Angular distribution in fast neutrons induced reactions on ^{64}Zn isotope

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Abstract. Cross sections, angular distributions, forward-backward asymmetry effect and alpha spectra in fast neutrons induced processes on 64Zn nucleus were investigated. Theoretical evaluations were realized using own authors codes and dedicated software for the investigation of the structure of atomic nuclei and nuclear reactions mechanisms. Contributions to the cross sections, angular correlations and alpha spectra of nuclear reactions mechanisms (direct, compound and pre-equilibrium ones) were obtained. Cross sections and angular distributions theoretical evaluations are in good agreement with existing experimental data from literature and those obtained in FLNP. Further, from the comparison of theoretical and experimental data, parameters of Wood-Saxon potential (volume, surface and spin-orbit each with real and imaginary part) were extracted.

For neutrons energy of few MeV's, experimental forward-backward effect was observed. For this incident energy of neutrons only compound mechanism is acting and therefore the measured asymmetry cannot be explained by the presence of direct processes. The possible explanations of the existence of measured forward-backward effect are also analyzed.

OUTLINE OF THE PRESENTATION

1. INTRODUCTION

Fast neutron reactions - investigated for a long time at LNF facilities

Fundamental research – new data on nuclear reaction mechanisms and structure of nuclei

Applicative researches – precise nuclear data for nuclear fission and fusion reactors; reprocessing of *U* and *Th* for transmutation and energy projects and ADS; Fast Neutron Activation Analysis

Neodymium Nucleus – Zn has five natural isotopes ^{64}Zn, ^{66}Zn, ^{67}Zn, ^{68}Zn, ^{70}Zn with the following abundances 49.2%, 27.7%, 4%, 18.5% and 0.6% respectively

^{64}Zn reactions with fast neutrons – Different values of experimental measured cross section

Investigated process: ^{64}Zn(n,α)^{61}Ni with fast neutrons 0.5 MeV - 25 MeV

2. ELEMENTS OF THEORY

Cross section for (n,α) reaction (Hauser – Feshbach) (HF)

- without fluctuation correction factor

$$\sigma_{n\alpha} = \pi \lambda_n^2 \frac{T_n T_\alpha}{\sum_c T_c}$$

- with fluctuation correction factor

$$\sigma_{n\alpha} = \pi \lambda_n^2 \frac{T_n T_\alpha}{\sum_c T_c} W_{n\alpha}$$

$T =$ **transmission coefficient**

$W_{n\alpha} =$ **width fluctuation correction factor**

Differential cross section

$$\frac{d\sigma}{d\Omega} = \pi \lambda^2 (2l+1) T_l \sum_J \frac{A_J\left(l, j \mid l', j' \mid \theta\right)}{1 + \sum_{p,q} \frac{T_p\left(E_q'\right)}{T_{l'}\left(E'\right)}}$$

$$A_J\left(l, j \mid l', j' \mid \theta\right) = \sum_{m,m'} \left|\left(l, j; 0m \mid l, j; Jm\right)\right|^2 \left|\left(l', j'; m' m - m' \mid l', j'; Jm\right)\right|^2 \left|Y_{l'm'}(\theta, \varphi)\right|^2$$

A contains the dependence on

- quantum numbers in incident and emergent channels (l, j, l’, j’, J, m)
- solid angle (Ω (θ,ϕ))

2. ELEMENTS OF THEORY

Quantum mechanical approach used

$$T(l,E) = 1 - \left|U_l(E)\right|^2$$

$W_l^+(r) =$ **Ingoing wave function**

$W_l^-(r) =$ **Outgoing wave function**

Reflection factor

$$U_l = \left\{ \frac{D_l - R\left[\frac{1}{W_l^-}\frac{dW_l^-}{dr}\right]}{D_l - R\left[\frac{1}{W_l^+}\frac{dW_l^+}{dr}\right]} \frac{W_l^-}{W_l^+} \right\}_{r=R}$$

