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JLAB PAC21
Jefferson Lab
12000 Jefferson Ave.
Newport News, VA 23606

Dear PAC Chairman,

On behalf of JLab the E99-003 collaboration, I would like to resubmit the proposal of E99-003 as is. The physics goals, experimental techniques and requirements have not changed. Since the approval of the JLab experiment E95-002 (later E99-003) a great deal of efforts, both theoretically and experimentally, have been invested in the study of the Strangeness-changing ($\Delta S=1$) hadronic weak interaction. On the theoretical side, after years of concerted efforts by a number of groups, the situation has clarified sufficiently that only experimental data with an accuracy of 10-20% can significantly advance the field. However, even though great experimental efforts have been expended in the same time period, the experimental accuracy of some observables is still nowhere this number. Thus, the JLab experiment E99-003 has become an even more important experiment that needs to be executed timely due to its unprecedented precision and unique experimental technique that minimizes ambiguities and systematic errors.

Although the proposal of E99-003 (previous E95-002) has sufficient detail of descriptions for the physics goal; experimental technique and beam requirement, I would like to provide a report (see attachment to this letter) that outlines the most recent development in this field. I hope this report can provide PAC members additional information on the development of this field and better view of the importance of this proposed JLab experiment. Please allow me to point out several key features about the status of the field and about our proposed experiment.

The $\Delta S=1$ hadronic weak decay, i.e. the $\Lambda N \rightarrow NN$ (nonmesonic) and $\Lambda \rightarrow N\pi$ (mesonic) decays in the nuclear medium after formation of Λ-hypernuclei, is a unique tool to study hadronic weak interactions. The measurements of the total lifetime τ_Λ, the neutron-induced ($\Lambda n \rightarrow nn$) nonmesonic decay rate, Γ_n, the proton-induced ($\Lambda p \rightarrow pn$) nonmesonic decay rate, Γ_p, and their A-dependencies into the heavy-mass region provide crucial information on such weak interaction mechanisms. As pointed out in theoretical studies, these observables can provide a direct measure of the level of violation of the empirical $\Delta I=½$ rule observed from free nonleptonic hyperon and kaon decays. The origin of this rule is still not completely understood. Furthermore, precision measurements of the above mentioned observables provide crucial data to test the validity of chiral effective field theories in the SU(3) realm, which has been put into question due to their failure to explain the nonleptonic weak hyperon decay rates.

Over the past several years, several theory groups (e.g., the Barcelona group under A. Ramos et al. and the Tokyo group under M. Oka et al.) have come to the conclusion that in a field-theory based meson-exchange description of the $\Lambda N \rightarrow NN$ process, kaon exchange must be included along with the dominant pion exchange and some unknown contact terms which could be modeled through vector mesons or direct quark exchange. The ratio Γ_n/Γ_p turns out to be the crucial observable: values of Γ_n/Γ_p around 0.5 or less can be accommodated by a pion plus kaon exchange description that obeys the $\Delta I=½$ rule. However, should Γ_n/Γ_p be around 1.0 or larger (as suggested by current measurements with very large error bars) the $\Lambda N \rightarrow NN$ reaction would be dominated by $\Delta I=½$ rule violating contact terms of unknown nature.

In the light mass region, due to the reasonable production yield of Λ-hypernuclei, all the observables mentioned above can be measured. Thus, experiments using secondary meson beams such as kaons and pions concentrated on the light mass region by measuring decay particles. Although many experimental techniques were aimed at better and more complete measurements, the accuracy of measurements has not yet improved significantly. In such measurements, the decay protons have a low energy cutoff in order to escape from the target and the requirement of penetration through a complicated detector system. Therefore, the missing portion of protons has to be modeled in terms of the energy spectrum. Detection of final state neutrons suffers from low efficiency and poor neutron energy determination. The recently (KEK) observed inconsistency in the proton and neutron energy spectrum raises questions on the contamination of the cascade nuclear decay and the presence of $\Lambda NN \rightarrow NNN$ three-body channels. However, tagging on correlated final-state nucleons gave extremely poor statistics. Thus, despite great experimental efforts at KEK, the error bar of the ratio Γ_n/Γ_p is still greater than 100% and thus the discrepancies with theory cannot be interpreted as being significant. From a practical point of view, it is impossible to measure precisely the A-dependence of the lifetime τ_Λ, using heavy hypernuclei with this technique as another alternative due to extremely low coincidence yield when tagging on both primary strangeness production and decay.

