Weak Production of Λ–particles at COSY

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Abstract

We propose to search for pure weak production of strangeness in the reactions dp $\rightarrow$ ppΛ, pd $\rightarrow$ Λpp, and pp $\rightarrow$ $\Delta^{++}\Lambda$ $\rightarrow$ p$\pi^+\Lambda$. Since strangeness conservation would need an additional K–meson with $\approx$500 MeV mass it is clear that we will investigate Λ-production below the K$^+\Lambda$–threshold. The strangeness-violating production process is based on the exchange of a charged W–boson which converts an u– into an s–quark on one side (p $\rightarrow$ Λ) and a d– into an u–quark on the other (n $\rightarrow$ p or p $\rightarrow$ Δ^{++} resp.). The experimental setup is based on the Time–Of–Flight detector (TOF) with its outer highly granulated time–of–flight scintillator hodoscopes, energy detector, and the LH$_2$–target. In addition there will be specific detectors in the target region for fast triggering, multiplicity determination, and track reconstruction. These are a silicon μ–strip decay spectrometer and an intermediate hemispherical scintillator hodoscope for detecting tracks from close to 0° up to 90°. The four-momentum vectors of all charged particles — the directly produced protons or p and π^+ resp., and the p and π^- coming from the delayed Λ–decay — will be determined. Moreover, the semiconductor counters allow an additional determination of the Λ–decay geometry and Λ–4-momentum vector. The main trigger signature of this reaction is the delayed Λ–decay. The whole inner part of the detector is designed to be rather massless in order to reduce secondary reactions in material. Especially charged particle production by neutrons from the target, which would feign delayed decays, have to be and can be reduced strongly. Our goal is to learn how small a branching ratio $R = \frac{\sigma_{\mathrm{dp}\rightarrow\mathrm{pp}\Lambda}}{\sigma_{\mathrm{dptotal}}}$ we can determine for kaon-less Λ–production. Actually we intend to reach $R < 10^{-8}$. From earlier experimental experience we know that $R < 10^{-6}$ can be reached safely. Physics however might happen at $R \leq 10^{-14}$ [1].

1 Motivation

We propose to measure at COSY-Jülich the inversion of the Λ–decay, the single strangeness production via weak interaction. The simplest possible reactions are dp $\rightarrow$ ppΛ or pd $\rightarrow$ Λpp, and pp $\rightarrow$ $\Delta^{++}\Lambda$ $\rightarrow$ p$\pi^+\Lambda$. These processes — viewed in terms of quarkline diagrams in Fig.1 and Fig.2 resp. — need a W–boson exchange.

Possible other dp-, pd-, and pp-reaction channels with weak single strangeness production can be divided into hyperon- and kaon-production according to their very different reaction thresholds. In all cases they are clearly below strangeness conserving reaction thresholds on the same target.

It is obvious that the appearance of a delayed Λ– (c_τ = 7.89cm) or K^0–decay (c_τ = 2.675cm) in interactions at beam momenta below the threshold