Solution of Radial Schrodinger Equation

$$W_l(r) \sim W_l^-(r) - U_l W_l^+(r)$$

Logarithmic derivative $D_l = R\left[\frac{1}{W_l}\frac{dW_l}{dr}\right]_{r=R}$

Radial Schrodinger Equation

$$\frac{d^2 W_l(r)}{dr^2} + \frac{2m}{\hbar^2}\left[E_l - V(r) - \frac{\hbar^2}{2m}\frac{l(l+1)}{r^2}\right] W_l(r) = 0$$

Antonio Foderaro, The Neutron Interaction Theory, The MIT Press, Cambridge, Massachusetts and London, England, 1971

2. ELEMENTS OF THEORY

Quantum mechanical approach used

For neutrons: combination of Neumann (*n*) and Bessel (*j*) functions

$$W_l^+(r) = kr\left[n_l(kr) + ij_l(kr)\right] \qquad W_l^-(r) = kr\left[n_l(kr) - ij_l(kr)\right]$$

For charged particles: combination of Regular (*F*) and Irregular (*G*) Coulomb functions

$$W_l^+(r) = kr\left[F_l(kr) + iG_l(kr)\right] \qquad W_l^-(r) = kr\left[F_l(kr) - iG_l(kr)\right]$$

Widths Fluctuation Correction Factor (WFC)

- Represents a correlation between incident and emergent channels
- At low energies WFC = 1
- Then slowly decreasing with energy
- Mainly three ways of evaluation
- Moldauer expression chosen

$$W_{ab} = \left(1 + \frac{2\delta_{ab}}{\nu_a}\right)\int_0^\infty \prod_c \left(1 + \frac{2T_c x}{\nu_c \sum_i T_i}\right)^{-\left(\delta_{ac} + \delta_{bc} + \frac{\nu_c}{2}\right)} dx$$

$$\nu_a = 1.78 + \left(T_a^{1.212} - 0.78\right) \cdot e^{-0.228\sum_c T_c}$$

P. A. Moldauer, Rev. Mod. Phys., v. 36, p. 1079, 1964

2. Computer codes and calculations

Own computer code

We implemented Hauser – Feshbach (HB) approach

We realized a software in Mathematica able to compute:

- The regular and irregular Coulomb functions for neutral and charged particles and their derivatives

- For Coulomb functions no approximations were used

- The transmission coefficients for neutral and charged particles

- Implementation of the quantum mechanical approach

- The cross section is obtained by taking into account the fluctuation factor and other open channels (n, n', p, γ)

- This software was used for the evaluation of the $^{147}Sm(n,\alpha)^{144}Nd$ cross section and alpha strength function

C. Oprea, A, Mihul, A.I. Oprea, (CERN-Proceedings-2019-001):126-130 / A.I. Oprea, C. Oprea, C. Pirvutoiu, D. Vladoiu, Rom Rep in Phys 63(1):107-114, 2011

2. Computer codes and calculations

TALYS software

- free software working under Linux operating system in continue development

- friendly interface

- a large number of models for nuclear structure and nuclear reactions (direct, compound, pre - equilibrium) implemented

- database on nuclear structure for a large number of nuclei

- allows to evaluate: nuclear structure data, inclusive and exclusive cross sections (XS)

- **Inclusive XS –** in a binary reaction A(a,b), b will be considered emergent particles from other possible open channels

- **Exclusive XS** – in a binary reaction b will be considered emergent particles from a well defined “b+B” exit channel

- **Talys** will be used in the XS calculations of fast neutron induced reactions with emission of alpha particles

The results were also compared between the two softwares for HB approach.

