PIONIC FUSION CLOSE TO THRESHOLD: $d + \alpha \rightarrow {}^6\mathrm{Li}^* + \pi^0$ AT CELSIUS*

M. Andersson[a], Chr. Bargholtz[a], K. Fransson[a]
L. Holmberg[a], K. Lindh[a], L. Mårtensson[a], I. Sitnikova[a]
P.-E. Tegnér[a], P. Thörngren Engblom[b], G. Weiss[a]
and K. Wilhelmsen Rolander[a]

[a]Department of Physics, Stockholm University
Box 6730, S-113 85 Stockholm, Sweden
[b]Department of Radiation Sciences, Uppsala University
S-751 21 Uppsala, Sweden

(Received July 30, 2000)

The isobaric analogue state of the ground state of the halo nucleus ^{6}He in ^{6}Li has been studied in a pionic fusion experiment at the CELSIUS storage ring facility in Uppsala, Sweden. The ^{6}Li ions were detected in a zero-degree spectrometer situated in the fourth quadrant of the CELSIUS ring. Differential cross-sections were measured at two energies corresponding to $E_{\mathrm{c.m.}}$=1.2 and 1.9 MeV above the absolute threshold. The total cross sections are $\sigma = 228 \pm 6\ ^{+70}_{-0}$ nb and $141 \pm 12\ ^{+42}_{-0}$ nb respectively.

PACS numbers: 25.10.+s, 25.40.Ve, 25.60.Pj, 21.60.Gx

Halo nuclei, *i.e.* nuclei composed of a tightly bound core surrounded by a dilute cloud of loosely bound nucleons are at the focus of many nuclear physics experiments, particularly at radioactive beam facilities. In this experiment the excited state at 3.56 MeV in ^{6}Li has been studied. This is the isobaric analogue state (IAS) of the the ground state of the two-neutron halo nucleus ^{6}He. The IAS is particle stable and is theoretically predicted to have an even more pronounced halo structure than ^{6}He [1]. The pionic fusion of a deuteron and an alpha particle was used as a probe particularly sensitive to the cluster structure of the final state. As both particles in the initial state have isospin $T = 0$ pionic fusion to the ground and first excited states in ^{6}Li is forbidden.

* Presented at the Meson 2000, Sixth International Workshop on Production, Properties and Interaction of Mesons, Cracow, Poland, May 19–23, 2000.

The experiment was done at the CELSIUS synchrotron and storage ring [2] at The Svedberg laboratory, Uppsala Sweden. The CELSIUS ring works with a electron-cooled circulating beam and thin internal targets, ensuring a high luminosity combined with accurate energy definition. In this experiment an alpha-particle beam was used together with a deuterium cluster-jet target. The average luminosity during the experiment was $(3\ ^{+0}_{-1})\times10^{29}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The inclusive $\mathrm{d}(\alpha,{}^6\mathrm{Li}^*_{3.56})\pi^0$ reaction was studied at two different beam energies, 417.95 and 420.30 MeV, corresponding to $E_{\mathrm{c.m.}}$=1.2 and 1.9 MeV above the absolute threshold in the center-of-mass (c.m.) frame.

Very close to threshold heavy reaction products carry most of the beam momentum and therefore travel close to the beam. In order to detect such reaction products a small size zero-degree spectrometer has been installed in CELSIUS [3]. The spectrometer uses the focusing and bending magnets of the storage ring in combination with a detector telescope made of high-purity germanium.

The detector telescope, consisting of three detector elements, is inserted into the vacuum of the CELSIUS ring itself, 6.1 m downstream from the target. Its radial position with respect to the beam is continuously adjustable to match the specific conditions for different experiments. In this particular case the first two detectors were transmission (ΔE) detectors of thicknesses 1.7 mm and 1.1 mm and the third was a thicker (2.1 mm) stopping (E) detector. The first transmission detector was position sensitive with its contacts divided into 18 horizontal strips of 2 mm width on one side and 66 1 mm wide vertical strips on the other side for measurements of angular distributions with a resolution of approximately 1 mrad.

Using the position information, complete angular distributions could be measured at both energies with acceptances ranging from 100% at 0° and 180° to 63% (34%) around 90° in the c.m. frame at the lowest (highest) beam energy.

The ^{6}Li events were selected by putting appropriate gates in the ΔE-ΔE-E spectrum.

In order to determine the differential cross section simulated events, generated by a Monte-Carlo ray-trace code, were fitted to experimental data adopting a Maximum-Likelihood method. Each event in the experimental data was characterized by its energy and its coordinates on the position-sensitive detector. The position information was binned in 4 mm wide vertical bins and 3 mm wide horizontal bins. The bin width in energy was 1 MeV, matching the resolution of the telescope. Experimental energy and position spectra are shown in Figure 1.