Nuclear fission has been used as a tool to access the nonmesonic decay of heavy hypernuclei in an attempt to measure the A-dependence of τ_Λ. For medium to heavy hypernuclei the contribution from mesonic channels is negligible due to Pauli blocking. Efforts were made in Kharkov, CERN, and COSY using low-duty factor electron, antiproton, and proton beams. Due to the low yield and unsuitable beam time structures, primary strangeness production was not identified but it was assumed that all delayed fissions came from hypernuclear decay. The lifetime of such decays was determined by the position distribution in the blocked shadow region of the fission fragment detectors. The main problem of such measurements is the model dependence on the recoil momentum and angular distribution of produced hypernuclei. As summarized in the attached report, the existing results including the most recent ones from COSY-13 are not consistent and systematic errors are large.

The proposed E99-003 utilizes the unique CEBAF beam structure and the excellent time reconstruction capability on the kaon spectrometer (SOS) and fission fragment detector. The coincidence of K^+ and fission not only singles out the primary strangeness production but also measures the lifetime of heavy hypernuclei from the Bi target directly. With precise measurement on the prompt fissions at the same time, the experimental systematic error will be eliminated. A detailed description of the experimental technique is available in the proposal.

Finally, we expect this experiment to be a gateway to future precision experiments. Besides verifying the yield, technique, and precision, it will provide us with valuable information on whether a systematic A- dependent study is feasible. Secondly, and more importantly, the fission technique will be examined in great detail under CEBAF beam conditions. It will provide us with information based on the low-pressure MWPC technique to develop a new experiment that would focus specifically on the precise measurement of Γ_n and the Γ_n/Γ_p ratio using the ${}^{10}_{\Lambda}$Be hypernuclei. Therefore, our collaboration believes that the JLab $\Delta S = 1$ weak interaction program has a unique opportunity to contribute important results to this field.

The experimental device has been developed, tested, and is ready to take beam. The experiment is simple to set up and run. The requested beam time is short. The analysis is rather straightforward. The impact on the field of weak hadronic interactions would be immediate. Therefore, I would like to request PAC21 to approve this experiment again with a reconsideration of its rating. If it is approved again, I would like to request scheduling of this experiment as soon as possible.

Sincerely,

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Status of the $\Delta S=1$ Hadronic Weak Interaction Program

Report to PAC21 on JLab E99-003

A. Margaryan and L. Tang
On behalf of E99-003 collaboration

December 3, 2001

1. Heavy hypernuclear lifetime measurement

Lifetimes of heavy hypernuclei-decisive for establishing the mass dependence of τ_Λ- have been studied only indirectly. The experimental technique so far applied is the recoil shadow method originally suggested by Metag et al. for the measurement of fission isomers [1]. It has been employed by Noga et al. [2,3], Amstrong et al. [4] and COSY-13 collaboration [5-12] in the hypernuclear lifetime measurements with electrons, antiprotons and protons, respectively. These published lifetimes of heavy hypernuclei are collected in the Table.

2. Kharkov experiment

Kharkov group earlier reported the detection of delayed fission following the interaction of 1.2 GeV electrons with bismuth nuclei [2]. The recoil shadow method was used. Fission fragments were registered by mica detectors as elongated tracks. It was possible to determine both the coordinates and orientation of the tracks in the detector. For each track registered in the shadow area of the detector the trajectory of fission fragment was restored, and the range of the fissile nucleus was determined with 0.5 mm resolution. The range distribution of fissile nuclei obtained at electron energy of 1.2 GeV was exponential in character. The mean range was L = (2.2 ± 0.5) mm which resulted a lifetime about an order of magnitude greater than the lifetime of free Λ, 200 ps. The cross section for the delayed electro-fission was measured to be $(6.5 \pm 1.0)10^{-33}$ cm^2 and the delayed-to-prompt fission cross-section ratio was $(2.5 \pm 1.0)10^{-5}$. Measurement at electron energy of 0.7 GeV revealed no delayed fission. It was considered to be the evidence, which suggests that the delayed fission observed at 1.2 GeV should be associated with hypernuclear decay, except the puzzles from measured long lifetime and an order of magnitude smaller cross section than expected from theoretical estimations [2].

