

Neutron-induced Cross Sections of Actinides via the Surrogate-reaction Method

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The surrogate-reaction method is an indirect way to determine cross sections for reactions that proceed through a compound nucleus. This technique may enable neutron-induced cross sections to be extracted for short-lived nuclei that otherwise cannot be measured. However, the validity of the surrogate method has to be investigated. In particular, the direct component of the surrogate reaction and the J^π dependence of the decay probabilities may question the method. In this work we study the reactions $^{238}\text{U}(\text{d},\text{p})^{239}\text{U}$, $^{238}\text{U}({}^3\text{He},\text{t})^{238}\text{Np}$, $^{238}\text{U}({}^3\text{He},{}^4\text{He})^{237}\text{U}$ as surrogates for neutron-induced reactions on ^{238}U , ^{237}Np and ^{236}U , respectively, for which good quality data exist. The experimental set-up enabled the measurement of fission and gamma-decay probabilities. The first results are hereby presented.

I. INTRODUCTION

Neutron-induced cross sections of short-lived nuclei are crucial for fundamental nuclear physics, astrophysics and also for applications such as reactor physics. In particular, (n,γ) cross sections on minor actinides are one of the largest sources of uncertainty in modelling new reactors for nuclear waste transmutation using fast neutrons. However, very often the high radioactivity of the actinide samples makes the direct measurement of these cross sections extremely difficult. The surrogate-reaction method is an indirect way to determine cross sections for compound-nuclear reactions. This method was first proposed by J. D. Cramer and H. C. Britt [1] in the seventies. It consists of using a transfer reaction to produce the same decaying nucleus as the one formed in the desired neutron-induced reaction. The transfer reaction leads to the heavy recoil nucleus of interest and to an ejectile. The identification of the ejectile permits to determine the mass A and charge Z of the decaying nucleus. In addition, one can deduce the excitation energy E^* of the heavy nucleus by measuring the kinetic energy and the emission angle of the ejectile. The measurement of the

number of coincidences between the ejectiles and the decay products normalized to the total number of detected ejectiles allows to extract the decay probability for the corresponding decay channel $P_{\text{decay}}^{A,\text{exp}}(E^*)$. According to the surrogate-reaction method, the neutron-induced cross section for the nucleus $A - 1$ is then given by

$$\sigma_{\text{decay}}^{A-1}(E_n) \cong \sigma_{\text{CN}}^A(E_n) \cdot P_{\text{decay}}^{A,\text{exp}}(E^*), \quad (1)$$

where $\sigma_{\text{CN}}^A(E_n)$ is the calculated cross section for the formation of the compound nucleus A after absorption of a neutron with energy E_n , it is usually obtained using optical model. In our case, we use the phenomenological optical model from TALYS [10]. The incident neutron energy E_n and the excitation energy E^* of the compound nucleus A are related by the expression $E^* = Sn + E_n(A - 1)/A$, where Sn is the one-neutron separation energy in the nucleus A . The benefit of the surrogate method is that in some cases the target needed is stable or less radioactive than the target of the corresponding neutron-induced reaction. For the surrogate method to work, the decaying nucleus has to be a compound nucleus. In addition, one has to consider the spin-parity differences between the neutron-induced and the surrogate reactions.

Indeed, at low excitation energies the decay probability strongly depends on J^π . Therefore, important deviations between the neutron-induced results and the ones

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obtained with the surrogate method may exist if the populated spin distribution in the neutron-induced and surrogate experiments are different. While it is rather well established that the surrogate method works well for fission at sufficiently high E^* (see e.g. [2]), several recent experiments have shown that gamma decay is very sensitive to the differences in the populated J^π distributions [3–5], which leads to important discrepancies between the surrogate results and the neutron-induced data at low excitation energies. This is probably due to the spin-parity selectivity of neutron emission [5]. This selectivity decreases strongly as the level density of the residual nucleus after neutron emission increases. Therefore, the discrepancies between the surrogate results and the neutron-induced data are expected to decrease with increasing mass of the decaying nucleus and with increasing excitation energy. In this work we study the validity of the surrogate method in the actinide region using an improved experimental set-up that enables the measurement of fission and gamma-decay probabilities. Thanks to this we can investigate the two main issues that determine the validity of the surrogate method: the compound character of the decaying nucleus and the J^π dependence of the decay probabilities.

