EXPERIMENTAL PROPOSAL FOR GSI-SIS

STUDY OF DEEPLY BOUND PIONIC 1s STATES IN Sn ISOTOPES

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Abstract: We propose to measure the binding energies and the widths of the deeply bound pionic $1s$ states in in various Sn isotopes in high resolution studies of the (d,^{3}He) transfer reaction. Due to the dominant population of substitutional configurations $(1s)_\pi \times (s_{1/2})_n^{-1}$ both quantities can be deduced in a model independent way. Their isotope dependence is expected to provide information on the unknown local isovector part of the pion-nucleus interaction. In a first experiment we plan to irradiate the isotopes ^{116,120,124}Sn. Based on the experience from previous experiments and on theoretical simulations we request a deuteron beam time of 71 shifts at $T_d = 250$ MeV/u with a high intensity $\geq 2 \times 10^{11}$/s and best possible beam quality ($\delta p/p \leq 2 \times 10^{-4}$) to measure the excitation energy spectra with an accuracy high enough to deduce the isotope shift of the $1s$ binding energy.

1. PHYSICS MOTIVATION

The present proposal is a continuation of the successful S160 experiment studying deeply-bound states in pionic atoms. The goals of the new experiment are:

1. unambiguous determination of the binding energy and width of the $1s$ state of pionic Sn using the recoilless population of the substitutional $(1s)_\pi \otimes (s_{1/2})_n^{-1}$ states, and

2. study of isospin dependence of the local part of the pion-nucleus optical potential in a wide range of $N - Z$.

1.1 Sensitivity of deeply-bound π^- states to the pion-nucleus optical potential

In 1996, the S160 collaboration discovered the deeply bound π^- states in lead ($\pi^- \otimes {}^{207}$Pb) in the ^{208}Pb(d,^{3}He) reaction[1, 2, 3]. As shown in Fig. 1(top), a distinct peak of the $(2p)_\pi \otimes (p_{3/2})_n^{-1}$ configuration (*i.e.* the pionic 2p state coupled to the $p_{3/2}$ neutron hole states) was observed at about 135 MeV excitation energy above the ^{207}Pb ground state.

Due to the large overlap of the pion wavefunction with the core nucleus, the binding energies and widths of such deeply-bound pionic states are very sensitive to the *local* part of the pion-nucleus optical potential. This was demonstrated in our recent publication[3], in which we showed that our ^{207}Pb result can set stringent constraints on models of the pion-nucleus interaction (see Fig. 2). Precise determination of the local part of the pion-nucleus optical potential leads, in turn, to the determination of the effective pion mass in nuclear matter, as has been discussed by several authors already [4, 5, 6].

Clearly, even more stringent constraints can be obtained from the measurement of the binding energy and width of the $1s$ pionic state, due to the larger pion-nucleus overlap. In our first experiment, this was not possible because the $1s$ state was not clearly separated from the $2p$ peak (see Fig. 1(top)), mostly due to the existence of a "shoulder" at $E_{ex} \sim 134$ MeV, which has a $(2p)_\pi \otimes (p_{1/2})_n^{-1}$ configuration. Depending on the assumed $(1s)_\pi/(2p)_\pi$ intensity ratio, the $1s$ binding energy B_{1s}

and width Γ_{1s} could be deduced only with large uncertainties as $B_{1s} \sim 6.7-7.0$MeV and $\Gamma_{1s} \sim 0.4 - 1.1$MeV.

In 1998, we therefore performed a new experiment using a ^{206}Pb target [7]; theory confirmed the expectation based on simple shell model systematics that the 'shoulder' should be eliminated in the ^{206}Pb(d,^{3}He) reaction (^{206}Pb $\approx$ ^{208}Pb $-$ two $p_{1/2}$ neutrons), hence the pionic $1s$ peak would be observed more clearly.

This was indeed the case, as shown in Fig. 1(bottom). A clearly separated peak of $(1s)_\pi$ was observed at $E_{ex} \sim 133$ MeV above the ^{205}Pb ground state. From this result, we expect a large step in improving the accuracy to $\Delta B_{1s} \simeq \pm 0.13$ MeV.

