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The cross-section data from neutron activation experiments on niobium in the NPI p-7Li quasi-monoenergetic neutron field

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Abstract. The reaction of protons on ^{7}Li target produces the high-energy quasi-monoenergetic neutron spectrum with the tail to lower energies. Proton energies of 19.8, 25.1, 27.6, 30.1, 32.6, 35.0 and 37.4 MeV were used to obtain quasi-monoenergetic neutrons with energies of 18, 21.6, 24.8, 27.6, 30.3, 32.9 and 35.6 MeV, respectively. Nb cross-section data for neutron energies higher than 22.5 MeV do not exist in the literature. Nb is the important material for fusion applications (IFMIF) as well. The variable-energy proton beam of NPI cyclotron is utilized for the production of neutron field using thin lithium target. The carbon backing serves as the beam stopper. The system permits to produce neutron flux density about 10^9 n/cm^2/s in peak at 30 MeV neutron energy. The niobium foils of 15 mm in diameter and approx. 0.75 g weight were activated. The nuclear spectroscopy methods with HPGe detector technique were used to obtain the activities of produced isotopes. The large set of neutron energies used in the experiment allows us to make the complex study of the cross-section values. The reactions (n,2n), (n,3n), (n,4n), (n,He3), (n,α) and (n,2nα) are studied. The cross-sections data of the (n,4n) and (n,2nα) are obtained for the first time. The cross-sections of (n,2n) and (n,α) reactions for higher neutron energies are strongly influenced by low energy tail of neutron spectra. This effect is discussed. The results are compared with the EAF-2007 library.

1 Introduction

Neutron generator based on p-^{7}Li reaction at NPI Rez allows us to study cross-section data using quasi-monoenergetic neutron spectra up to 35 MeV neutron energy. Rez apparatus is described in details in ref. [1]. Therefore we are able to measure cross-section data at incident neutron energies higher than 20 MeV, where such data are scarce. Such data are needed for various technological applications like IFMIF as well. We measured our data for 7 proton beam energies and therefore we are able to analyse cross-section in the complexity. Two sets of different neutron spectra are used in the analysis: measured by TOF methods [2] and simulated. The results are compared with cross section data from EAF-2007 library [3].

2 Experimental equipment

The overall view of the target station for p-Li experiments is shown in Fig. 1 (left). The detail view of the reaction chamber is shown in Fig. 1 (right). Irradiated Nb foils are placed on the right side of the apparatus at distances 48 and 88 mm from the Li foil.

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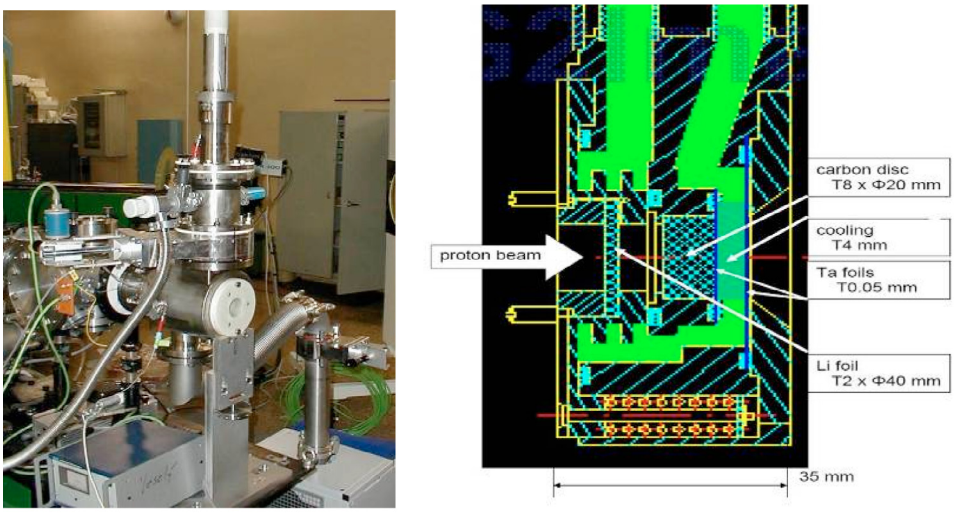

Fig. 1. The overall view to the target station of NPI p-^{7}Li neutron source (left). The detail view of the reaction chamber (right).