Kharkov group then made repeated measurements [3] using the same recoil-distance technique but with improved spatial distribution detection and resolution in order to make experimental setup sensitive to the lifetime in the range of 200 ps. The obtained range distribution of fissile nuclei was expressed as a sum of two exponential distributions with two mean ranges: L_1 = (0.07 ± 0.02) mm and L_2 = (1.4 ± .5) mm. As a result, two half-lives of Bi hypernuclei with the mean lifetimes $(0.8 \pm .15)10^{-10}$ s and $(1.5 \pm 0.4)10^{-9}$ s were revealed. Neither of the extracted long and short lifetimes was close to the free Λ lifetime (see in attached table).

3. CERN experiment

Such delayed fissions were investigated at CERN using cooled antiprotons beam with beam momentum of 100 MeV/c [4]. The annihilation of antiprotons in the target is accompanied by K^+K^-

- pair emission. The secondary interaction of the K+N = Λ+π inside the nucleus may produce a trapped Λ hyperon, thus produce a hypernucleus. The experimental set-up at CERN was similar to that used in the Kharkov experiment, except that instead of mica detectors, position-sensitive parallel-plate avalanche counters were employed. This allowed registration of two fragments in coincidence, information on their ionizing power, time-of-flight and folding angle. It provided reliable selection and resolution for the delayed fission events with the range of recoil nuclei shorter than 0.5 mm. The long-lived component found at Kharkov could not be observed at CERN. However, the errors for τ_Λ in the measurements from CERN [4] were so large (see in attached table), so that no severe constraints can be imposed on the various theoretical models for the nonmesonic decay.

4. Julich experiment

A novel approach to produce heavy hypernuclei for lifetime measurements using proton collisions on heavy targets like U, Bi or Au [5-12] was applied by the COSY-13 Collaboration. The same fission process and experimental technique (LPMWPC) as that applied in our proposed JLab E99-003 were used. Since the beam time structure does not allow a direct measurement, the same recoil shadow method was used. Fragments reached the shadow region were translated into lifetime by using a theoretical model that gives the momentum distribution of hypernuclei and assumed that every event was from the hypernuclear decay. The transport approach was employed and provided information on i) the formation cross section of 'hot' hypernuclei as well as on ii) the properties of the hypernuclei produced, i.e. primary mass, charge, excitation energy, linear momentum, angular momentum etc., in a given reaction. The latter information then is used to evaluate for each event the subsequent statistical decay as well as the probability of a heavy hypernucleus to survive in competition with prompt fission. Thus, the final distribution in terms of mass and charge of the 'cold' hypernuclei was evaluated together with their individual (A and Z dependent) velocity distribution in the laboratory frame. The final charges and masses of 'cold' hypernuclei were correlated to form a valley of stability. The resulting two-dimensional spectra of charge Z and mass A of cold hypernuclei are shown in fig.3 from ref. [12]. It must be pointed out that although the distribution in mass differ by only about 10 to 30 nucleon mass units for different targets, they have some common overlap region in the tails. Furthermore, the Λ induced fission probability essentially depends on the fissility parameter Z^2 /A and only a fraction of the (A, Z) distributions of hypernuclei created in the p + A interactions lead to actual delayed fission events, i.e. essentially for Z^2 /A $\geq$ 34. Due to the rather large dispersion in the (A, Z) distribution of cold hypernuclei the observation of delayed fission of these nuclei does not give an information on the lifetime of specific heavy hypernuclei, i.e. with fixed atomic number Z and mass A, but it rather provides a lifetime averaged over a group of different hypernuclei. When averaging over the experimental results for all targets one thus obtains a value for τ_Λ that corresponds to an average over all nuclei with mass A $\geq$ 180.

Kaons were not identified due to low yield, thus a hypernuclear production was not positively identified. The Λ production was verified only by using two different beam energies, below and above Λ production threshold. In the lower energy case, no significant delayed fission events were seen.

The lifetimes were extracted by comparing the experimental distributions to the simulated distributions given by an assuming the velocity distribution of the hypernuclei obtained from theoretical calculations. The lifetime of the Λ - hypernuclei was treated as a free parameter in the fitting procedure. Thus they were model dependent. Since the number of events in the position distributions was not large in some measurements, a Poisson instead of Gaussian probability distribution was used. The best lifetime τ_Λ was searched by the 'maximum likelihood' method, which allows an estimate of the statistical error for τ_Λ.