The instrumental precision would be even much better, since the statistical and systematic errors are as small as 0.04 MeV and 0.03 MeV, respectively. There are however uncertainties in the determination of B_{1s} and Γ_{1s} related to the neutron hole spectrum of ^{205}Pb: The $(1s)_\pi$ peak in ^{205}Pb is of non-substitutional character and composed of two substates, $(1s)_\pi \otimes (f_{5/2})_n^{-1}$ and $(1s)_\pi \otimes (p_{3/2})_n^{-1}$, which are separated by only 260 keV and experimentally not resolved. Their relative strength can thus not be determined in the experiment and model based assumptions have to be used. Depending on the relative weight of these two substates in the decomposition of the $(1s)_\pi$ peak the deduced B_{1s} varies within the uncertainty given above.

1.2 Substitutional $1s$ states in Sn isotopes

As previously discussed each pionic state populated in the (d,^{3}He) reaction in general couples to several possible neutron hole excitations of the core nucleus which makes the interpretation of the measured excitation spectrum more complicated. In special cases, however, substitutional configurations, in which both the created π^- and the removed neutron have the same angular momentum, are dominantly populated. The enhancement of these substitutional states is most effective for $\vec{L} = \vec{l_\pi} + \vec{l_n} = 0$ in recoilfree kinematics. This has clearly been demonstrated in case of pionic Pb for the $(2p)_\pi$ state which is dominantly populated in the substitutional configurations with neutron hole states of $p_{3/2}$ and $p_{1/2}$ (for ^{207}Pb) and of $p_{3/2}$ (for ^{205}Pb). To obtain similar conditions for the pionic $1s$ state allowing to deduce its binding energy and width in a model independent way, nuclei with low-lying $s_{1/2}$ neutron states with good single particle properties should be chosen as targets for the (d,^{3}He) reaction, and the incident d energy should be carefully tuned to the condition of zero momentum transfer. Theoretical studies by Umemoto *et al.* [8] suggest that these requirements can be fullfilled with Xe and Sn targets and a deuteron incident energy of 250 MeV/u.

Since Xe targets would be difficult to be used in a high resolution experiment at the FRS, we propose to study the (d,^{3}He) reaction on Sn targets at $T_d = 250$ MeV/u. As shown in Fig. 3 this energy is very close to the 'magic' energy where the momentum transfer vanishes. Fig. 4 shows the predicted [8] energy dependence of the population of the $(1s)_\pi \otimes (s_{1/2})_n^{-1}$ and the $(1s)_\pi \otimes (d_{5/2})_n^{-1}$ state indicating that $T_d = 250$ MeV/u is a best choice in terms of the yield for the substitutional configuration $(1s)_\pi \otimes (s_{1/2})_n^{-1}$ and for the $(s_{1/2})_n^{-1}/(d_{5/2})_n^{-1}$ ratio. Note that we chose a higher incident energy ($T_d = 300$ MeV/u) in the previous experiments resulting in a small but finite momentum transfer in order to provide sufficient cross section to populate both the $(2p)_\pi$ and the $(1s)_\pi$ state (and to allow direct comparison of the

^{207}Pb and ^{205}Pb results) whereas in the new experiment we want to focus on the almost exclusive population of the $1s$ state in the substitutional configuration.

Umemoto *et al.* [9] calculated excitation energy spectra for the (d,^{3}He) reaction on a whole range of stable Sn targets (^{112}Sn through ^{124}Sn) at $T_d = 250$ MeV/u. They find that almost pure $(1s)_\pi \otimes (s_{1/2})_n^{-1}$ peaks are expected for $^{116-124}$Sn allowing the model independent determination of B_{1s} and Γ_{1s}, while admixtures of other neutron hole states are more difficult to be resolved for ^{112}Sn and ^{114}Sn targets. The theoretical energy spectra were folded with a 300 keV (fwhm) Gaussian for the instrumental resolution which we expect to achieve as discussed in section 2. Based on the prediction, we will be able to clearly identify the $1s$ peak located at about 4 MeV below the free π^- production threshold, while contributions from higher pionic states are small compared to the $1s$ state.

