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# Isobaric analog states of neutron-rich nuclei. Doppler shift as a measurement tool for resonance excitation functions

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**Abstract.** We present a new approach for the measurement of resonance excitation functions of neutron-rich nuclei using Doppler shift information. Preliminary data from the first application of the method is presented in the spectroscopy studies of $^7$He isobaric analog states in $^7$Li.

**PACS.** 25.60.-t Reactions induced by unstable nuclei – 25.40.Kv Charge-exchange reactions – 27.20.+n $6 \leq A \leq 19$

## 1 Introduction

Radioactive beams provide new opportunities for spectroscopy studies of drip line nuclei. Neutron-rich beams can populate high isospin states which are isobaric analogs of even more exotic neutron-rich systems [1]. We propose a method in which high isospin states are populated in resonance interaction of protons with neutron-rich beams. A $\gamma$-ray is then detected from the daughter nucleus created in a subsequent neutron decay. Information about the total and differential cross-sections of the created high isospin states can be extracted from the shape of the observed Doppler shifted $\gamma$-spectrum.

## 2 The method

The thick target inverse geometry technique [2] was successfully used to study proton-rich nuclei [3,4]. Recently it has been used in studies of exotic neutron-rich systems [5,6]. In the latter experiments, the differential cross-section for $(p,p)$ and $(p,n)$ reactions populating high isospin states was measured at backward angles. The method presented here is a further development of the idea to study exotic neutron-rich nuclei through their isobaric analog states populated in well understood simple reactions [1]. We describe the technique using spectroscopy of $^7$He isobaric analog states in $^7$Li as an example.

In $^6\mathrm{He}+p$ scattering, one can populate states with isospin $T=3/2$ in $^7$Li. These states are isobaric analogs of the levels in $^7$He. The populated $T=3/2$ states have only two open isospin allowed channels: proton decay back to $^6$He or neutron decay to $T=1$ states of $^6$Li, see fig. 1a. As follows from the wave function of the populated $T=3/2$ states,

$$\frac{1}{\sqrt{3}}\Psi(^6\mathrm{He})\Psi(p)+\sqrt{\frac{2}{3}}\Psi(^6\mathrm{Li},T=1)\Psi(n), \quad (1)$$

the neutron decay is dominant and the reduced decay widths for the open channels are related as $\gamma_n/\gamma_p=\sqrt{2}$. The $T=1$ state of $^6$Li populated via the $(p,n)$ reaction can decay only by isospin forbidden channels. Therefore,

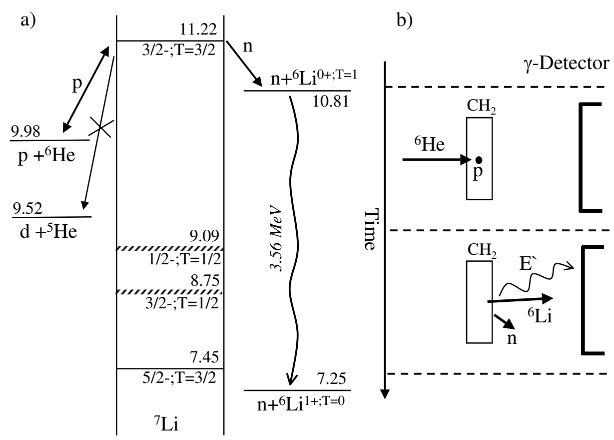


**Fig. 1.** a) Decay scheme for $T=3/2$ resonances in $^7$Li and b) kinematic scheme of the experiment.

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the probability for $\gamma$ transition is enhanced with respect to the particle decays. For the specific case of the first $T=1$ state in $^6$Li, particle decay also violates the parity conservation law and therefore only $\gamma$ decay is allowed. Thus, measuring the characteristic 3.56 MeV $\gamma$-ray from the decay of the first $T=1$ state in $^6$Li is a clear signature that a $T=3/2$ state in $^7$Li was populated. This chain of transmutations is typical for the isobaric analog states of neutron-rich nuclei close to the line of stability. What is special for the described example is the 100% probability for $\gamma$ decay of the first $T=1$ state in $^6$Li.