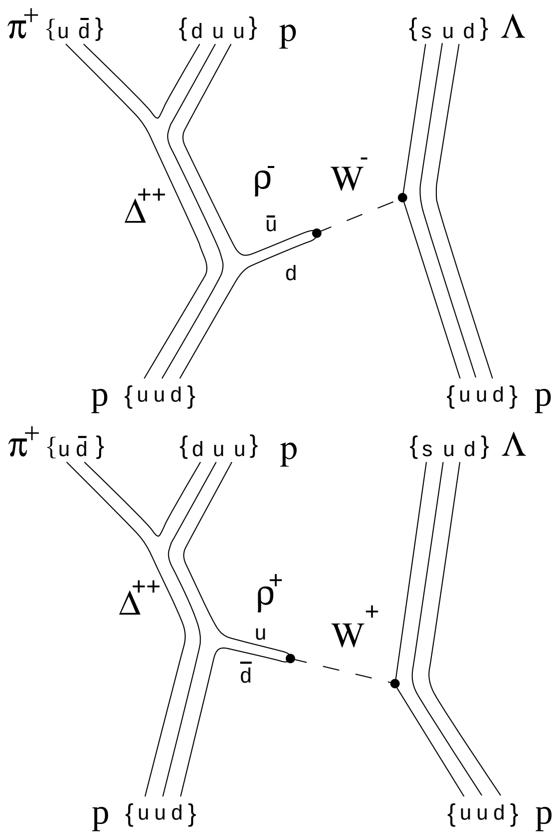

Figure 1: Quarkline diagrams for $pp \to \Delta^{++}\Lambda \to p\pi^+\Lambda$

	Threshold of Reaction	$\sqrt{S}$ GeV/c^2	p_{beam} GeV/c	T_{beam} GeV
	$pp \to p\pi^+\Lambda$	2.1935	1.3276	0.6874
$\to$	$pp \to \Delta^{++}\Lambda$	2.3476	1.7648	1.0604
	$pp \to pnK^+$	2.3715	1.8324	1.1204
	$pp \to ppK^0$	2.3742	1.8402	1.1273
$\to$	$pd \to \Lambda pp$	2.9922	0.7707	0.0276
	$pd \to \Lambda p\pi^+n$	3.1330	1.0979	0.5059
	$pd \to \Lambda\Delta^{++}n$	3.2872	1.4273	0.7698
	$pd \to pnnK^+$	3.3111	1.4772	0.8117
	$pd \to ppnK^0$	3.3138	1.4829	0.8166
$\to$	$dp \to pp\Lambda$	2.9922	1.5406	0.5516
	$dp \to np\pi^+\Lambda$	3.1330	2.1947	1.0114
	$dp \to n\Delta^{++}\Lambda$	3.2872	2.8531	1.5388
	$dp \to pnnK^+$	3.3111	2.9530	1.6227
	$dp \to pnpK^0$	3.3138	2.9644	1.6323

Table 1: Some strangeness non-conserving channels in pp–, pd–, and dp–reactions at COSY

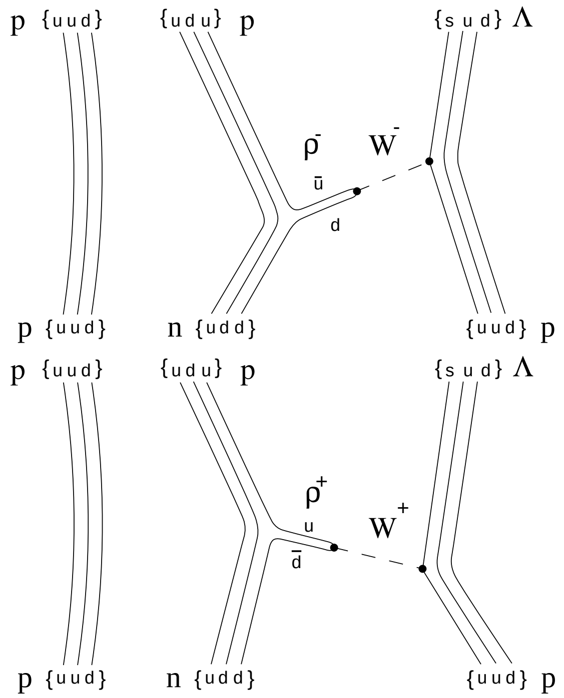

Figure 2: Quarkline diagrams for pd $\rightarrow$ ppΛ

Threshold of Reaction	$\sqrt{S}$ GeV/c^2	p_{beam} GeV/c	T_{beam} GeV
pp $\rightarrow$ pK$^+\Lambda$	2.5475	2.3390	1.5819
pd $\rightarrow$ pK$^+\Lambda$n	3.4871	1.8441	1.1308
dp $\rightarrow$ pK$^+\Lambda$n	3.4871	3.6864	2.2605

Table 2: Associated strangeness production channels in pp–, pd–, and dp–reactions at COSY

of associated strangeness production (see tables 2 and 3) is a clear signal for strangeness violating weak production.

The reaction pp $\rightarrow$ p$\pi^+\Lambda$ is at first sight attractive since it resembles the reaction pp $\rightarrow$ pK$^+\Lambda$ in kinematics and could be studied to some extent already with the setup of our experiment E–7 (Proposal 15). However, the fact that pp $\rightarrow$ p$\pi^+\Lambda$–production threshold is higher than the threshold for allowed ΛK$^+$–production on heavy targets makes it a bad choice. In contrast the situation is perfect for pd $\rightarrow$ Λpp and dp $\rightarrow$ ppΛ. Here the reaction thresholds are far below those of pA $\rightarrow$ AK$^+\Lambda$ and dA $\rightarrow$ AK$^+\Lambda$n respectively. The main advantage of the dp– over the pd–experiment is the extremely easy and efficient determination of the kinematics of the two prompt protons, which at 1730 MeV/c have LAB–angles below 25° and momenta between $292 < p < 809$ MeV/c ($44 < T < 300$ MeV). It is evident, that one has to start by measuring this reaction, and extend the physics program on the other channels afterwards.