1.3 The $(1s)_\pi$ isotope shift

Sn forms a long chain of stable isotopes, allowing the possibility to measure for the first time the isotope shift of deeply bound pionic states. We propose to measure this isotope shift by comparing the pionic excitation spectra in the irradiation of ^{116}Sn, ^{120}Sn, and ^{124}Sn targets. While the comparison of two isotopes would already allow to deduce an isotope shift, we consider it important to compare at least three isotopes, in order to have a consistency check of the systematic behaviour and first data on its A dependence. The remaining Sn isotopes including the more complicated cases ^{112}Sn and ^{114}Sn are candidates for future studies.

We now briefly discuss the importance to measure the isotope shift of deeply bound pionic states. It is known that the local part of the pion-nucleus optical potential can be decomposed into two parts, an isoscalar and an isovector part. In the Ericson-Ericson formulation, the local potential can be written as

$$V(r) = -\frac{2\pi}{\mu}[\epsilon_1 b_0 \rho(r) + b_1(\rho_n(r) - \rho_p(r)) + \epsilon_2 Re B_0 \rho^2(r)]$$

where $\epsilon_1 \equiv 1 + \mu/M$, $\epsilon_2 \equiv 1 + \mu/2M$, and μ being the pion mass and M being the nucleon mass. The sensitivity of deeply bound pionic states to the isovector part, in particular to the neutron skin, was theoretically studied by Toki *et al.* [10].

So far in the analysis of the Pb results a separate determination of the $b_0(\rho_n + \rho_p)$ (isoscalar) and the $b_1(\rho_n - \rho_p)$ (isovector) part was not possible, and we concentrated on the b_0 part assuming the model parameter values for b_1. In the present proposal, by comparing the B_{1s} for Sn isotopes, we gain direct access to the isoscalar and isovector part of the pion-nucleus potential. Further insight is expected from the comparison of the binding energies in Sn and Pb since their N/Z ratios are very different.

The isovector part of the pion-nucleus potential is particularly interesting because the πN scattering length and the pion decay constant f_π are directly related according to the low energy theorem of Tomozawa and Weinberg [11]

$$T_{\pi^- p}(\omega, \vec{q} = 0) = -T_{\pi^- n}(\omega, \vec{q} = 0) = \frac{\omega}{2 f_\pi^2} + \mathcal{O}(\omega^2, m_\pi^2).$$

The pion decay constant is the fundamental order parameter of spontaneous chiral symmetry breaking of QCD, and its medium dependence could indicate partial restoration of chiral symmetry at finite density.

The predicted [9] $1s$ and $2p$ pionic binding energies and widths in Sn isotopes are given in Table 1. The prediction shows that the instrumental precision, taking a statistical uncertainty of 0.03 MeV for the *relative* uncertainty of the binding energies, is expected to be sufficient to allow a determination of the pionic isotope shift.

Predicted isotope shifts for Sn isotopes				
target nucleus	B_{1s}	Γ_{1s}	B_{2p}	Γ_{2p}
^{112}Sn	3997.8	424	2293.9	130
^{114}Sn	3953.1	398	2287.2	124
^{116}Sn	3910.5	374	2280.6	120
^{118}Sn	3871.7	355	2274.7	116
^{120}Sn	3836.7	338	2269.2	114
^{122}Sn	3803.4	325	2264.3	113
^{124}Sn	3773.5	309	2258.7	112

Table 1: Predicted [8] values of the pionic binding energies and widths B_{1s}, Γ_{1s}, B_{2p} and Γ_{2p} for various Sn isotopes as targets for the (d,^{3}He) reaction populating the pionic states $\pi^- \otimes {}^{A-1}$Sn. All values are given in keV.

2. EXPERIMENTAL CONDITIONS

Fig. 6 shows the experimental setup at the FRS. The setup is almost identical to that of the previous experiments of the S160 collaboration. The targets are 1.5 mm strip 20 mg/cm^2 thick ^{116}Sn, ^{120}Sn and ^{124}Sn. The first part of the FRS will be used as a spectrometer to analyze the ^{3}He momentum with a dispersion of about 6,500 mm. At the dispersive central focal plane F2, we will install two sets of drift chambers (DC1 and DC2) with high rate capability to reconstruct the particle tracks and measure the ^{3}He momentum. The second part of the FRS will be used as a 36 meter beam transfer line to provide a flight path long enough for the particle identification. We will install one segmented scintillation counter at F2 (SC1) and two scintillation counters at F4 (SC2 and SC3). The scintillation detector at F2 simultaneously serves as degrader of $\sim$1 g/cm^2 thickness and allows to suppress the intense proton rate from deuteron breakup due to the different energy loss. Fig. 7 shows a two dimensional plot of the time of flight between F2 and F4 vs. the energy loss in the scintillation counter at F4 in the previous S160 experiment. Perfect particle identification will be achieved also in the proposed experiment.

