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Measurement of the γ emission probability of ^{173}Yb using surrogate reactions

O. Delaune[1,a], A. Blanc[1], J.T. Burke[2], R. Casperson[2], P. Chau Huu-Tai[1], E. McCleskey[3], M. McCleskey[3], V. Méot[1], O. Roig[1], and A. Saastamoinen[3]

[1] *CEA, DAM, DIF, F-91297 Arpajon, France*
[2] *Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[3] *Cyclotron Institute, Texas A&M University, 3366 TAMU, College Station, USA*

Abstract. We performed the ^{174}Yb(p,d) reaction in order to measure the gamma-emission probability of ^{173}Yb. The identification of the ejectiles — allowing us to tag the production of ^{173}Yb nuclei — was performed using the STARLiTeR detector system. Unusually, the "statistical" γ-rays were used to determined the gamma-emission probability and a spin distribution was extracted from it. A comparison with the spin distribution from the ^{174}Yb(^{3}He,α) reaction shows that the transferred angular momentum is similar in both reactions.

1 The surrogate reaction method

Radiative neutron capture cross section measurements on stable nuclei are performed using a rather well mastered technique. However, it is much less straightforward when these cross section measurements are performed on radioactive nuclei. Such measurements being very challenging and even impossible to do, the surrogate reaction method, initially introduced by Cramer and Britt in 1970 [3], is used to obtain some informations about these unstable nuclei.

The surrogate reaction method is based on the hypothesis that the decay of a compound nucleus is independent from its formation. Thus, the principle is to use a different target (stable or less radioactive) coupled to a suitable beam in order to produce the same compound nucleus whose the decay is then studied as illustrated by the Eq. 1.

$$\begin{aligned} n + X &\rightarrow Z^* \\ a + Y &\rightarrow Z^* + b \end{aligned} \tag{1}$$

In Hauser-Feshbach theory [4], the radiative neutron capture cross section $\sigma^{A-1}_{(n,\gamma)}$ can be related to the compound nucleus formation cross section $\sigma^A(E_n, J, \pi)$ and to the decay branching ratio of the compound nucleus $G^A_\gamma(E^*, J, \pi)$ via the following equation (the width fluctuation correlations between entrance and exit channels are neglected) [5]

$$\sigma^{A-1}_{(n,\gamma)}(E_n) \approx \sum_{J,\pi} \sigma^A(E_n, J, \pi) G^A_\gamma(E^*, J, \pi) \tag{2}$$

where J and π are the spin and the parity respectively. E_n and E^* are the kinetic energy of the incident neutron and the excitation energy of the compound nucleus respectively. Both quantities are linked together through the Eq. 3

$$E^* = E_n \frac{M^{CN} - 1}{M^{CN}} + S^{CN}_n \tag{3}$$

where M^{CN} is the mass of the compound nucleus and S^{CN}_n its neutron separation energy.

The compound nucleus formation cross section is usually determined from optical model calculation whilst the branching ratio G^A_γ is measured. Experimentally, one measures the decay probability P_γ. It is related to the branching ratio via the relation

$$P_\gamma(E^*) = \sum_{J,\pi} F^A(E^*, J, \pi) G^A_\gamma(E^*, J, \pi) \tag{4}$$

where $F^A(E^*, J, \pi)$ represents the probability that the compound nucleus is produced in the state J^π with an excitation energy E^*.

Usually, the surrogate reaction method is used within the Weisskopf-Ewing limit [6] which stipulates that the branching ratio for the decay of the compound nucleus does not rely on the spin and the parity of the compound nucleus but only on its excitation energy. Thus, Eq. 2 becomes

$$\sigma^{A-1}_{(n,\gamma)}(E_n) \approx \sigma^A(E_n) G^A_\gamma(E^*) \tag{5}$$

and $G^A_\gamma(E^*) = P_\gamma(E^*)$.