Threshold of Reaction	$\sqrt{S}$ GeV/c^2	p_{beam} GeV/c	T_{beam} GeV
$pA \rightarrow AK^+\Lambda$	211.6093	1.3125	0.6751
$dA \rightarrow AK^+\Lambda n$	212.5488	1.7363	0.6803

Table 3: Associated strangeness production channels in p– and d–reactions on heavy target nuclei (A=210)

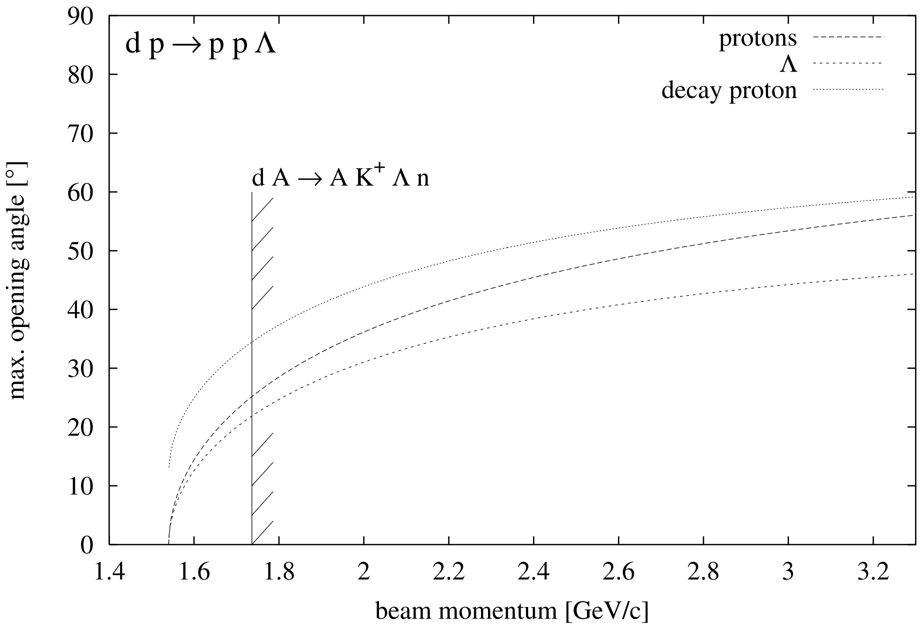

Figure 3: Maximum particle angles in LAB

2 Reaction Kinematics

In the following we will concentrate on the reaction $dp \rightarrow pp\Lambda$ since it allows for high acceptance and can be performed slightly below all strangeness conserving thresholds, namely at 1730 MeV/c. It is obvious that the maximum opening angle is then below 25° for the directly produced protons and below 35° for the Λ–decay protons (Fig.3 and 4). A complete reconstruction of the two prompt protons 4-momenta $\mathcal{P}_{p_i}$ allows to indentify the Λ by missing-mass ($\mathcal{P}_\Lambda = \mathcal{P}_{\text{entrance}} - \mathcal{P}_{p_3} - \mathcal{P}_{p_4}$ and $\mathcal{P}_\Lambda^2 = m_\Lambda^2$). Moreover, the 4-momentum vectors of the Λ and its decay particles $\Lambda \rightarrow p\pi^-$ (charged decay mode fraction 64 %) can be reconstructed from the decay pattern independently once more. In addition, measuring the velocities of the decay particles allows to improve further on that. This overdetermination is the key property needed to get a very clean event sample. Taking into account that the cross section of weak processes is proportional to the relative energy $\epsilon = \sqrt{S - 2m_p - m_\Lambda}$ in the reaction it is clear that the beam momentum should be as high as possible (1730 MeV/c).