The energy resolution of the experiment is estimated to be 300 keV (FWHM). Its main contributions are due to the momentum spread of the incident deuteron beam assumed to be $\delta p/p = 2 \times 10^{-4}$ (0.18 MeV), the energy loss difference of the incident beam and the outgoing ^{3}He in the target (0.21 MeV), the target width (0.10 MeV) and the detector resolution (0.06 MeV). The beam momentum spread can possibly be further reduced by using the SIS cooling at the expense of increased cycle time, while filling the SIS ring not too far below the space charge limit. The

SIS machine group is encouraged to explore this possibility which would allow further improvements of the instrumental resolution. The SIS machine group is also encouraged to explore the conditions for an increase of the beam intensity compared to the previous experiments.

For the momentum calibration of the spectrometer, we will use a polyethylene target $(CH_2)_n$ as a proton target. In the limited solid angle of the FRS, the emitted ^{3}He nuclei from the two body reaction of $p(d, ^3\mathrm{He})\pi^0$ are almost mono-energetic and will form a narrow peak in their momentum spectrum. This peak will also be used to correct for the drift of the whole system during the beam time. The dispersion of the spectrometer will be measured by using at least three different incident beam energies and measuring the tracks of the attenuated beam at the dispersive focal plane F2. The acceptance function of the FRS also has to be known precisely; it will be measured by producing a flat momentum/charge spectrum with fragmentation of a heavier projectile in a thick target (in the previous S160 experiment fragmentation of ^{12}C was used).

The parameters of the proposed experiment are compared with those of previous experiments of the S160 collaboration in Table 2.

Comparison of experimental conditions			
	Apr. 96	Nov. 98	Proposed
Target material	^{208}Pb	^{206}Pb	^{116,120,124}Sn
Target thickness	45 mg/cm^2	25 mg/cm^2	20 mg/cm^2
Target width	2 mm	1.5 mm	1.5 mm
Drift chamber position resolution	0.3 mm	0.3 mm	0.3 mm
Magnification (Target - F2)	1.2	1.2	1.2
Beam	deuteron	deuteron	deuteron
Beam energy	300 MeV/u	300 MeV/u	250 MeV/u
Beam intensity	1.0×10^{11}/sec	2.0×10^{11}/sec	2.0×10^{11}/sec
Beam momentum spread	3.5×10^{-4}	2×10^{-4}	2×10^{-4}
Experimental resolution	480 keV	300 keV	300 keV
Total number of ^{3}He events	69000	95000	—

Table 2: Comparison of the experimental conditions of the proposed experiment with previous experiments of the S160 collaboration.

3. BEAM TIME REQUEST

Since the experimental conditions are very similar to those of the previous S160 experiment, we can estimate the required beam time on a solid basis. The theoretically estimated $1s$ peak cross section with ^{116}Sn target ($\sim 35\mu$b/sr/MeV) is about 2/3 of that of the $2p$ peak of the S160 experiment studying pionic Pb ($\sim 55\mu$b/sr/MeV), and the cross section with the ^{124}Sn target ($\sim 55\mu$b/sr/MeV) is about the same. The total *live* time spent in the second S160 experiment was 240 hours i.e. 30 shifts. The target thickness becomes 20 mg/cm^2 instead of 25 mg/cm^2 to keep the same energy resolution with smaller incident beam energy. However the number of atoms per unit volume increases by factor of about $208/124 \simeq 1.7$. In or-

Beam time request					
	S160		Proposed experiment		
	Apr. 96	Nov. 98	—		
Target [d in mg/cm^2]	^{208}Pb [50]	^{206}Pb [25]	^{116}Sn [20]	^{120}Sn [20]	^{124}Sn [20]
Estimated cross section [$\frac{\mu b}{sr \cdot MeV}$]	55	55	35	50	55
Shake down	5	5		5	
Calibration	3	6	6	4	4
Production	14	30	22	16	14
Total (shifts)	22	41		71	

