Attempts to infer the neutron inelastic cross sections using charged particle induced reactions

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Abstract
Two experiments were performed at the Tandem accelerator of the Horia Hulubei National Institute for Physics and Nuclear Engineering, IFIN-HH with the purpose to investigate the possibility to use alpha-induced reactions for the calculation of neutron inelastic cross sections based on the Bohr hypothesis of the compound nucleus. A first experiment compared the gamma production cross sections excited in the ^{25}Mg(α, $n\gamma$)^{28}Si and the ^{28}Si(n, $n'\gamma$)^{28}Si reactions. A second measurement, supported by the ERINDA project, was dedicated to the measurement of ^{70}Zn(α, $n\gamma$)^{73}Ge cross sections with the purpose of inferring the neutron inelastic cross sections on ^{73}Ge.

1 Introduction

The future nuclear facilities are expected to have a crucial impact on the economical development of the human civilization. In this context, the current request for precise measurements of neutron-induced reaction data on specific materials is increasingly significant.

A particular emphasis is made on the specific cases where the direct measurement of cross sections is difficult or impossible, like in the case of radioactive targets. During the past decade numerous attempts were made to use the so-called *surrogate method* which relies on the use of charged-particle beams to mimic the neutron-induced reactions. In particular the *surrogate ratio method* proved rather successful in several studies being applied to neutron induced capture and fission reactions [1–6].

We intend therefore to investigate the possibility of inferring neutron inelastic cross sections from charged particle induced reactions based on the well-known Bohr hypothesis [7]. Two such attempts were performed using the experimental setups presented in the second section of this paper. The first attempt, dedicated to the comparison of the ^{25}Mg(α, $n\gamma$)^{28}Si and the ^{28}Si(n, $n'\gamma$)^{28}Si reactions is described in Ref. [12]. We will give here an overview of this work in the third section. A second experiment, supported by the ERINDA project, consisted in the measurement of the gamma production cross sections in the ^{70}Zn(α, $n\gamma$)^{73}Ge reaction. These data are currently under analysis and preliminary results will be shown in the fourth section.

2 Experimental details

Two experimental facilities were used in the present work. The neutron inelastic cross sections on ^{28}Si were measured using the spectrometer GAINS (Gamma Array for Inelastic Neutron Scattering) at GELINA (Geel Linear Accelerator), the neutron source of EC-JRC-IRMM, Belgium. The ^{25}Mg(α, $n\gamma$)^{28}Si and the ^{70}Zn(α, $n\gamma$)^{73}Ge reactions were investigated at the Tandem accelerator of IFIN-HH, Romania. In both cases we used HPGe detectors to determine the gamma production cross section for the strongest transitions of in the final nucleus.

Fig. 1: The GAINS array used at EC-JRC-IRMM to determine the neutron inelastic cross sections on ^{28}Si.

2.1 The GAINS setup at the GELINA neutron source of IRMM

The GELINA neutron source operated by EC-JRC-IRMM produces a white neutron flux with energies ranging from $\approx$70 keV to $\approx$18 MeV at a repetition rate of 800 Hz. Neutron pulses are produced within 1 ns following an intense gamma flash. Multiple flight paths are available. The energy of the neutrons is determined using the time-of-flight technique [8].

The GAINS array (Fig. 1) used to detect the gamma rays emitted during the inelastic scattering of neutrons on ^{28}Si is located in a cabin 200 m away from the neutron source [9, 10]. It consists of eight HPGe detectors placed at 110° and 150° with respect to the beam (the neutron flux is collimated so that in the 200 m cabin it constitutes a beam with a diameter of 61 mm). The special choice of the detection angles allows a precise integration of the angular distribution of the gamma rays emitted in the reaction. The beam was monitored with a ^{235}U fission chamber [11].

The ^{nat}Si sample of 1.326(1) g/cm^2 was irradiated for about 1000 h.

2.2 The gamma array at the Tandem accelerator of IFIN-HH

We used the Tandem facility operated by IFIN-HH to accelerate alpha particles to energies ranging between 5 MeV and 23 MeV.

During the ^{25}Mg(α, $n\gamma$)^{28}Si experiment a simple setup was used (Fig. 2-(b)) consisting of two HPGe detectors placed at 30° and 70° respectively with respect to the beam axis. The beam was integrated using a Faraday cup placed after the target. The self-supported ^{25}Mg sample had an areal density of 0.63(2) mg/cm^2. We used an irradiation time of 3-4 h for each alpha energy.

The ^{70}Zn(α, $n\gamma$)^{73}Ge reaction was investigated using the same accelerator but an upgraded detection setup. This was RoSphere, an array able to hold up to 25 HPGe detectors or a combination of HPGe and $LaBr_3$ detectors (Fig.2-(a)). We used 11 detectors placed at 37°, 70°, and 90°. The ^{70}Zn enriched sample of 2 mg/cm^2 was placed inside a Faraday cup serving as beam integrator.

