. [23] and Soewarsono et al. [11]; and (3) the middle group measured by Menlove et al. [12], Sakuma et al. [24], Lu et al. [10], and Adamski et al. [25]. The ^{23}Na(n,2n)^{22}Na of the neutron energies from 13.5 MeV to 38.5 MeV were also calculated by Uwamino et al. using the NEUPAC codes, which prefers the data of the lowest group [26]. The ^{23}Na(n, 2n)^{22}Na reaction was also evaluated by a statistical model [27], of which the result prefers the results of Menlove et al. [12] and Filatenkov et al. [9]. Rochman et al. also investigated the ^{23}Na(n, 2n)^{22}Na reaction using the Talys code, but the inputs parameters for the optical potential were adjusted to seek for the smallest group of the measured results [28]. In this work, by using the default parameters in Talys1.4, the result prefers the results of Xu and Lisken et al. [7, 8] above E_n=14MeV, which is the largest group of the measured results. The divergence among the measured and theoretical results of the ^{23}Na(n, 2n)^{22}Na reaction above $E_n = 14$ MeV indicates that it may be important to re-investigate the reaction experimentally.

In Fig. 3, the yields of residues in the different channels of the neutron induced reactions on ^{23}Na are plotted. For ^{23}Na, the (n, n) reaction is the main channel in the calculated range of E_n, and the (n, γ) reaction also takes place in the entire range (with no lowest energy threshold) and forms a peak around $E_n = 20$ MeV, but the probability is much smaller than the other channels. Compared with the (n, n) and (n, γ) reactions, the other reactions have the lowest energy thresholds. The (n, p) reaction can only happen when $E_n > 4$ MeV, and the cross section increases fast with E_n and reaches the maximum value at E_n=11 MeV; when $E_n > 11$ MeV, the cross section decreases with the increasing E_n slowly. The (n, 2n) reaction, with ^{22}Na being the residue nucleus, happens when $E_n > 7.6$ MeV and the peak forms at E_n=14.8 MeV; when $E_n > 11$ MeV the cross section is larger than 100 mb, and in fact the cross section is larger than 300 mb in the range of E_n=13–23.8 MeV; the (n, np) reaction takes place when $E_n > 13.2$ MeV and the cross section of ^{22}Ne becomes larger than 100 mb when $E_n > 15.8$ MeV. The probability of the (n, np) reactions is similar to the (n, n) reaction when $E_n > 20$ MeV. At the same time, it should be noted that the probability

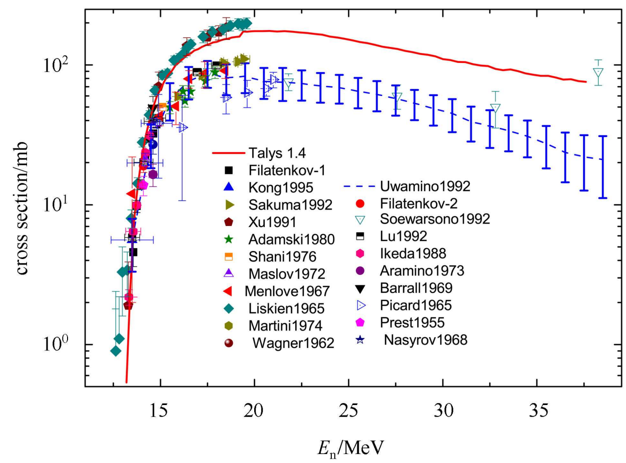

Fig. 2. (color online) The yield of ^{22}Na in the measured and calculated for the ^{23}Na(n,2n)^{22}Na reaction. The experimental results of ^{22}Na are extracted from the EXFOR library [6].

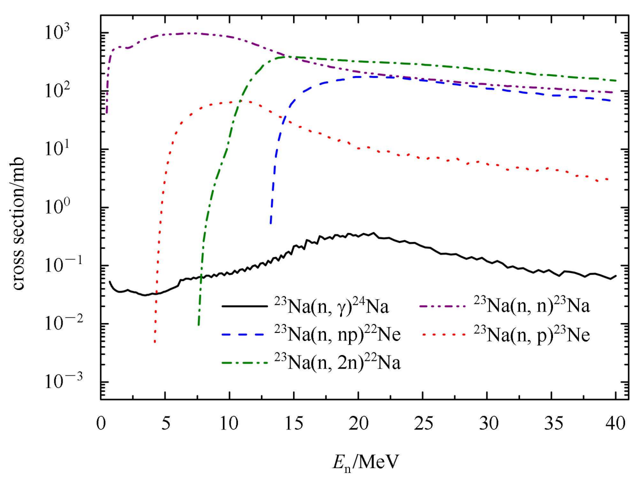

Fig. 3. (color online) The yield of residues produced in the different channels of the n+^{23}Na reactions calculated by Talys1.4.

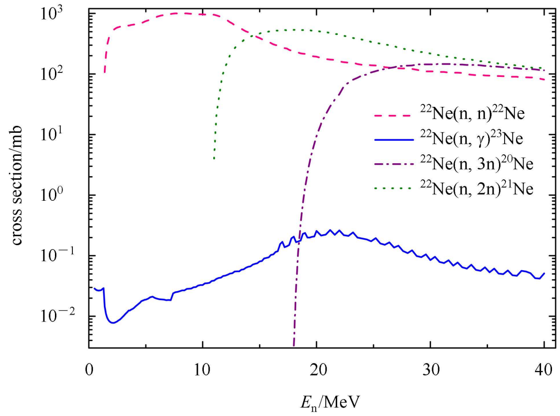

Fig. 4. (color online) The yield of residues produced in the different channels of the n+^{22}Ne reactions calculated by Talys1.4.

of the (n, 2n) reaction is larger than that of the (n, n) reaction.

The ^{22}Ne nucleus can be produced via the ^{23}Na(n, np) channel, and at the same time it is the daughter nucleus of ^{22}Na after the β^+ decay. The neutron induced reactions on ^{22}Ne are also investigated using Talys1.4. The calculated results are plotted in Fig. 4. Though the ^{22}Ne(n, γ) reaction happens in very low neutron incident energy (the cross section is very low), the ^{22}Ne can only be produced in pure ^{23}Na when $E_n > 13.2$ MeV. And when $E_n > 13.2$ MeV, ^{21}Ne can be produced through the ^{22}Ne(n, 2n) channel (the lowest E_n for this channel is 11 MeV in the calculated result; the cross section of ^{21}Ne is 320 mb at E_n=13.2 MeV). The ^{22}Ne(n, 3n)^{20}Ne reaction can only take place above $E_n > 18$ MeV. ^{23}Ne can be produced both through the ^{22}Ne(n, γ) and the ^{23}Na(n, np) channels, but ^{23}Ne has a very short half-life 37.24 s and decays to ^{23}Na. Thus if ^{22}Ne can be produced from ^{23}Na, ^{23}Ne and ^{21}Ne can also be produced through neutron induced reactions on ^{22}Ne.

4 Summary

In summary, the neutron induced ^{23}Na reaction is investigated using the Talys1.4 code. The calculated results of the ^{23}Na(n, 2n)^{22}Na reaction are found to agree with the experimental results measured by Xu and Lisken et al. Since there is large divergence among the results of the ^{23}Na(n, 2n)^{22}Na reaction above E_n=14 MeV both experimentally and theoretically, it is suggested to re-investigate the reaction experimentally. The cross sections of residues in the (n, n), (n, γ), (n, p), and (n, np) of ^{23}Na reaction channels are presented, and the neutron induced ^{22}Ne reactions are also investigated at the same time.

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