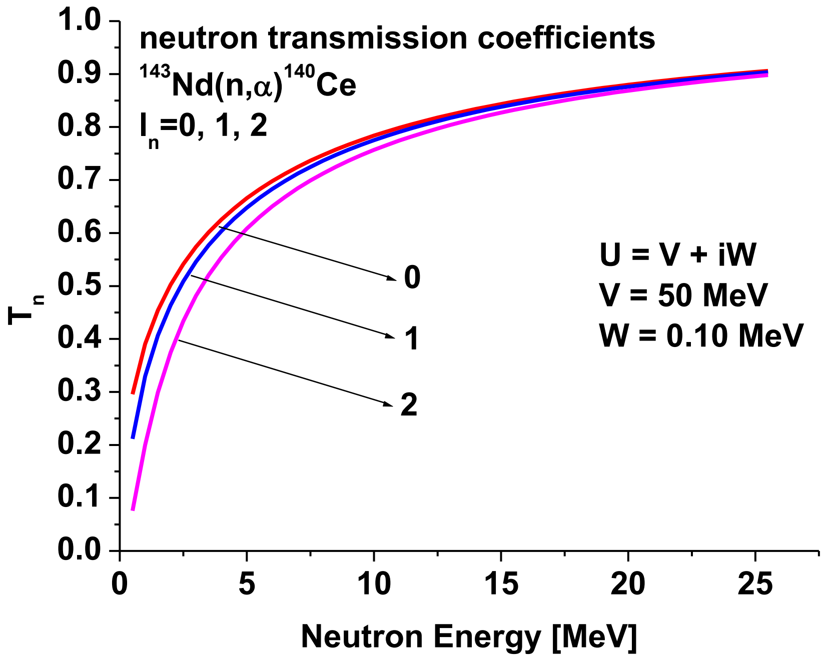
A.J. Koning, S. Hilaire and M.C. Duijvestijn, .TALYS-1.0., Proceedings of the International Conference on Nuclear Data for Science and Technology, April 22-27, 2007, Nice, France, editors O.Bersillon, F.Gunsing, E.Bauge, R.Jacqmin, S.Leray, EDP Sciences, p. 211, 2008

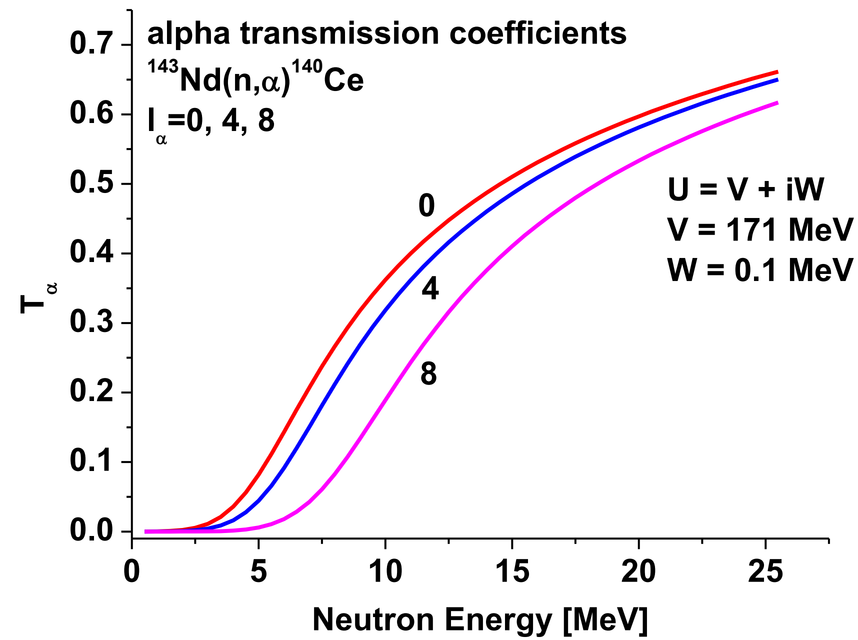
3. Results and discussion. Transmission coefficients

^{143}Nd(n,α)^{140}Ce ($Q_{n\alpha}$ = 9.72 MeV) neutrons 0.5 to 25 MeV - orbital momentum l_n = 0,1