The proposed reaction is nor a scattering of pointlike fermions on each other, like in νe–reactions, neither a scattering of leptons and quarks in hadrons, like

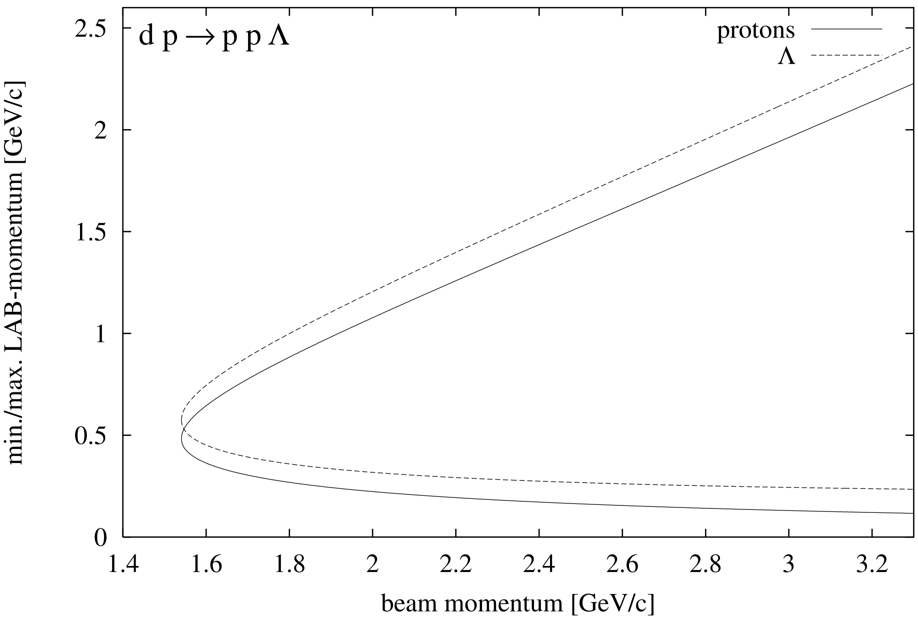

Figure 4: Minimum and maximum momenta of directly produced particles in LAB

in νN–reactions with its interesting connection to hadronic structure functions. Here we have to deal with weak interactions of bound quarks with bound quarks. The cross section may be higher as in lepton–lepton or lepton–hadron scattering since the number of participating quark–quark configurations is four. Reaction partners in these processes are valence quarks bound in nuclei with their momentum distributions. Most interesting in these reactions could be the chance to get new access to structure functions of nucleons.

3 Detector

The detector arrangement is based on the TOF–system [2] with its highly granulated large scintillator hodoscopes and an additional energy detector behind the 'quirl' (schematically shown in Fig.5), which is capable to stop and measure reaction protons with highest possible energy. Since all protons appear below 35° in the laboratory system it is sufficient to place the LH_2–target $\leq$ 83 cm in front of the 'quirl' with its 1.16 m diameter or $\leq$ 2.14 m in front of the 'quirl' plus 'ring' forward hodoscope combination (3 m diameter) in order to assure 100 % acceptance for the reaction protons. Both solutions are easy to realize with the modular vacuum system of the TOF cetector. For the short version, the additional 90–fold granulated energy detector behind the 'quirl' improves the precision of the kinematical reconstruction remarkably and seems to be neccessary for an optimum result.

Specific additions are needed in the decay region, i.e. in the inner part close to the thin–walled LH_2–target. Cooling of the active target volume is done by a small copper cooling finger fed into the TOF–vacuum from upstream