In such measurement, the systematic errors arise from:

a.) the velocity distribution of hypernuclei;
b.) unisotropic emission of fission fragments;
c.) nonuniform irradiation of the target by the proton beam and beam halos;
d.) change of position and shape of targets during the measurements;
e.) background treatment in case of low statistics, and
f.) search procedure (χ^2 or maximum likelihood methods) for the best lifetime.

Detailed simulations have been carried out to determine the variation in the lifetime τ_Λ according to the error sources listed above. The lifetimes were reported to be: 130 ± 13 (stat) ± 15 (syst); 161 ± 7 (stat) ± 14 (syst); 138 ± 6 (stst) ± 17 (syst) ps for Au, Bi and U targets, respectively [6,10,11]. However, we would like mention that different search procedure result different best τ_Λ values (see results for U target in the table). Another important ingredient for the data analysis was the velocity distribution of the hypernuclei in the laboratory. It was mainly determined by the nucleon-nucleon and hyperon-nucleon cross section in the initial stage of the reaction as modeled by the transport approach. Although it was shown in comparison to independent experimental data that the momentum transfer to the residual nucleus is well described by the transport approach in p + U reactions for T_{lab} = 0.5 – 3 GeV, however, there are no experimental data to test transport approach parameters and predictions in the case of residual hypernuclei.

5. Comparison with electron induced reactions

COSY result for bismuth target is about two times greater than Kharkov's short-range component. In both cases the reported errors were small, which indicates the importance of the direct measurements, free from model dependent interpretations. The Kharkov's long-range component has not been observed by other experiments. The recoil range distributions (see Fig.6, 7 and 5 from [12]) in the position interval between 20-35 mm are approximately constant, while the theoretical distributions with a 161 ps lifetime changes about order of magnitude.

Comparison with antiproton induced reactions

COSY result for bismuth and uranium targets is within the statistical error limits in agreement with the lifetimes extracted from antiproton experiments [4](see Table).

Comparison with recent theoretical predictions

Over the past several years, several theory groups (e.g., the Barcelona group under A. Ramos et al. and the Tokyo group under M. Oka et al.) have come to the conclusion that in a field-theory based meson-exchange description of the $\Lambda N \rightarrow NN$ process, kaon exchange must be included along with the dominant pion exchange and some unknown contact terms which could be modeled through vector mesons or direct quark exchange [13,14]. The ratio Γ_n/Γ_p in light hypernuclei (A=5-16) turns out to be the crucial observable: values of Γ_n/Γ_p around 0.5 or less can be accommodated by a pion plus kaon exchange description that obeys the ΔI=½ rule. However, should Γ_n/Γ_p be around 1.0 or larger (as suggested by current measurements with very large error bars) the $\Lambda N \rightarrow NN$ reaction would be dominated by ΔI=½ rule violating contact terms of unknown nature.

Recently, results of a new evaluation of the decay rates for medium to heavy Λ-hypernuclei based on the Propagator Method were reported in ref.[15]. The parameters of the model were adjusted to reproduce the nonmesonic width of $^{12}{}_{\Lambda}C$ hypernuclei. It was assumed that the $\Delta I = ½$ rule is valid. Then the decay rates for heavier hypernuclei have been predicted. The obtained total width is nearly constant with A, and reproduce experimental lifetimes, measured directly at BNL and KEK up to $^{56}{}_{\Lambda}Fe$ (see Fig.1 from ref.[15]). The predicted lifetime for $A \approx 200$ by this theory is about 188 ps that is in contradiction with results reported by COSY-13 group. The mass dependence of the Λ-lifetime in hypernuclei may be due several effects:

a.) Pauli blocking;
b.) the variation of the Λ-nucleus potential with mass A;
c.) the variation of the ratio N/Z with the mass of hypernuclei.