Table 3: Requested beamtime in comparison to the previous S160 experiments.

der to clearly observe the separated $1s$ peak with each isotope, we should have a similar amount of ^{3}He as observed in the previous S160 experiment. Thus the required shifts for production runs will be $30 \times 55/35 \times 20/25 \times 1/1.7 \sim 22$ shifts for the ^{116}Sn target, $30 \times 55/50 \times 20/25 \times 1/1.7 \sim 16$ shifts for the ^{120}Sn target and $30 \times 1 \times 20/25 \times 1/1.7 \sim 14$ shifts for the ^{124}Sn target. We need $6 + 4 + 4 = 14$ shifts for the calibration of the whole system and additional 5 shifts to achieve the smallest possible momentum spread as well as an optimum and stable overlap of the beam with the strip target, and to determine higher order aberrations of the beam optics at the FRS. This adds up to 71 shifts as shown in Table 3. This request does *not* include commisioning time to study the operation of the SIS cooling system.

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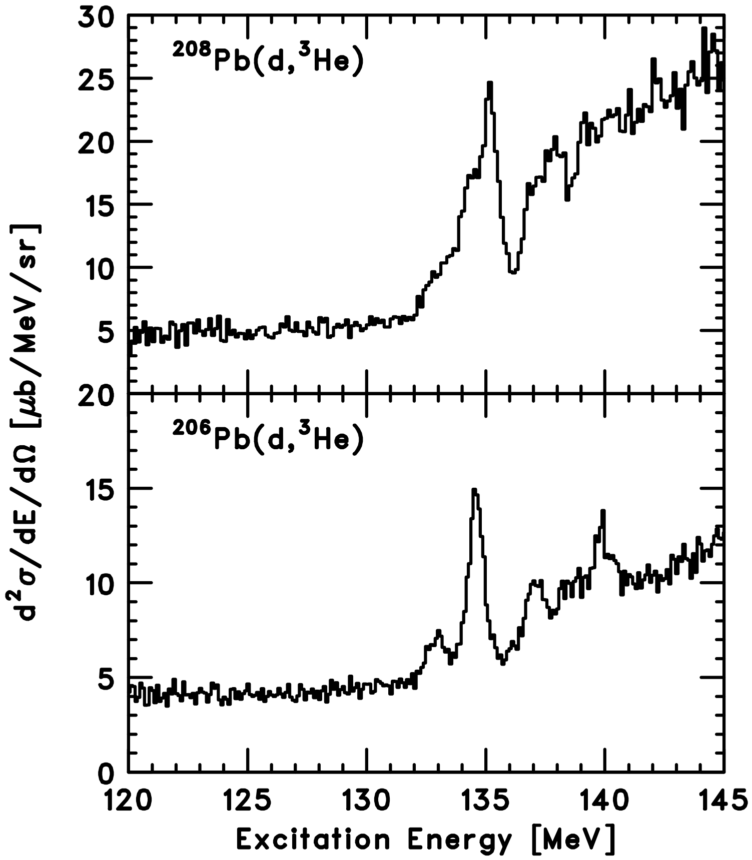

Figure 1: The measured excitation energy spectra in the first (upper) and the second (lower) experiment of S160 with respect to the ^{207}Pb and ^{205}Pb ground states, respectively.