Applied with some success to study the fission [1, 2], the validity of the surrogate reaction method is undergoing on the nuclei from the rare earth region. Some works have shown that the transferred angular momentum in a (p,d) on rare-earth nuclei is around $5\hbar$ [7]. This value is similar to the one found in (^{3}He,α) reactions implying also rare-earth nuclei [8]. Both values are much higher than the angular momentum transferred in a neutron-induced reaction. The comparison is not direct since the compound nuclei are not the same. Here, we want to perform a direct comparison, i.e. involving the same compound nucleus. Thus, we

[a] e-mail: olivier.delaune@cea.fr

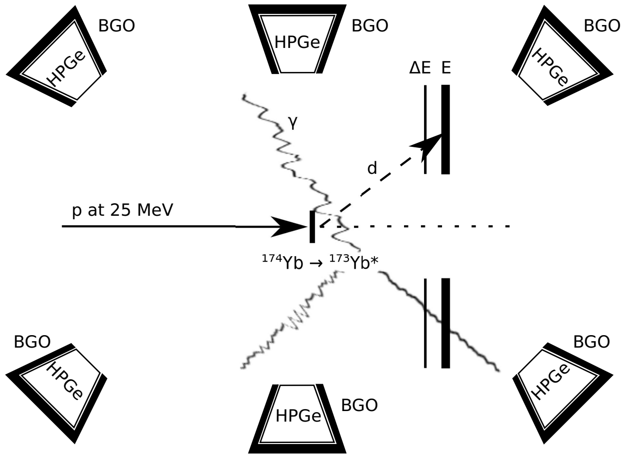

Figure 1. Schematic view of the experimental setup. Proton beam accelerated at 25 MeV impinged on ^{174}Yb target. Deuterons d produced by the reaction are detected by the STARS detectors (ΔE-E telescope). The LIBERACE HPGe detectors collected the γ-rays emitted by ^{173}Yb in coincidence with the deuterons.

performed the ^{174}Yb(p,dγ)^{173}Yb reaction. A previous experiment studying the decay of ^{173}Yb used the surrogate reaction ^{174}Yb(^{3}He,$\alpha\gamma$)^{173}Yb [9]. The radiative capture cross section extracted from this surrogate reaction was about 10 times larger than the cross section measured with a neutron beam [10] due to the higher transferred angular momentum. In both experiments, we used the same experimental technique that uses the "statistical γ-rays" and that will be described in the Sec. 2.2.

2 Experiment

2.1 Experimental setup

A schematic view of the experimental setup is shown in Fig. 1. A proton beam was accelerated at 25 MeV (~ 2-enA) within the K150 superconducting cyclotron in the Cyclotron Institute at Texas A&M University. It impinged on a 600 μg/cm^2 thick self-supporting ^{174}Yb target. The ^{173}Yb nuclei are produced via the reaction ^{174}Yb(p,dγ)^{173}Yb, used as the surrogate reaction for the ^{172}Yb(n,γ) reaction.

The deuterons were collected and identified using the STARS setup (Silicon Telescope Array for Reaction Studies) [11] allowing to determine that ^{173}Yb nuclei were produced. The STARS setup was composed of one ΔE-E telescope located forwards from the target. It was composed of two annular silicon detectors highly segmented allowing to measure both the polar angle θ and the azimuthal angle φ. The telescope covers angles ranging from 40°to 65°.

The ΔE detector was 150 μm thick while the E one is 1007 μm thick. An aluminium foil, 200 μg/cm^2 thick, was placed in front of each telescope in order to remove the δ electrons coming from the target.

To detect γ-rays in coincidence with deuterons, we used the LIBERACE setup (Livermore-Berkeley Array for Collaborative Experiments) [11]. It is composed of 6 clovers of high purity germanium detectors coupled to bismuth germanate oxide (BGO) crystal in order to remove the events coming from Compton diffusion.

A full description of the experimental setup is given in the Ref. [11].

2.2 Gamma emission probability

The gamma emission probability is defined as

$$P_\gamma(E^*) = \frac{N_{\gamma-d}(E^*)}{N_d(E^*)\epsilon(E^*)} \tag{6}$$

where $N_{\gamma-d}$ is the number of coincidences between a γ-ray and a deuteron, N_d is the number of single deuterons and ϵ represents the probability to detect a γ cascade. Experimentally, N_d is determined when a particle passes through the ΔE and the E detectors and is identified as a deuteron, and $N_{\gamma-d}(E^*)$ corresponds to the number of events where a deuteron is detected in coincidence with any γ-ray as proposed by Boutoux *et al.* [12].