- Spin and parity of ^{143}Nd and ^{140}Ce nuclei, $J^{\Pi} = (7/2)^-$ and 0^+ respectively
- considered γ, p, n, n', α channels;

Neutron energy dependence of neutron and alpha transmission coefficients

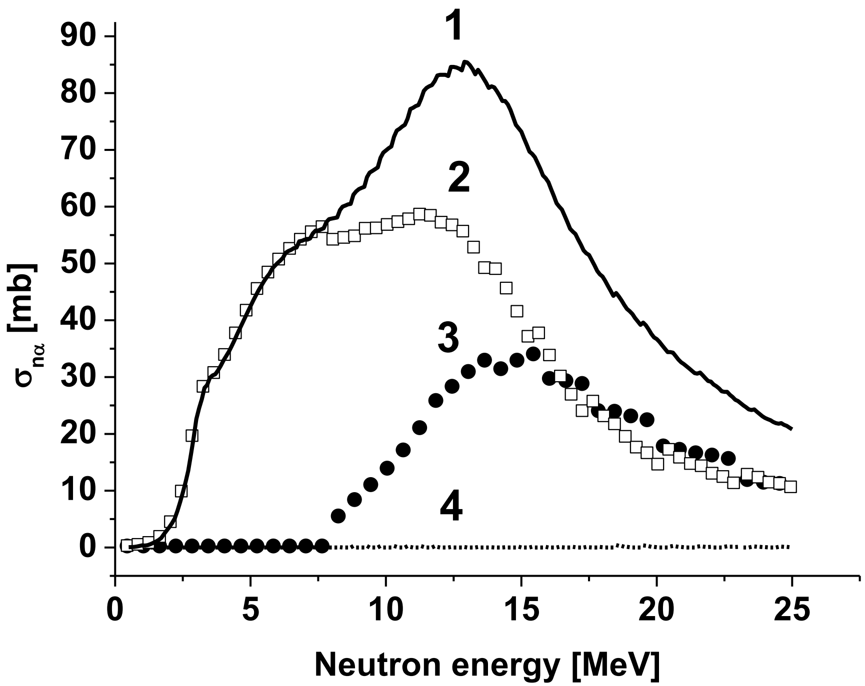




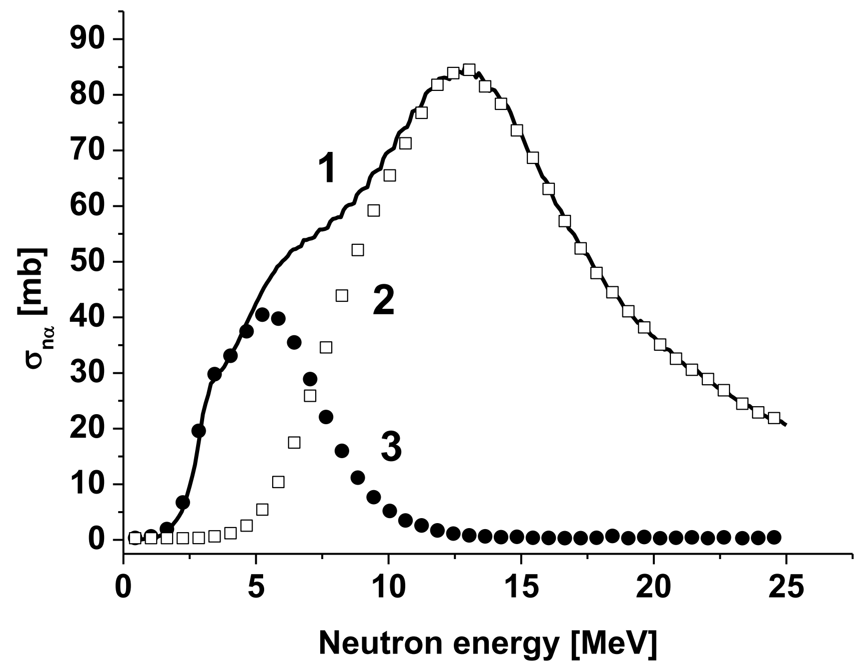
Orbital momentum: neutrons – l_n = 0,1,2; alphas – l_α = 0,4,8