In ref. [16] it was shown that the last effect is the most important one, because such a variation can lead to a mass dependence of the Λ-lifetime in hypernuclei only if the ratio of the neutron-induced over the proton-induced decay rates Γ_n/Γ_p deviates from unity. The calculations were performed for several ratios Γ_n/Γ_p while $\Gamma_n+\Gamma_p$ was held constant. $\Gamma_n+\Gamma_p$ was fixed by the requirement that the constructed model has to describe the lifetime data for light hypernuclei, i.e. $^{11}{}_{\Lambda}B$, $^{12}{}_{\Lambda}C$. The lifetimes calculated for hypernuclei for the mass number A = 200 and for the $\Gamma_n/\Gamma_p = 1$ coincide to that one obtained by Propagator Method [15] (see Fig. 9 from Ref.[12]). Taking this into account it has been stated [12], that the lifetimes obtained at Julich by the COSY-13 group would constitute a strong violation of the $\Delta I = ½$ rule in the weak nonmesonic $\Lambda N \rightarrow NN$ process in heavy hypernuclei.

6. Conclusion

The KEK result obtained by direct measurement seems to suggest that the lifetime of Λ hypernuclei has saturated around 200 ps already in the region of $^{28}{}_{\Lambda}Si$. Recently performed calculations [13,14] nicely reproduce this behavior if $\Delta I=1/2$ rule in the weak nonmesonic $\Lambda N = NN$ process is assumed valid. Simulations performed in the Ref. 14 shows that the mass dependence of the Λ-lifetime in hypernuclei is sensitive to the ratio Γ_n/Γ_p. Thus, a precise knowledge of the lifetimes of light and heavy hypernuclei can be used to determine the $\Gamma_n + \Gamma_p$, as well as the ratio Γ_n/Γ_p.

The CERN result within the statistical error limits is in agreement with the lifetimes extracted from proton experiments. The COSY-13 result is slightly smaller than that expected from the saturation behavior observed at KEK and in contradiction with theoretical predictions if assume that $\Delta I = 1/2$ rule is valid.

Nowadays, the main problem concerning the weak nonmesonic decay rates is to carry out precise and direct measurements of $\Gamma_n + \Gamma_p$ (lifetime) and Γ_n and/or Γ_p.

The experiment E99-003 can carry out such task with minimum effort and excellent accuracy. As a byproduct we will test the ability of low-pressure technique to detect fission fragments as well as alpha particles in the real experimental conditions and check the possibility of investigating weak nonmesonic decays of $^{10}{}_{\Lambda}Be$ hypernucleus produced in $^{10}B(e,e'K^+)$ reaction at CEBAF. As shown recently [15,16] this will allow to carry out an accurate and direct measurement of Γ_n.

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Table. The lifetime of heavy hypernuclei measured with electron, antiproton ant proton beams.

Target and projectile	τ_{Λ} / ps	Ref. Comment
Bi + e	2700 ± 500	[2]
Bi + e	1500 ± 400 80 ± 15	[3] new measurement with an essentially improved spatial distribution
Bi + antiproton	180 ± 40 (stat) ± 60 (sys)	[4]
U + antiproton	130 ± 30 (stat) ± 30 (sys)	[4]
U + proton	240 ± 60	[5] low statistics, Gaussian distribution in the number of events, χ^2 fit
U + proton	194 ± 55	[10]reanalysis of data from [5], Poisson distribution in the number of events, maximum likelihood method
U + proton	239 ± 26	[7] moderate statistics, several targets, Gaussian distribution in the number of events, χ^2 fit
U + proton	218 ± 35	[10]reanalysis of the data from [7], Poisson distribution in the number of events, maximum likelihood method
U + proton	152 ± 10 (stat) ± 25 (syst)	[8] moderate statistics, large background, Poisson distribution in the number of events, maximum likelihood method
U + proton	138 ± 6 (stat) ± 17 (syst)	[10] good statistics, Poisson distribution in the number of events, maximum likelihood method
Bi + proton	145 ± 7 (stat) ± 23 (sys)	[5]
Bi + proton	161 ± 7 (stat) ± 14 (sys)	[6] reanalysis of data from [5]
Au + proton	130 ± 13 (stat) ± 15 (syst)	[11]