3 Analysis

The two silicon detectors (ΔE-E of the telescope) were calibrated using a ^{226}Ra α source. The resolution (FWHM) is typically of 52 keV for the ΔE detector and of 45 keV for the E one at 7690 MeV.

Then, the total kinetic energy of the deuterons, $\mathrm{T_e}$, is obtained using the Eq. 7

$$\mathrm{T_e} = \Delta\mathrm{E} + \mathrm{E} + \delta\mathrm{E}_{\text{non-measured}} \tag{7}$$

where

- ΔE is the energy deposited in the ΔE detector; the energy is collected from the rings because of the better energy resolution compared to the one obtained from the sectors. In the case where two rings are hit, if they are adjacent, both energies are summed;
- E is the energy deposited in the E detector; it is coming from the sectors;
- $\delta\mathrm{E}_{\text{non-measured}}$ corresponds to the non-measured energy losses; they are estimated using the SRIM software.

From the polar angle of the ejectile, θ_e, given by the ring which is hit and the total kinetic energy of the ejectile, T_e, the excitation energy E^* of the recoil nucleus can be determined via the Eq. 8

$$\begin{aligned} E^* &= Q + T_\mathrm{b} - T_\mathrm{e} - \frac{M_\mathrm{b}T_\mathrm{b} + M_\mathrm{e}T_\mathrm{e}}{M_\mathrm{r}} \\ &+ \frac{2\cos(\theta_e)\sqrt{M_\mathrm{b}T_\mathrm{b}M_\mathrm{e}T_\mathrm{e}}}{M_\mathrm{r}} \end{aligned} \tag{8}$$

where Q is the Q-value of the reaction, T is the total kinetic energy and M the mass. The indices b, e and r correspond respectively to the beam, the ejectile and the recoil nucleus. A two-body reaction is assumed to establish this relation as well as the fact that the excitation energy of the system is fully transferred to the recoil nucleus.

4 Results

From the Eq. 6, we determined the γ-emission probability for each excitation energy as shown in the Fig. 3.

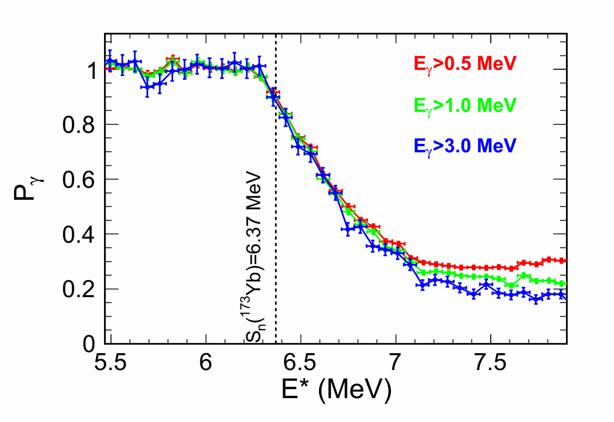

Figure 2. Evolution of the gamma emission probability P_γ as a function of the γ energy cut-off. The red, green and blue P_γ correspond to the P_γ determined considering the γ-rays with an energy greater than 0.5 MeV, 1 MeV and 3 MeV respectively.

Usually, the $N_{\gamma-d}$ value is determined by tagging on a given γ-transition on which the γ-cascade terminates. It works quite well on the even-even nucleus but for other nuclei, the P_γ may be biased if some cascades do not pass through this transition or if the level scheme is not known precisely.