Niobium foils diam. 15 mm and weights approx. 0.75 g were irradiated at the distances of 48 and 88 mm from the lithium foil. The typical proton beam current was 3 μA, typical time of irradiation (at one proton beam energy run) was 20 h. The time profile of the proton beam current was monitored. Proton beam energies of 19.8, 25.1, 27.6, 30.1, 32.6, 35.0 and 37.4 MeV were used at 7 experimental runs.

Irradiated samples were investigated by means of gamma spectroscopy methods. Two HPGe detectors of 23 and 50% efficiencies and FWHM of 1.8 keV at 1.33 MeV were used. Activated isotopes were identified on the basis of half-lifes, gamma ray energies and intensities. Experimental results RR were obtained as number of produced atoms/1 μA of proton beam/1 kg of mass of target.

3 Neutron spectra

Neutron spectra consist of quasi-monoenergetic part corresponding to the reactions to g.s. and 0.429 MeV state in ^{7}Be, low-energy tail generated a) by reactions on ^{7}Li leading to further excited states in ^{7}Be and other reactions on ^{7}Li and b) by reactions of protons on carbon stopper.

Parameter RR is simply connected with the product of neutron spectrum NS(E) and cross section CS(E): RR $\sim \int \mathrm{NS(E)} \times \mathrm{CS(E)}\, \mathrm{dE} \sim \sum \mathrm{NS(E)} \times \mathrm{CS(E)}\, \Delta\mathrm{E}$. The corresponding set of equations is to be solved.

Two sets of neutron spectra were used in our evaluation.

– Spectra measured using TOF by Y.Uwamino et al. [2] at long distance (the neutron spectra for the proton energies not included in [2] were calculated according procedure described in ref. [4]). The example of the spectrum is shown in Fig. 2. We used closer geometry and therefore e.g. different distances of Li and C foils and angular dependency are not included in such an analysis.
– Spectra simulated [5], experimental conditions (Li foil, thick C beam stopper, alcohol coolant, flanges, experimental hall) included. For the simulation at both distances MCNPX and LA-150h proton cross section library were used. Spectra used in our analysis for geometry 88 mm (distance Li foil – Nb foil) are shown in Fig. 3.

4 Data analysis

The observed reactions are listed in Table 1. Isotope Nb93 is only one stable isotope of Nb.

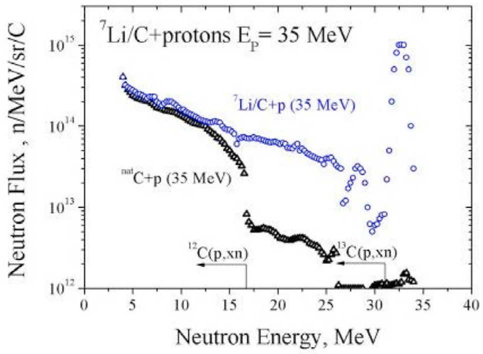

Fig. 2. Typical neutron spectrum (TOF) [2].

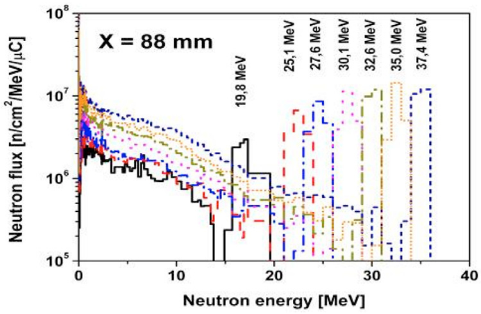

Fig. 3. Neutron spectra (simulated) [5].