Suppose that a thick proton target ($(\mathrm{CH}_2)_n$) is used to stop the $^6$He beam. Interaction of $^6$He with protons can take place at any energy from the maximum (beam energy) to zero populating $T=1/2$ and $T=3/2$ resonances in $^7$Li. When a $T=3/2$ resonance is populated, it will decay with highest probability to neutron and $^6$Li($0^+$, $T=1$) state (see fig. 1). Velocity of $^6$Li will depend on the velocity of $^7$Li and the angle at which the neutron was emitted. The excited $^6$Li nucleus decays by $\gamma$ emission before it loses any energy in the target (the width of $0^+$, $T=1$ resonance is 8 eV) and information on the velocity of $^6$Li is preserved in the Doppler shift of the $\gamma$-ray. Therefore a $\gamma$-detector placed at a fixed angle will observe a Doppler shifted and broadened peak. The shift comes mainly from the velocity of $^7$Li while the broadening will depend on the angular distribution of the emitted neutron. The magnitude of the peak will depend on the reaction yield. Therefore by using a detector at fixed angle with known absolute efficiency, one can extract information about the total and the differential cross-sections as a function of energy and angle in one run without changing the experimental conditions. In addition, the measurement is insensitive to the energy resolution of the beam.

## 3 Isobaric analog states of $^7$He

The method described above was first applied to the study of $^7$He isobaric analog states. Figure 2 shows part of the spectrum from HPGe Clover detector placed at 0° with respect to the beam velocity. The continuous curve corresponds to the population of the isobaric analog of the $^7$He ground state in $^7$Li. The curve was obtained by folding the cross-section from a two channel $R$-matrix calculation and all kinematic effects, see sect. 2. There is no arbitrary normalization in the above calculation. The resonance parameters used for the g.s. were taken from ref. [6]. The contribution of the direct charge-exchange process was estimated with the code TWAVE [7] and was found to be negligible. Based on this calculation, one can see that the first peak in the spectrum is related to the g.s. and that there is a clear excess of counts at higher $\gamma$-ray energies which corresponds to $^6$Li($0^+$, $T=1$) nuclei with higher velocity (higher excitation energies of $^7$Li).

In the spectroscopic studs of $^7$He an interesting finding was made by M. Meister *et al.* [8]. Evidence was obtained for a very low-lying $1/2^-$ state (spin-orbit partner of the ground state) with essentially single-particle ($^6$He(g.s.) + $n$) structure. An attempt to find the analog

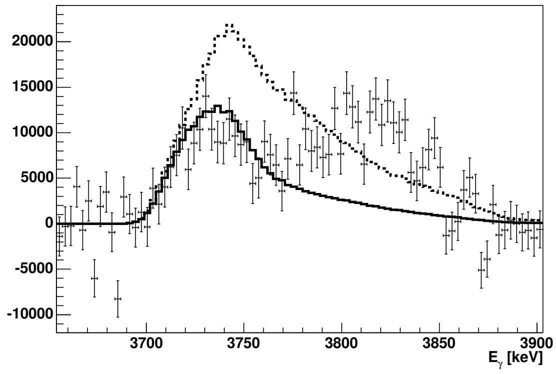


**Fig. 2.** Final spectrum of the Doppler shifted 3.56 MeV $\gamma$-rays obtained by subtraction of the carbon contribution form the $\mathrm{CH}_2$ target, a linear Compton background and dividing by the absolute detector efficiency. Solid line shows the contribution of the known g.s. resonance $T=3/2$, $J=3/2^-$ in $^7$Li. Dotted line was obtained by taking into account the narrow low-lying $1/2^-$ state proposed in [8].

of this resonance in $^7$Li ($T=3/2$ $1/2^-$) revealed no narrow resonances in this region [6]. The results obtained in ref. [6] are confirmed by the data presented here. The isobaric analog of a low-lying narrow $1/2^-$ resonance in $^7$He is not observed. The expected shape of the $\gamma$ spectrum in case of population of a resonance with parameters from ref. [8] is shown with a dotted line in fig. 2. It is clearly seen from the figure the magnitude and the shape of the data is not reproduced. The present results and these of [6] are completely independent since different techniques were used to measure different quantities. Therefore, the existence of the state with parameters proposed in [8] can be reliably excluded.

## 4 Conclusion

We propose a new method for spectroscopic studies of neutron-rich nuclei close to the border of stability. As an example, the $^7$He isobaric analog states of $^7$Li were studied. The measured $\gamma$-ray spectra show clear evidence that isobaric analog states of $^7$He were excited. The existence of a narrow low-lying $1/2^-$ state in $^7$He is ruled out. We present evidence for higher-lying resonances in $^7$He. We believe that the presented technique will be very useful in the future for studies of nuclei at the drip line.

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