Calculated with our soft based quantum mechanical approach

3. RESULTS AND DISCUSSIONS

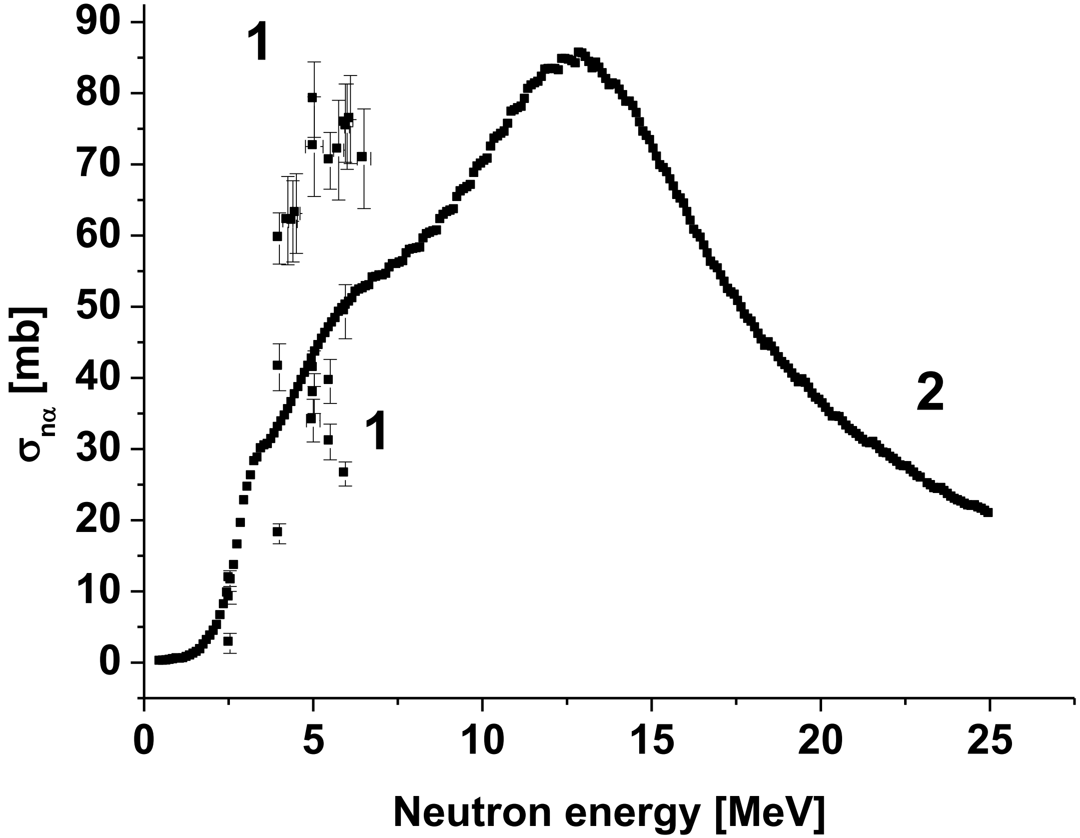


Cross section of $^{64}Zn(n,\alpha)^{61}Ni$ reaction. Contribution of Nuclear reaction mechanisms; 1) Total (1 -> 2 + 3 + 4) 2) Compound 3) Pre-equilibrium 4) Direct.