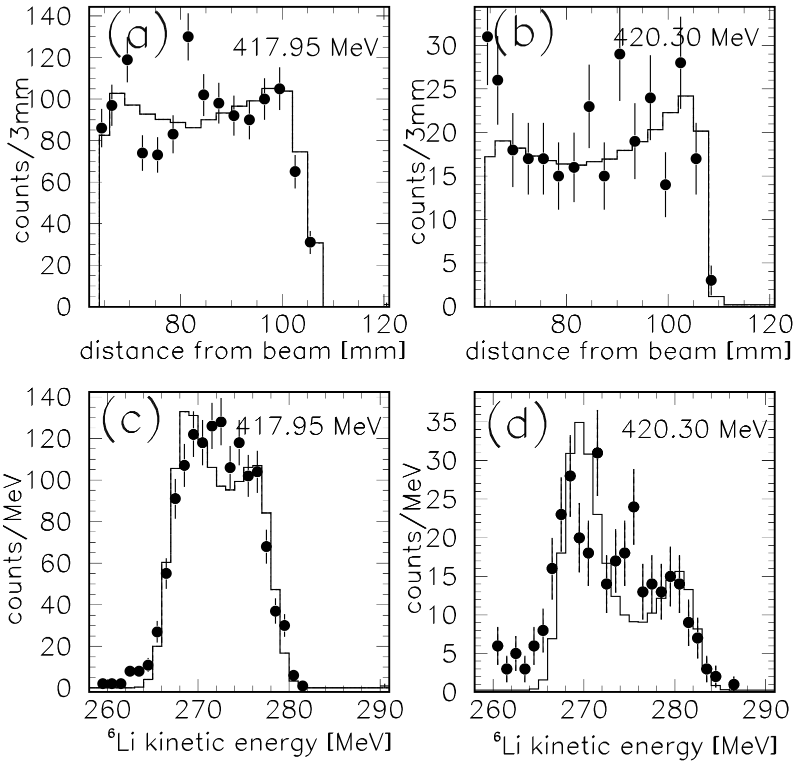

Fig. 1. Position and energy spectra. The filled circles represent experimental data and the histograms results from the fits described in the text. Top: horizontal position distributions for (a) 417.95 MeV and (b) 420.30 MeV. Bottom: energy spectra for (c) 417.95 MeV and (d) 420.30 MeV. For (d) events with energies between 266 and 286 MeV were included in the fit.

The following expression for the differential cross section was assumed:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{c.m.}} = \sum_{n=0}^{2} a_n P_n(\cos\theta_{\mathrm{c.m.}}), \tag{1}$$

where $P_n(\cos\theta_{\mathrm{c.m.}})$ are Legendre polynomials and $\theta_{\mathrm{c.m.}}$ is the c.m. angle of the excited ${}^6\mathrm{Li}^*$ ion with respect to the beam. The size and divergence of the beam, the effect of the gamma decay, and the energy resolution of the telescope were taken into account in the simulation. The expansion coefficients, a_n, were determined from the fit. The beam energy was treated as a free parameter in the fitting procedure and the results were 417.95 ± 0.07 MeV and 420.30 ± 0.07 MeV. The results from the fits are presented in figure 1 and in Table I.

TABLE I

Beam energy and expansion coefficients obtained from the fits of simulated data to experimental. The uncertainties are purely statistical. For the absolute luminosity we have used the upper limit and thus the numbers presented represent lower limits. The ratio between the cross-sections is independent of the 30% downward uncertainty in the absolute luminosity. Higher order terms are redundant in the fit to the data.

Results from fits			
Beam energy (MeV)	a_0 (nb/sr)	a_1 (nb/sr)	σ (nb)
417.95±0.07	18.2±0.5	-2.1±0.8	228±6
420.30±0.07	11.2±1.0	-4.8±1.0	141±12

We measure a strong forward-backward asymmetry for the d(α,^{6}Li*)π^0 reaction that grows rapidly with energy, while the total cross section decreases by about 40% over 0.7 MeV. In a simple cluster model it has been shown [4] that these specifics of the differential cross section reflect the nuclear structure involved, and in particular the halo structure of the final nucleus.

The present result for the total cross section, $\sigma = 228 \pm 6\ ^{+70}_{-0}$ nb 1.2 MeV above threshold, is approximately a factor of 10 smaller than that measured for the d(p,π^0)^{3}He reaction at the same energy [5]. In light of the much larger degree of coherence required in the present process this difference is not surprising. Comparing with the cross sections measured for the ^{3}He(^{3}He,^{6}Li)π^+ reaction [6, 7] involving the same total number of nucleons we see that they are of a comparable magnitude.

The authors wish to thank Davor Protic and the personnel at the detector laboratory in Jülich for manufacturing the germanium detectors. We are greatly indebted to the CELSIUS group for providing excellent experimental conditions. Help from Linda Gerén during the analysis is gratefully acknowledged. This work was in part funded by the Swedish Natural Science Research Council (NFR).

REFERENCES

[1] B.V. Danilin *et al.*, *Phys. Rev.* **C43**, 2835 (1991).

[2] C. Ekström *et al.*, *Phys. Scr.* **T22**, 256 (1988).

[3] Chr. Bargholtz *et al.*, *Nucl. Instrum. Methods* **A390**, 160 (1997).

[4] M. Andersson *et al.*, *Phys. Lett.* **B481**, 165 (2000).
[5] V.N. Nikulin *et al.*, *Phys. Rev.* **C54**, 1732 (1996).
[6] Y. Le Bornec *et al.*, *Phys. Rev. Lett.* **47**, 1870 (1981).
[7] L. Bimbot *et al.*, *Phys. Lett.* **B114**, 311 (1982).