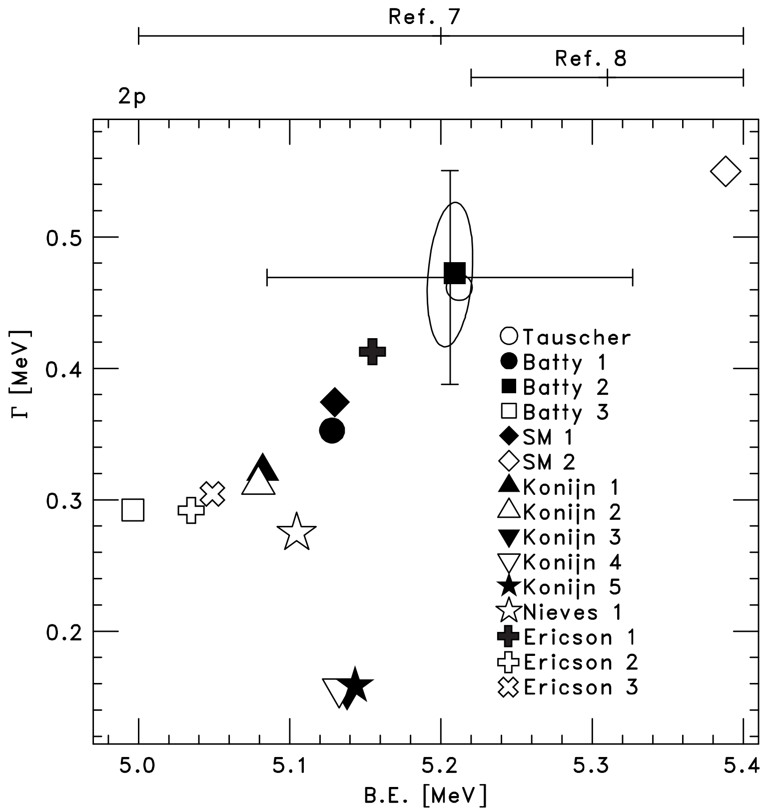

Figure 2: A comparison of the obtained B_{2p} and Γ_{2p} with the existing theoretical values. The solid ellipse shows the statistical error (1-σ) and the bars show the systematic errors.

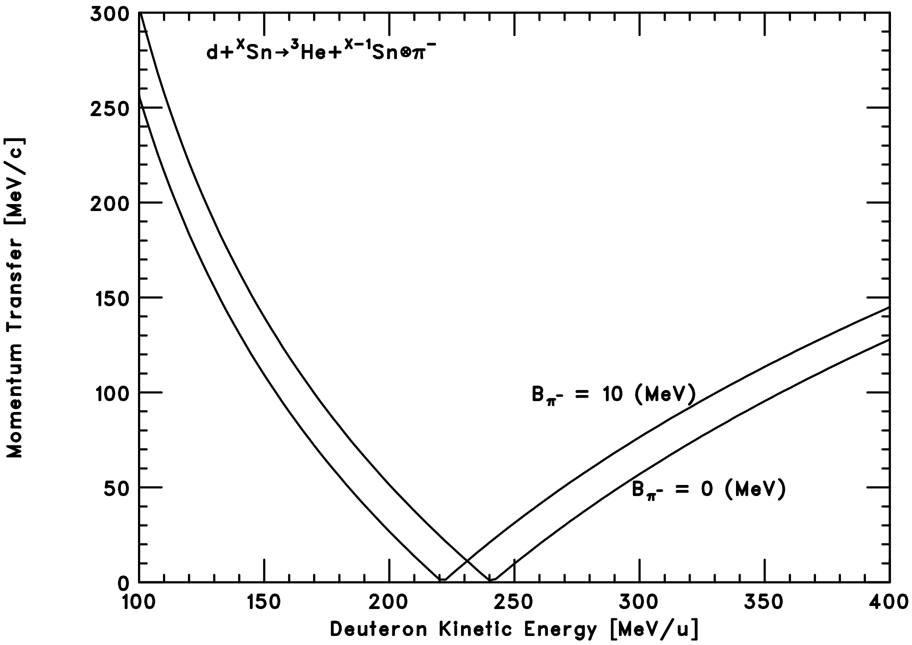

Figure 3: Momentum transfer of the (d,^{3}He) reactions vs. the incident deuteron beam energy.