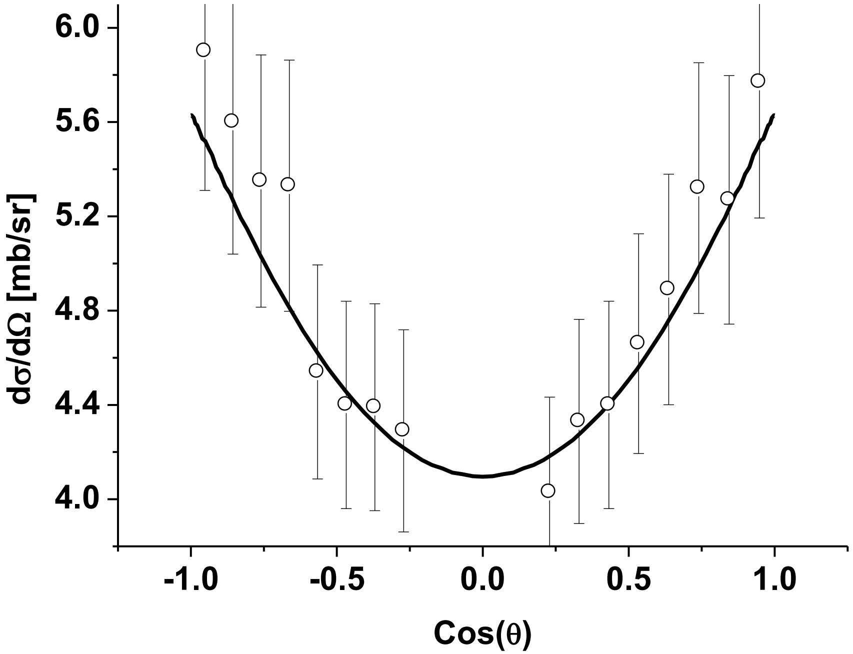
Cross section of $^{64}Zn(n,\alpha)^{61}Ni$ reaction. Contribution of discrete and continuum states of residual nuclei; 1) Total (1 -> 2 + 3) 2) Continuum 3) Discrete

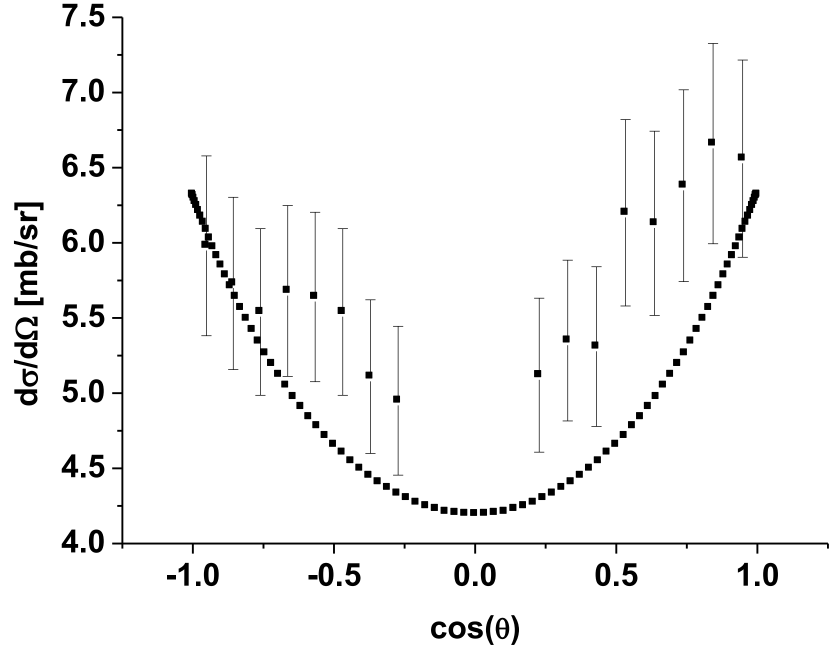
3. RESULTS AND DISCUSSIONS



Comparison between experimental and theoretical data. Points – experiment. Line – Talys evaluation

3. RESULTS AND DISCUSSIONS





Differential cross-section was evaluated for a large incident neutrons energy range. In Fig - Talys calculations and experimental data of $^{64}Zn(n,\alpha)^{61}Ni$ differential cross section for E_n = 4 and 5.5 MeV respectively.