Table 1. Isotopes observed from irradiation of Nb foils.

Isotope	T1/2	reaction	threshold (MeV)
Nb90	14.60 h	(n,4n)	29.078
Nb91m	60.86 d	(n,3n)	16.999
Nb92m	10.15 d	(n,2n)	9.063
Y91m	49.71 m	(n,3He)	8.362
Y90m	3.19 h	(n,α)	0
Y88	106.65 d	(n,α 2n)	13.554

4.1 Error analysis

Only the gamma spectroscopy errors (min. 3%) are used in the next part of the discussion of the results. The systematical errors of our beam current measurement (5%) and the error of beam current measurement of Y. Uwamino [2] as 10% should be added to gamma spectroscopy errors. The uncertainty of MCNPX is estimated as 10% for quasi-monoenergetic neutrons.

5 Experimental results

The experimental cross sections CS as a function of neutron energy En are shown in next figures. Our experimental data are presented for both irradiation distances 48 and 88 mm of Nb foils from the Li foil. In each case the different neutron spectra (see previous part of article) are used in the analysis, Y. Uwamino (Uw TOF) [2] and simulated (MCNPX) [5].

EAF-2007 library cross sections are shown as well; the proper feeding of the studied nuclei and possible other reaction channels (e.g. α+) are included. EXFOR data are shown as well.

We have to subtract low energy bump of cross sections lower ~20 MeV in two reactions ((n,2n) and (n,α)). For this purposes we use EAF-2007 library [3]. Firstly we will discuss these reactions. Subtraction of this bump in other reaction does not strongly influence the results.

5.1 Reaction (n,2n)

The activation cross-sections of isomeric state ^{92m}Nb were measured. The spectrum tail to lower energies below our experimental points is subtracted using EAF-2007 cross section library. Error of subtraction procedure as 5% is accepted. The high energy bump in the case of UwTOF spectra disappear when real experimental geometry (MCNPX) is taken into account. The data are close to EAF-2007 library. See Fig. 4.

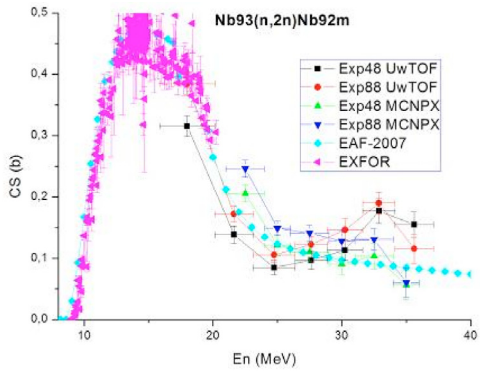

Fig. 4. Reaction ^{93}Nb(n, 2n)^{92m}Nb.

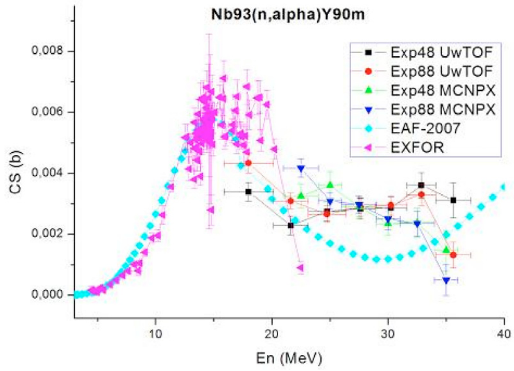

Fig. 5. Reaction ^{93}Nb(n, α)^{90m}Y.