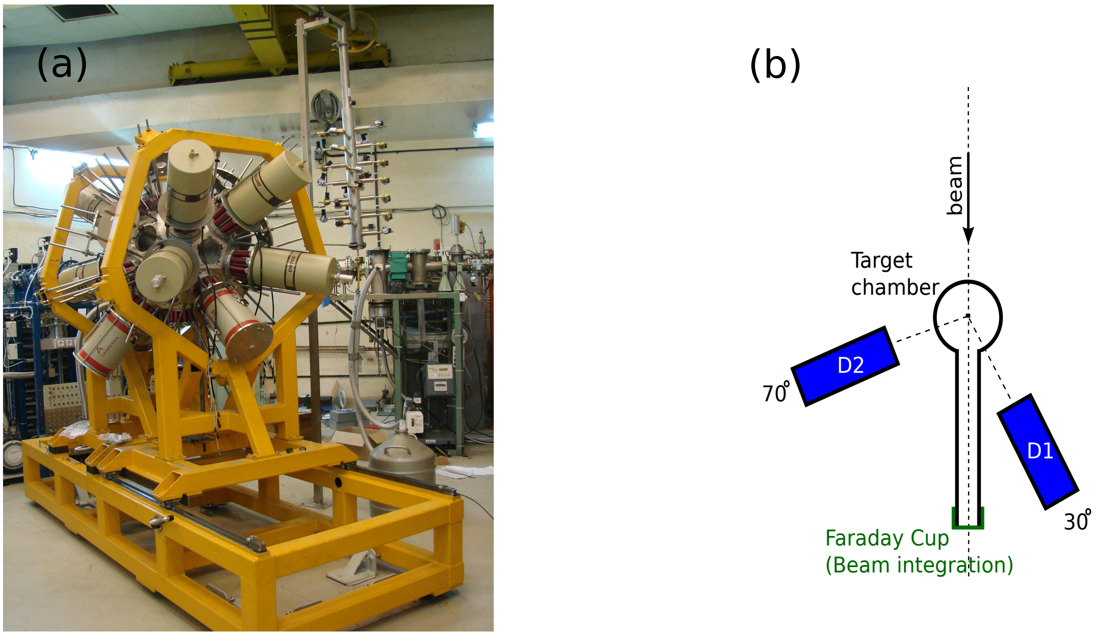

Fig. 2: (a) RoSphere, the gamma array used for the investigation of the ^{70}Zn(α, $n\gamma$)^{73}Ge reaction. (b) Scheme of the detection setup used for the determination of gamma production cross sections excited in the ^{25}Mg(α, $n\gamma$)^{28}Si reaction at the Tandem accelerator of IFIN-HH

3 Comparison of the gamma production cross sections in ^{28}Si excited through the (α, n) and the (n, n') reactions

The basic idea of the comparison presented in Fig. 3 relies on the hypothesis formulated by N. Bohr in Ref. [7]: due to the fact that the projectile/ejectile needs a short time to cross the target/recoil nucleus compared to lifetime of the compound nucleus, the final channel should not depend - in a first approximation - on the input channel. We compare indeed two cases where the compound nucleus is the same (^{29}Si) and the final channel coincides as well.

However, as discussed in Ref. [12], several aspects should be addressed while doing such a comparison:

– The Q-value is different in the two cases. Therefore in order to perform a meaningful comparison the gamma production cross sections from Fig. 3 are displayed as a function of the total excitation energy in the compound nucleus ^{29}Si.
– The Coulomb barrier in case of the alpha-induced reaction limits the energy range where the cross sections can be compared to values larger than E*(^{29}Si)≈17 MeV.
– The total angular momentum available in the compound nucleus is also different in the two cases because the initial participants to the reaction have different spins: the ground state of ^{28}Si has J^{π}=0^{+} while the ground state of ^{25}Mg has J^{π}=5/2^{+}.
– As a consequence of the previous argument, the interplay of various reaction mechanisms - direct, preequilibrium and compound nucleus - may be different in the two reactions.

Fig. 3 shows that the gamma production cross sections excited in the two reactions have the same order of magnitude but may differ by about 50%. The TALYS calculations reproduce acceptably well the (n, $n'\gamma$) data but the first two transitions excited through the (α, $n\gamma$) reaction are poorly described.