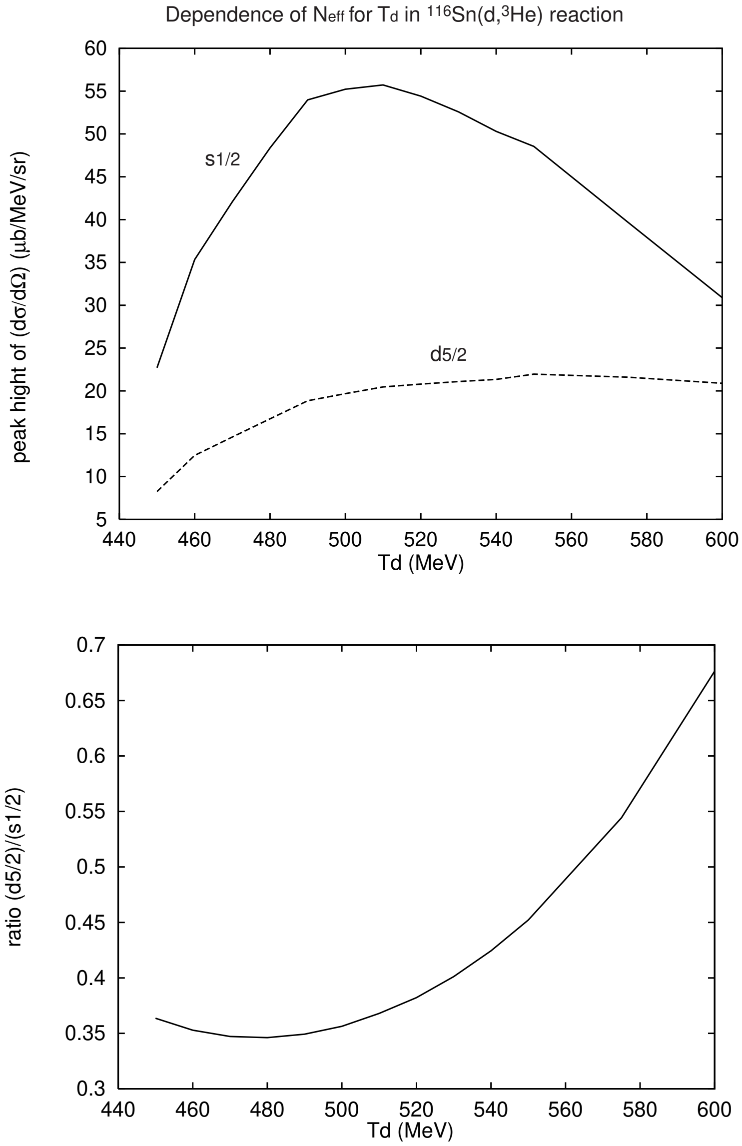

Figure 4: Predicted [8] beam energy dependence of the population of the pionic 1s state in the ^{116}Sn(d,^{3}He) reaction. The upper part shows the contribution of the dominant neutron hole states $s_{1/2}$ and $d_{5/2}$ (maximum cross section of the respective peaks *not* including the instrumental width), and the lower part their ratio. $T_d =$ 500 MeV is the optimum energy both for the absolute and the relative strength of the substitutional configuration $(1s)_\pi \otimes (s_{1/2})_n^{-1}$.