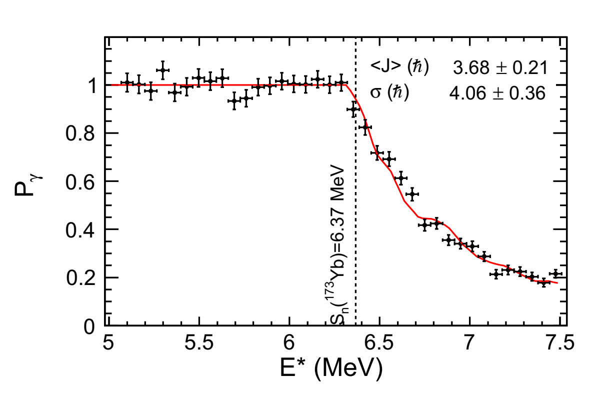

Figure 3. Gamma emission probability P_γ as a function of the excitation energy E*.

To bypass these problems, we used the EXEM method. This method relies on the hypothesis that the variation of the γ-cascade detection efficiency below the neutron separation energy can be extrapolated above this energy. Below the neutron separation energy S_n, the only way for the compound nucleus to release its excitation energy is to emit γ-rays. Thus, the gamma emission probability is equal to 1 and the γ-cascade detection efficiency is determined by $\epsilon(E^* < S_n) = \frac{N_{\gamma-d}(E^*<S_n)}{N_d(E^*<S_n)}$.

Above the neutron separation energy, γ-rays from the ^{174}Yb(p,dnγ)^{172}Yb* channel may be detected. In order to suppress this contribution, a threshold in energy is applied. If the threshold is high enough, the γ-rays coming from the nucleus produced after the neutron evaporation will be removed as shown on Fig. 2.

The γ-emission probability has been fitted using a relation similar to the Eq. 4. The F^A function is defined as

$$F^A(E^*, J, \pi) = \frac{1}{2}\frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{\left(J-\overline{J}\right)^2}{2\sigma^2}\right) \quad (9)$$

The spin distribution is assumed to be described as a Gaussian distribution ($\overline{J}$ is the centroid of the Gaussian and σ corresponds to the standard deviation of the Gaussian) and to not depend on the excitation energy. In addition, both parities are assumed to be equiprobably populated. The other term from the Eq. 4, the branching ratio G_γ, is given by the TALYS 1.2 code [13]. Some informations related to the technical aspects are given in the Ref. [14].

The result of the fit, shown on the Fig. 3, leads to a mean value of $\overline{J} = 3.68 \pm 0.21\hbar$ and to a standard deviation of $\sigma = 4.06 \pm 0.36\hbar$ as parameters for the spin distribution. These values have to be compared to the ones got from the study of the ^{174}Yb(^{3}He,α)^{173}Yb reaction [9]: $\overline{J} = 3.87 \pm 0.21\hbar$ and $\sigma = 3.22 \pm 0.21\hbar$. Both spin distributions are rather similar. This can be interpreted as the fact the angular momenta transferred by the (p,d) and the (^{3}He,α) reactions are quite similar confirming the findings from a previous work where a comparison of the transferred angular momenta was done among different systems and reactions [7].

References

[1] G. Kessedjian *et al.*, Phys. Lett. B **692**, 297 (2010)
[2] C. Rodríguez-Tajes *et al.*, Phys. Rev. C **89**, 024614 (2014)
[3] J. D. Cramer and H. C. Britt, Nucl. Sc. Eng. **41**, 177 (1970)
[4] W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952)
[5] J. E. Escher *et al.*, Rev. Mod. Phys. **84**, 353 (2012)
[6] V. F. Weisskopf and D. H. Ewing, Phys. Rev. **57**, 472 (1940)
[7] T. J. Ross *et al.*, Phys. Rev. C **85**, 051304 (2012)
[8] M. Guttormsen *et al.*, Nucl. Phys. A **573**, 130 (2012)
[9] G. Boutoux *et al.*, Phys. Lett. B **712**, 319 (2012)
[10] K. Wisshak *et al.*, Phys. Rev. C **61**, 065801 (2000)
[11] S. Lesher *et al.*, Nucl. Instr. Meth. A **621**, 286 (2010)
[12] G. Boutoux *et al.*, Nucl. Instr. Meth. A **700**, 59 (2013)
[13] A. Koning, S. Hilaire and M. Duijvestijn, http://www.talys.eu
[14] O. Delaune *et al.*, to be submitted to Phys. Rev. C