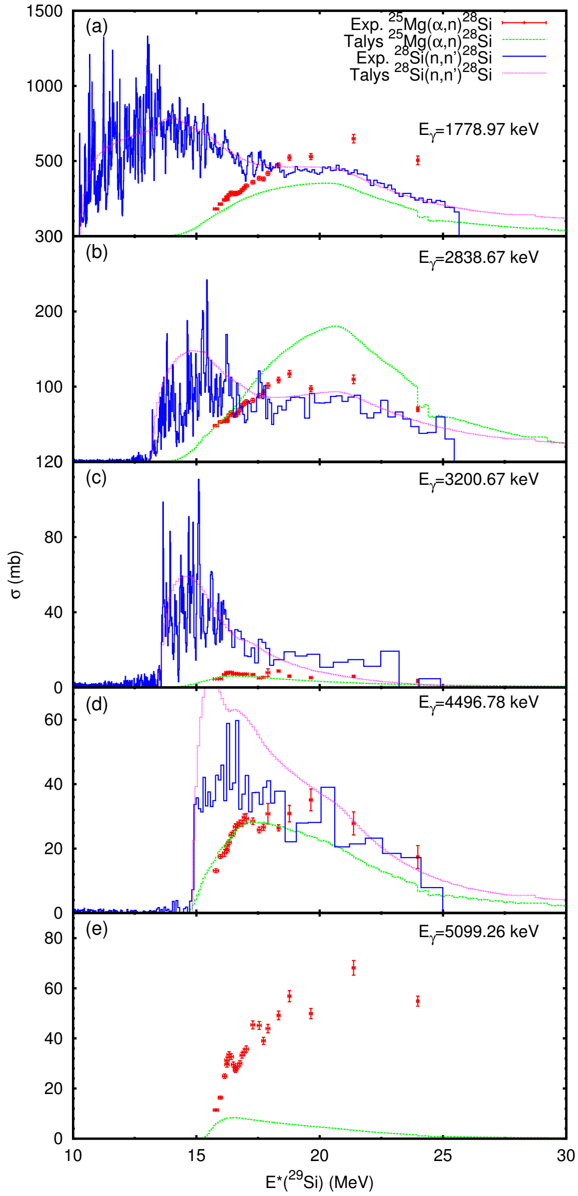

Fig. 3: Comparison of the gamma production cross sections in ^{28}Si excited through the ^{28}Si$(n, n'\gamma)^{28}$Si and the ^{25}Mg$(\alpha, n\gamma)^{28}$Si reactions [12].

4 Preliminary results of the ^{70}Zn$(\alpha, n\gamma)^{73}$Ge experiment

As already mentioned, the ^{70}Zn$(\alpha, n\gamma)^{73}$Ge data are currently under analysis. The reaction was not previously investigated with the purpose to determine cross sections. An experiment was performed with Ge(Li) detectors in the seventies at E_α=14.2 MeV aiming at the investigation of the structure of ^{73}Ge [13]. The improved resolution of our HPGe detectors allows the identification of an increased number of transitions.

Unfortunately, the first gamma transitions in ^{73}Ge (E_γ=13.3 keV, 53.4 keV, 68.7 keV) could not be detected with our system. However we identified using the evaluated level scheme from Ref. [14] a large number of transitions in the energy range 200-1000 keV coming from ^{73}Ge, although the coincidence matrices were not yet investigated.

Fig. 4 displays the production cross sections of the gamma rays of 284.9, 297.3, 325.7 and

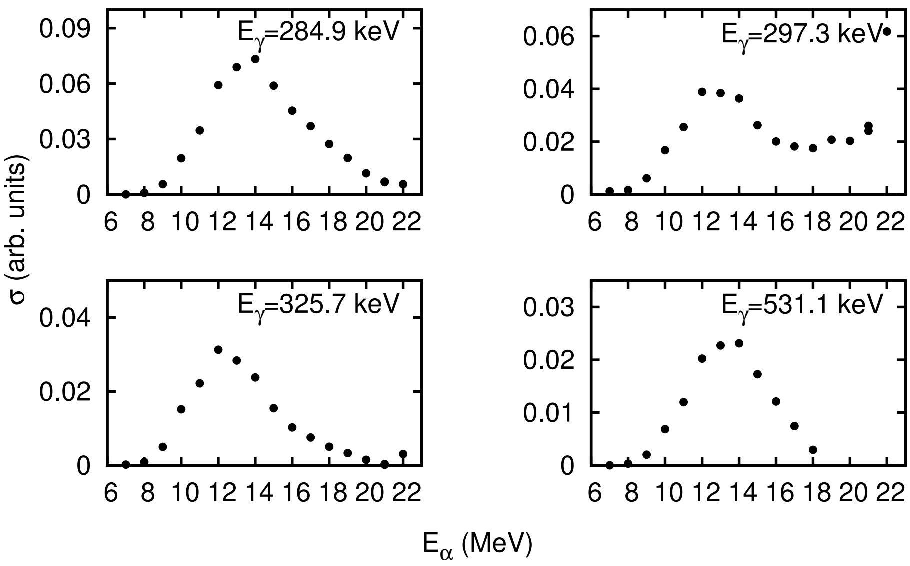

Fig. 4: Production cross sections for gammas excited through the ^{70}Zn(α, $n\gamma$)^{73}Ge. Preliminary results. On the x-axis the energy of the incoming alphas is plotted, not corrected for the energy lost in the target.

531.1 keV decaying from the 4th, 5th, 6th and 11th excited level in ^{73}Ge. However the absolute values of the cross sections were not yet determined and these data should be considered as preliminary, unchecked results. Moreover the alpha energies were not corrected for the energy lost in the target.

5 Conclusions

An experimental effort is ongoing with the purpose of investigating to which extent the Bohr hypothesis could be employed to infer neutron inelastic cross sections from charged particle induced reactions. The first comparison was performed for the case of the ^{28}Si nucleus excited through the $(n, n'\gamma)$ and $(\alpha, n\gamma)$ reactions. The analysis for an experiment investigating the ^{70}Zn(α, $n\gamma$)^{73}Ge reaction is ongoing.

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