II. EXPERIMENT

The experiment was performed in June 2012 at the Oslo cyclotron. We used a $260 \mu\text{g}/\text{cm}^2$ ^{238}U target with 99.7% isotopic purity produced at GSI on a ^{12}C backing with a thickness of about $10 \mu\text{g}/\text{cm}^2$. Two different beams were used, a deuteron beam of 15 MeV and a ^3He beam of 24 MeV. The experimental set-up is represented in Fig. 1. The ejectiles were detected at backward angles with the SiRi multi-strip silicon $\Delta E/E$ detector [6]. SiRi provided the identification of the ejectiles, as well as their kinetic energy and angle. Fission fragments were detected in coincidence with the ejectiles. The fission detectors were located at forward angles and consisted of 4 PPACs covering a solid angle of 41.1% out of 4π . The reaction chamber housing SiRi, the PPACs and the ^{238}U target were surrounded by the CACTUS array comprising 28 high-efficiency NaI detectors. CACTUS was used to detect gamma rays with energies ranging from a few keV to about 10 MeV in coincidence with the ejectiles. The aim of the experiment was to study the transfer reactions $^{238}\text{U}(\text{d},\text{p})$, $^{238}\text{U}(\text{d},\text{t})$ and $^{238}\text{U}(\text{d},\text{He})$ serving as surrogates for the neutron-induced reactions $^{238}\text{U}+\text{n}$, $^{237}\text{Np}+\text{n}$ and $^{236}\text{U}+\text{n}$, respectively.

Fission or gamma-decay probabilities are obtained following the expression

$$P_{\text{decay}}^{A,\text{exp}}(E^*) = \frac{N_{\text{coinc}}(E^*)}{N_{\text{singles}}(E^*) \cdot \epsilon_{\text{decay}}(E^*)}, \quad (2)$$

where N_{coinc} is the number of coincidences between the ejectiles and the fission or the γ -ray detector, N_{singles} is the total number of ejectiles and ϵ_{decay} is the efficiency of

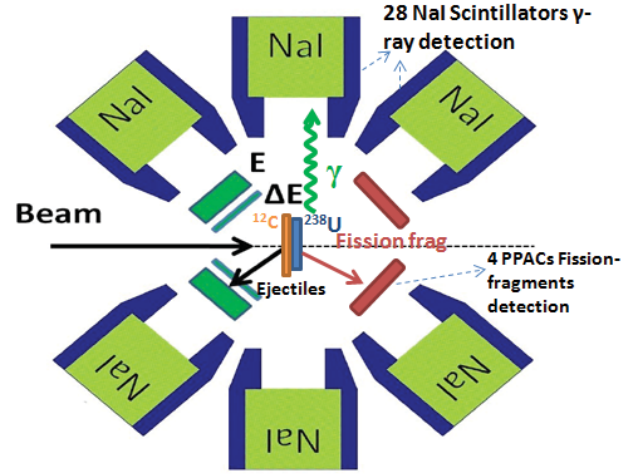


FIG. 1. Schematic view of the set-up for decay-probability measurements with the SiRi telescope and the fission detector inside the CACTUS NaI array.

the fission or the γ -ray detector. The identification of the ejectiles and the determination of their energy and scattering angle are achieved using the Si telescopes. With this information and the associated Q-values, the excitation energy E^* of the corresponding decaying nucleus is obtained. Fig. 2 illustrates the identification achieved in one of the telescopes strip through the conventional energy-loss vs. residual-energy plot. The $N_{\text{singles}}(E^*)$ quantity is obtained by selecting one type of light particles whereas the number associated of compound nuclei $N_{\text{coinc}}(E^*)$ that undergo gamma emission is obtained by selecting the ejectiles detected in coincidence with a gamma event in one of the NaI detectors.

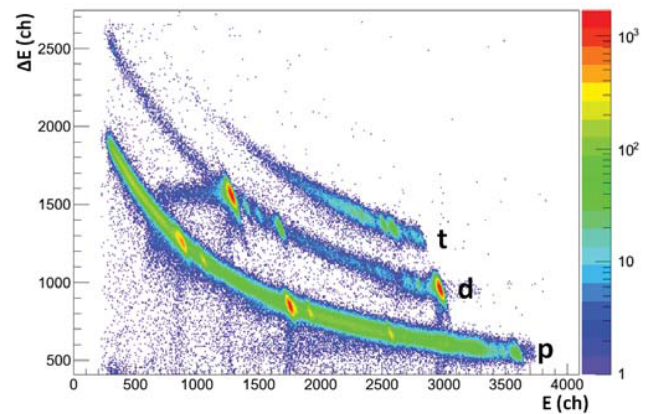


FIG. 2. Energy loss ΔE versus residual energy E in one of the telescopes strip at 140 degrees for the $^{238}\text{U}+\text{d}$ reaction

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