Cross section computed with Talys. In Fig., experimental cross section for the same energies are $\sigma_{na}(E_n$ = 4 MeV) = (59.6⊕3.3) mb and $\sigma_{n\alpha}(E_n$ = 5.5 MeV) = (70.5⊕4.0) mb respectively, therefore it was necessary to find a new set of new of Wood-Saxon potential parameters in order to have the same cross section value in theory and experiment. If this assumption is fulfilled than measured differential cross section is described very well by theoretical evaluation for neutrons energy E_n = 4 MeV and satisfactorily for E_n = 5.5 MeV. For both neutrons energy, 4 and 5.5 MeV, Talys evaluation shown the presence of only compound mechanism and no direct process.

3. Results and discussion. A_{FB} Forward – Backward Ratio

Punctual target A_{FB} ratio

Direct Method

$$A_{FB} = \frac{A_{FW}}{A_{BW}} = \frac{\int_0^{\pi/2} W(\theta)\sin(\theta)d\theta}{\int_{\pi/2}^{\pi} W(\theta)\sin(\theta)d\theta}$$

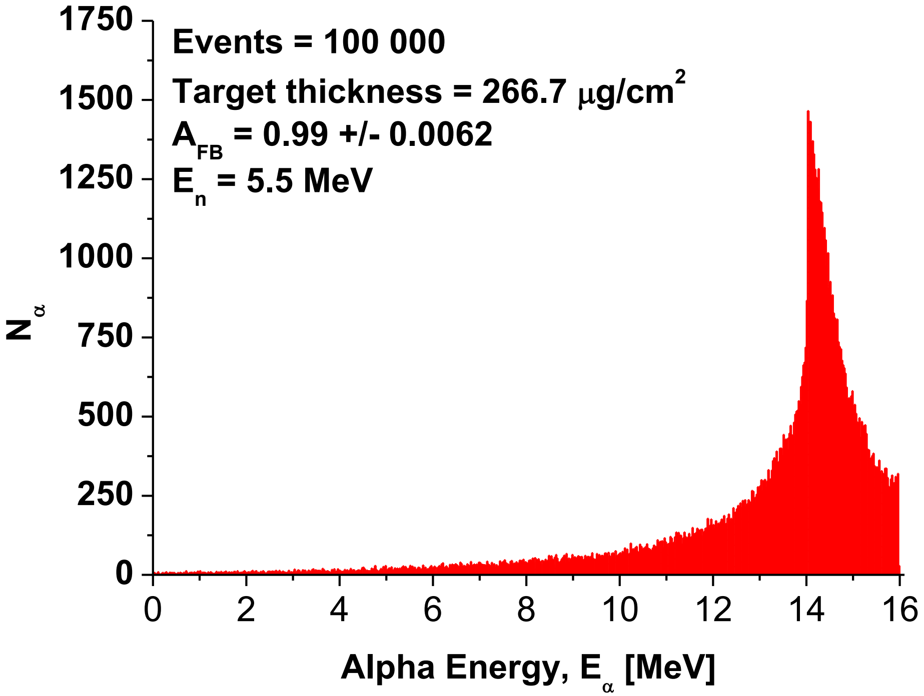
Finite target with thickness g -> A_{FB} – evaluated by MC simulation

$$\frac{2\pi}{\sigma_{n\alpha}} \int_0^{\theta_c} W(\theta)\sin(\theta)d\theta = r \Rightarrow \theta_c, r \in [0,1), \theta \in [0,\pi)$$

Simple MC modeling of alpha particles going out from a finite ^{64}Zn target with radius 10 cm:

- by direct method angular correlation is obtained -> W(θ)
- using alpha particle energy loss in ^{64}Zn from tables is determined if particle is escaping from the target
- energy and number of alphas going out from the target are determined
- different thicknesses g[μg/cm^2] are tested (g = 266.3 μg/cm^2)
- for A_{FB} measurements it is necessary that g[m]<p_{max}[m] (alpha particles maximum path s)
- direct component cannot give such a high forward asymmetry -> possible interference with elastic, inelastic and proton channels where direct process is important.