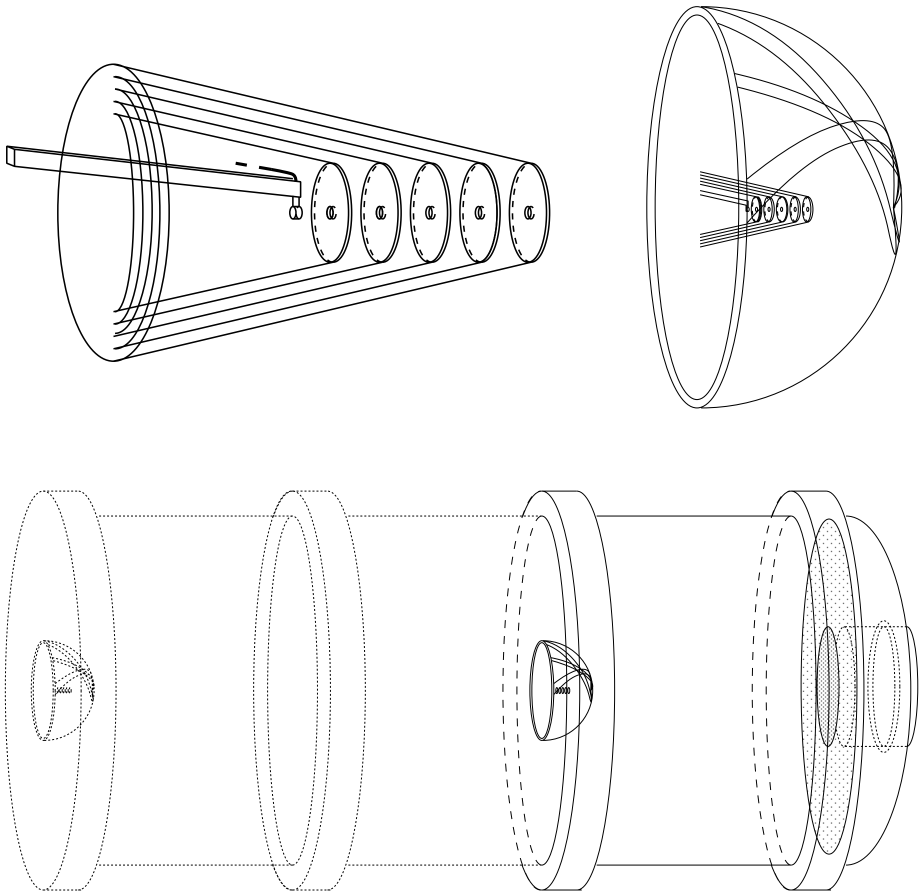

Figure 5: Schematic of the detector setup: top–left: target and Si–decay spectrometer, top–right: intermediate sperical hodoscope, bottom: complete setup with outer TOF detector and optional energy detector behind foreward 'quirl'

adding a minimum amount of material into the target region. This target setup has already been built with 1 μ mylar windows and is functioning without problems [3]. An array of thin disc-shaped silicon μ–strip counters with beam hole and a 'quirl'–like rotationally symmetric 100–fold segmentation on both sides follows. This allows for $\sim 10^4$ pixels. The first of these, together with the outer hodoscope gives the online trigger, based on the increase of track multiplicity from two to four. The silicon counters are arranged such that they cover most of the Λ–decays. In order to approach the ideal case of a 'mass–less' detector the room–temperature Si–counters are mechanically supported by cones made of Kapton–foil which also carry the conductor paths for power supply and signal readout. The 'quirl' structure has been tested successfully in the GEM-detector with germanium counters [4].
This 'decay spectrometer' is surrounded by a hemispherical 3–layer scintillator hodoscope with a topology similar to the TOF–'quirl'–detector with a radius of ≤ 0.5 m and an angular coverage from from $> 1°$ to $\geq 90°$. The scintillators are ≤ 3 mm thick. This hodoscope is especially useful to locate pion tracks with large track angles which might miss the silicon strips. With about 200 radiator elements we will obtain an average pixel size of 1 msr.

4 Principle of Measurement

The candidates for the reaction channel dp $\to$ ppΛ are selected online by the fast 'delayed decay' trigger, which is based on the demand for a multiplicity of two in the first counters close to the target, and four charged particles in the 'outer' detectors. This trigger condition suppresses all prompt reactions, but can be fulfilled by various event constellations — which of course have nothing to do with the wanted reaction:

- Neutral particle production in the target with subsequent reactions of these neutrals into charged products in matter, e.g.:
  - pp $\to$ pπ^+n in target and nA $\to$ ppX, nA $\to$ p$\pi^+\pi^-$X later.
  - pp $\to$ ppπ^0 in target with subsequent $\pi^0 \to \gamma\gamma$ where the γ's make pair–production γA $\to$ e$^+$e$^-$X.

  Because all these unwanted secondary reactions can only take place in material, it is clear that a 'mass–less' detector is needed!
- Multi–particle production in the target and failure of the close detector components to identify real tracks.

In the offline analysis these remaining wrong reactions have to be identified and rejected. First exactly four tracks have to be found (hits in the 'inner' part of the experiment are connected to hits in the 'outer' part).

- The geometrically reconstructed origin of two charged tracks must lie inside the target volume (promptly produced protons) whereas the origin of the other two charged tracks must be located behind the target (delayed decay).

There are additional conditions the tracks must fulfill:

- The plane defined by the tracks of the delayed decay particles must include the reaction point in the target volume.

- The reconstructed Λ–direction (from target to vertex point) must lie between the decay tracks.

Furthermore, reaction kinematics supplies additional conditions:

- The two prompt tracks have to lie within the kinematic limits: e.g. the maximum production angles $\Theta_{\max}$ [4], time–of–flight–, dE/dx–, and optionally energy measurements must agree with the reaction kinematics.