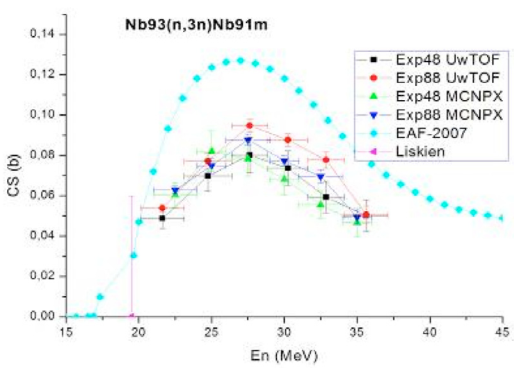

Fig. 6. Reaction ^{93}Nb(n, 3n)^{91m}Nb.

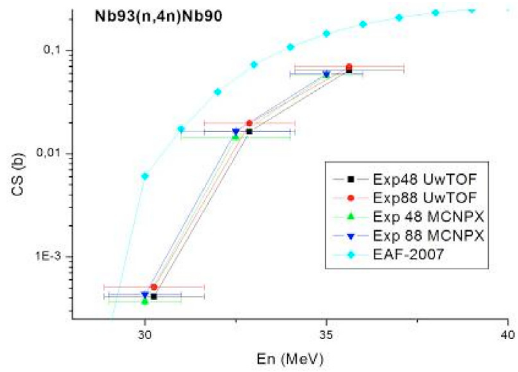

Fig. 7. Reaction ^{93}Nb(n, 4n)^{90}Nb.

5.2 Reaction (n,α)

The activation cross-sections of isomeric state ^{90m}Y were measured. Similarly to the previous reaction the low energy part is subtracted using EAF-2007 data, error of 10% is accepted. The behaviour of the MCNPX data was correctly described in (n,2n) reaction. We may come to the conclusion that EAF-2007 database does not correctly describe the reaction ^{93}Nb(n, α)^{90m}Y. See Fig 5.

5.3 Other reactions

Reaction (n,3n) activated isomeric state ^{91m}Nb (Fig. 6), reaction (n,4n) activated ground state ^{90}Nb (Fig. 7), reaction (n,^{3}He) activated isomeric state ^{91m}Y (Fig. 8) and reaction (n,α 2n) activated ground state ^{88}Y (Fig. 9).

The EAF-2007 data are substantially higher than the experimental ones in the reactions (n,3n), (n,4n) and (n,3He). The data of (n,α 2n) reaction are described properly using EAF-2007.

The energy intervals used in VITAMIN J+ for higher energies are too large for cross section calculations and MCNPX simulations.

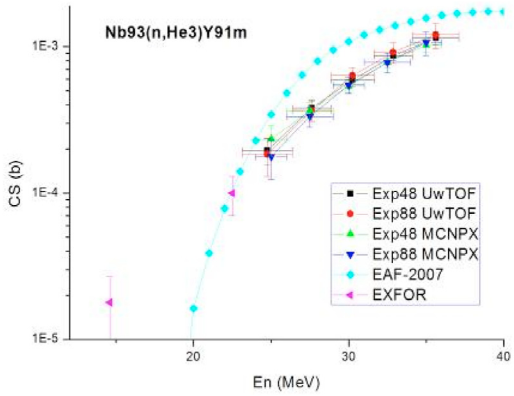

Fig. 8. Reaction ^{93}Nb(n,^{3}He)^{91m}Y.

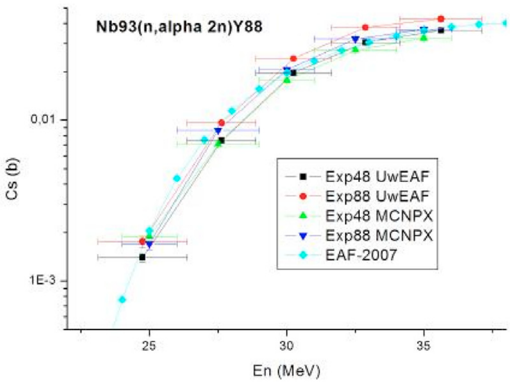

Fig. 9. Reaction ^{93}Nb(n, α 2n)^{88}Y.