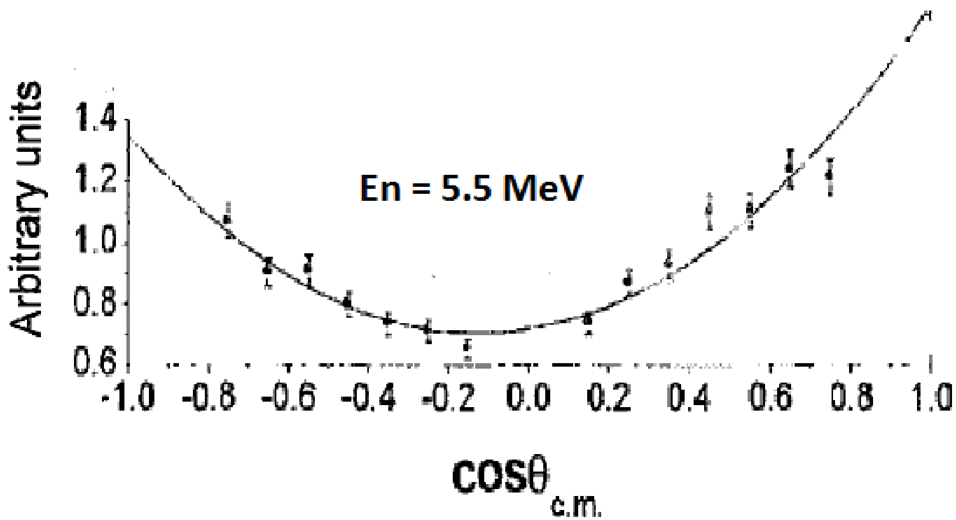
3. RESULTS AND DISCUSSIONS



Target with finite thickness
- Energy loss evaluated with SRIM
- Practically no asymmetry has been obtained by simulations for any energy

From Figure – Experimental A_{FB}

A_{FB} =1.016 ⌖ 0.09 – high error due to small number of experimental data



Data measured at FLNP JINR Dubna
Using a Grid-Ionization Chamber

3. RESULTS AND DISCUSSIONS

Parameters of Wood-Saxon Potential in incident and emergent channels

Ch	Volume WS- Real		
	V [MeV]	r_V [fm]	a_V [fm^{-1}]
n	52.69	1.203	0.668
α	169.37	1.184	0.676
	Spin – orbit – Real		
	V_{SO} [MeV]	r_{VSO} [fm]	a_{VSO} [fm^{-1}]
n	5.08	1.024	0.590
α	0	0	0

Ch	Volume WS - Imaginary		
	W [MeV]	r_W [fm]	a_W [fm^{-1}]
n	0.19	1.279	0.668
α	25.70	1.340	0.500
	Spin – orbit - Imaginary		
	W_{SO} [MeV]	r_{WSO} [fm]	a_{WSO} [fm^{-1}]
n	0.01	1.024	0.590
α	0	0	0

Components of WS Potential with Real and Imaginary Part
A) Volume B) Surface C) Spin-orbit

4. Conclusions

Cross sections

Good description of fast neutrons (0.5 – 25 MeV) CS experimental data using own codes and Talys

Differential cross sections were evaluated

Concurrence of different nuclear reaction mechanism were evidenced

Asymmetry effects

Analyzed A_{FB} ratio. High difference between theory and experiment. Evaluation of direct component, for different configurations and energy cannot give such a high forward asymmetry -> It can be explained by the presence of channel with an important direct component

Future tasks

- New theoretical evaluations based on the new XS and diff. XS measurements in wide neutron energy interval

- To determine for each energy the contribution of nuclear reaction mechanisms based on future experimental data

- Improvements of Monte Carlo simulation

- Theoretical follow up of new nuclear experimental data on strength functions

Present work - proposal for new experiments at FLNP JINR Dubna Facilities