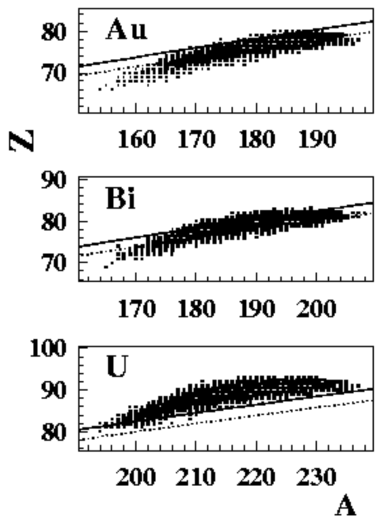

FIG. 3: Two dimensional spectra from CBUU + evaporation calculations in charge Z and mass A of hypernuclei for p + ^{197}Au at T$_p$=1.7 GeV, p + ^{209}Bi at T$_p$=1.9 GeV and p + ^{238}U at T$_p$=1.9 GeV. The solid and dashed lines indicate hypernuclei of fissility $Z^2/A = 34$ and 32, respectively. Delayed fission events essentially stem from nuclei with fissility parameter $Z^2/A \geq 34$.

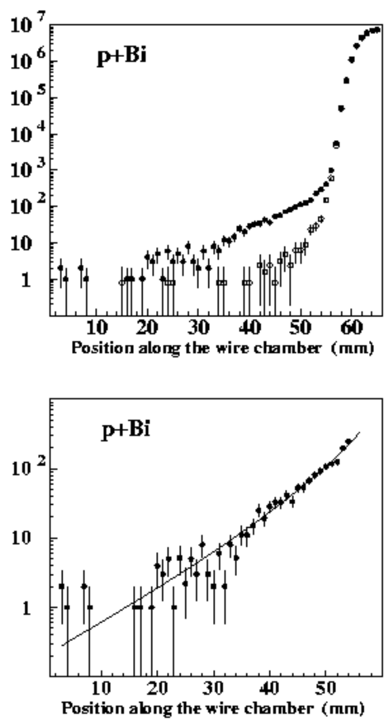

FIG. 6: The same distributions as in Fig. 5 for the $p+Bi$ experiment (from ref. [25]).

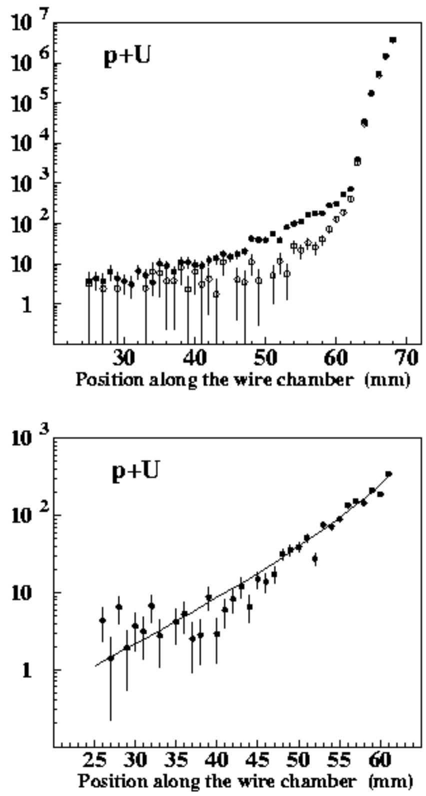

FIG. 7: The same distributions as in Fig. 5 for the $p + U$ experiment (taken from ref. [39]).

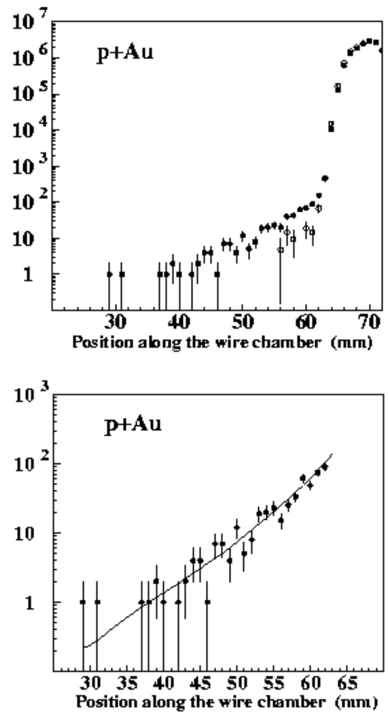

FIG. 5: Upper part: The position distribution of hits of fission fragments in the position sensitive detectors for the $p + Au$ experiment (from ref. [38]). The full dots represent the data for T_p=1.9 GeV whereas the open circles show the data for T_p=1.0 GeV renormalized in the bright part of the detectors to the 1.9 GeV data. Lower part: The position distribution of hits from the delayed fission fragments of hypernuclei in the shadow region obtained by subtracting the background (renormalized data taken at 1.0 GeV) from the data measured at 1.9 GeV. The solid line shows the result of the simulation with the extracted value for the lifetime according to the maximum likelihood method.