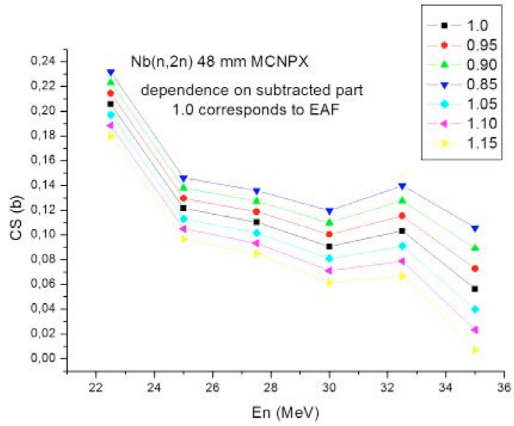

Fig. 10. Dependence of CS data on multiplications coefficients, reaction^{93}Nb(n, 2n)^{92m}Nb.

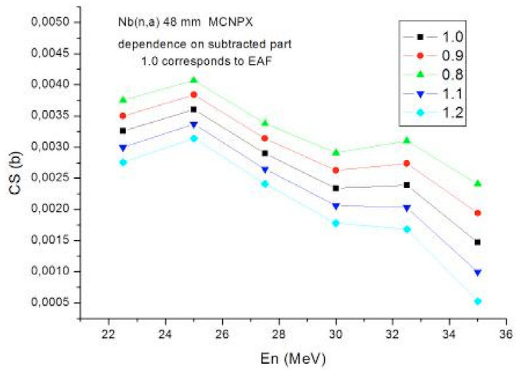

Fig. 11. Dependence of CS data on multiplications coefficients, reaction ^{93}Nb(n, α)^{90m}Y.

6 Errors and correlations – some comments

6.1 The influence of cross-section low energy bump

We will discuss the effect of low-energy cross-section bump (neutron energies < ~20 MeV) on our data in more details (reactions (n,2n) and (n,α)). For this purposes we introduce the coefficient M which multiply EAF data in this region (M = 1 means EAF-2007 library). Examples of such analyses are shown in Figs. 10, 11 for the reactions (n,2n) and (n,α), respectively.

The errors of these data are not shown due to complexity of the pictures. The difference between CS data for M=1 and CS data for other values M are within errors or close to the value.

6.2 The effect of correlation coefficients

The set of equations presented in section 3 is written as the matrix $RR = A^{*}CS$. Solving this equation we introduce correlations between CS. Let we introduce weight matrix W, where only diagonal elements are non zero and equals reciprocal squares of errors of RR. Then error matrix of CS is $(A'WA)^{-1}$.

Analysing the obtained data we come to the conclusion that the effect of correlations is rather small in our case.

7 Conclusions

Quasi-monoenergetic neutron production based on p-^{7}Li source is used to study high energy neutron reactions on ^{93}Nb target. New cross section data for energy of neutrons higher than 23 MeV on niobium for the reactions (n,2n), (n,3n), (n,4n), (n,3He), (n,α) and (n,α 2n) are presented. These data are needed for technological applications like IFMIF and serve as the test of neutron databases and nuclear models as well. Experimental cross sections are obtained for the distances 48 and 88 mm of irradiated foils from Li foil for both neutron spectra: measured TOF and simulated MCNPX.

Taking into account the fact that MCNPX simulation describes properly the cross section behaviour in (n,2n) reactions we may suppose that EAF-2007 database (including possible reaction channels) does not correctly describe experimental data in (n,α+) reaction.

EAF-2007 data overestimate evidently the experimental ones in reactions (n,3n), (n,4n) and (n,3He). The data of (n,α 2n) reaction are described properly.

The gamma spectroscopy errors only are shown in our work. Systematical lowering of about 10–20% of CS data at 48 mm comparing to CS data a 88 mm geometry have to be studied in future. We came to the conclusion that the energy intervals in VITAMIN J+ structure for higher energy regions are too large for both the cross section presentation and MCNPX simulations.

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