- The 4-momentum vectors of the prompt particles $\mathcal{P}_{p_3}$ and $\mathcal{P}_{p_4}$ must reconstruct the Λ–4-momentum vector and the Λ–mass $\mathcal{P}_\Lambda^2 = m_\Lambda^2$. Here the energy measurement in the thick absorber counter behind the forward TOF 'quirl' can improve the missing mass resolution.

- The decay pattern and the velocity–information of the decay particles combined with mass assumptions m_p and m_{π^-} allow an independent determination and confirmation of the Λ–mass $\mathcal{P}_\Lambda^2 = m_\Lambda^2$ and kinematical consistency.

With similar experimental criteria in the LEAR PS185–experiment we succeed to measure $\overline{p}p \rightarrow \overline{\Lambda}\Lambda$ cross section down to 0.2 μb out of $\sim$ 100 mb total cross section under quite difficult background conditions [?] (and even on a polyethylene target). This corresponds to $R \sim 2 * 10^{-6}$.

The reconstructions rely to a large extent on geometrical precision and therefore basically on the quality of the cooled beam. The interaction volume in the target has to be very small in comparison to the volume where Λ–decays occur, in order to obtain a safe identification of delayed decays. This requires small LH_2–targets and this, of course, limits the luminosity,

The acceptance for the dp $\rightarrow$ ppΛ–reaction in the setup in Fig.5 is composed by

- the acceptance for the prompt protons, where $\geq$ 90 % can be simply achieved in all regions of pp phase space, due to the narrow cone of emission.

- the acceptance for Λ–determination via pπ^-–decay vertex reconstruction. This depends on the charged decay probability ($\Lambda \rightarrow p\pi^-$) which is 0.64. Further more it depends on the kinematically determined decay point distribution. The decay length is $L_d = c\tau_\Lambda \frac{p_\Lambda}{m_\Lambda}$. Since with $p_{\text{beam}} =$ 1730 MeV/c we have $383 < p_\Lambda < 914$ MeV/c we find $2.3 < L_d < 6.5$ cm. In the worst case we loose $\sim$ 20 % of low energy Λ's which decay in front of the first silicon counter (already four tracks within 5 mm distance from the target), and we loose $\sim$ 20 % of high energy Λ's which decay after the last silicon detector (no vertex information is obtainable). Of course, most of the late decays can be still evaluated with hit information from the spherical hodoscope and the large outer hodoscopes alone. Problematic are the large angle pions which may miss the silicon counters and may decay before hitting the scintillator hodoscopes. These losses are in the order of 20 %. So a conservative estimate for overall ppΛ–acceptance is $\epsilon_{eff} = 0.64 * 0.90 * (1 - 0.2) * (1 - 0.2) * (1 - 0.2) \geq 0.30$

First experience in measuring dp $\rightarrow$ ppΛ can of course be obtained with the accepted and nearly finished setup of our TOF–experiment E–7 (pp $\rightarrow$ pK$^+\Lambda$, COSY-Proposal 15). One goal of the present proposal is to extend the angular acceptance up to 90°.

5 Rates and Request

For the experimental setup we assume

target thickness	1 mm $LH_2 \Rightarrow d = 4.2 * 10^21 \frac{\text{protons}}{\text{cm}^2}$
average deuteron beam current	$I = 10^8 \frac{\text{deuterons}}{\text{s}}$
$\Rightarrow$ Luminosity	$L = I * d = 4.2 * 10^29 \frac{1}{\text{scm}^2}$

With a total dp-cross section of $\sigma = 80$ mb $= 8 * 10^{-26}$ cm^2 we get a reaction rate of $\sigma L = 3.3 * 10^4 \frac{\text{reactions}}{\text{s}}$. In order to limit the branching ratio $R = \frac{\sigma_{\text{dp}\rightarrow\text{pp}\Lambda}}{\sigma_{\text{dp}\ total}}$ to $R < 10^{-8}$ we need in principle a total number of $Z = \frac{k}{R\epsilon_{\text{eff}}}$ reactions in the target. With $k = 3$ the branching limit $R < 10^{-8}$ has a probability of 95 %. The necessary 10^9 reactions will be reached within $\sim 3 * 10^4$ seconds ($< 1/2$ day). Of course, the real problem for this experiment lies in the purity of evaluation and the control of the systematic errors. Therefore we ask for one week of deuteron beam time at 1.730 GeV/c with $\geq 10^8 \frac{\text{deuterons}}{\text{s}}$ average.

References

[1] We are grateful to A.Thomas who stimulated this activity and brought to our attention already in 1983 that R might be remarkably larger.

[2] COSY-Proposals 9,12,15

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