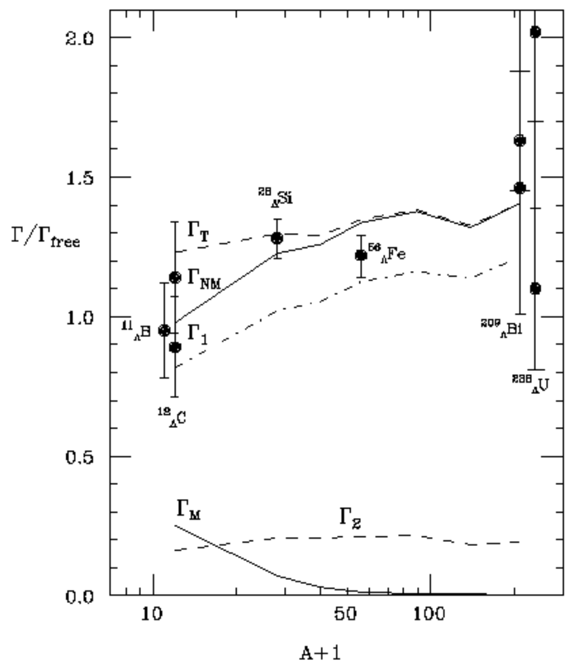

Figure 1. Λ decay widths in finite nuclei as a function of the mass number A.

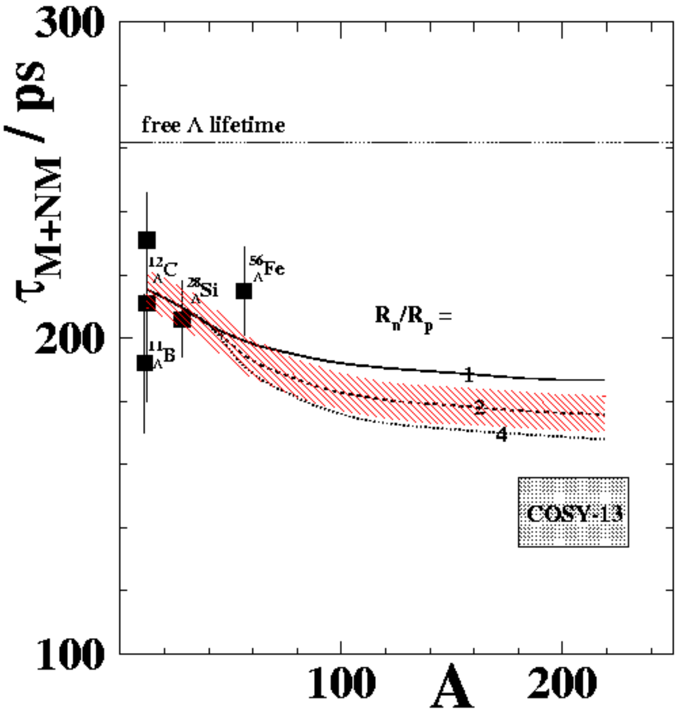

FIG. 9: Calculations of the Λ-lifetime τ_{M+NM} due to the mesonic and nonmesonic decay as a function of the hypernucleus mass A in the valley of stability (from ref. [15]) in comparison to the data of Refs. [17, 21]. The COSY–13 collaboration result for nuclei with masses $A \geq 180$ is marked by the hatched area labelled "COSY–13". Width and height of this rectangle represent the range of hypernucleus masses involved and the error of the lifetime determination, respectively. In the theoretical calculations both mesonic and non-mesonic decay modes are taken into account whereas the unknown ratio of the weak decay rates R_n/R_p is treated as a parameter with values: $R_n/R_p = 1,2,4$. The hatched area around the dashed line (corresponding to R_n/R_p=2) shows the $\pm\sigma$ uncertainty in the magnitude of the weak transition $\sim (R_n + R_p)$ determined from the lifetimes of light hypernuclei with A≈ 12.