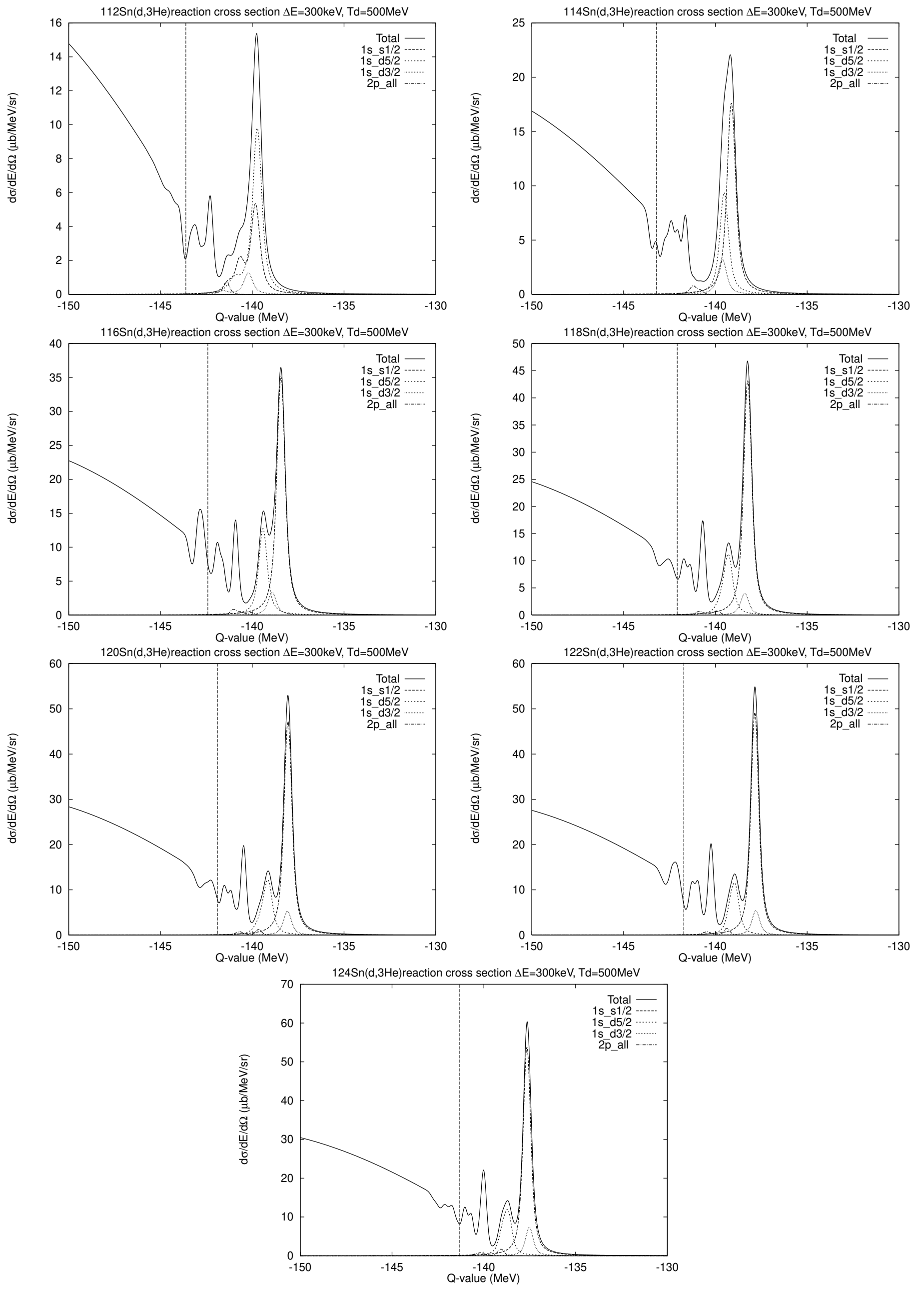

Figure 5: Calculated [9] Q value spectra for the $^{112-124}$Sn(d,^{3}He) reaction at T_d = 250 MeV/u. An experimental resolution of 300 keV (FWHM) was assumed. The Q value is related to the excitation energy E_{ex} above the $^{A-1}$Sn ground state by $E_{ex} = \Delta E_0 - Q$, where $\Delta E_0 \simeq$ few MeV is given by the mass differences of the nuclear ground states involved.

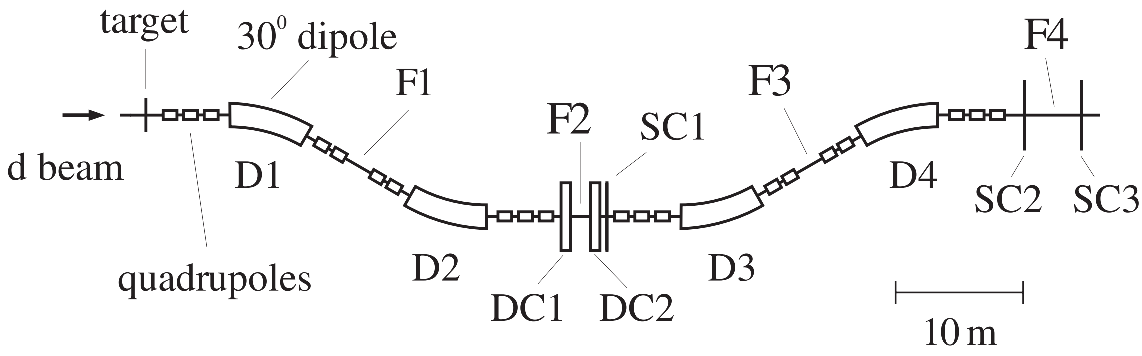

Figure 6: The proposed experimental setup at the GSI Fragment Separator.

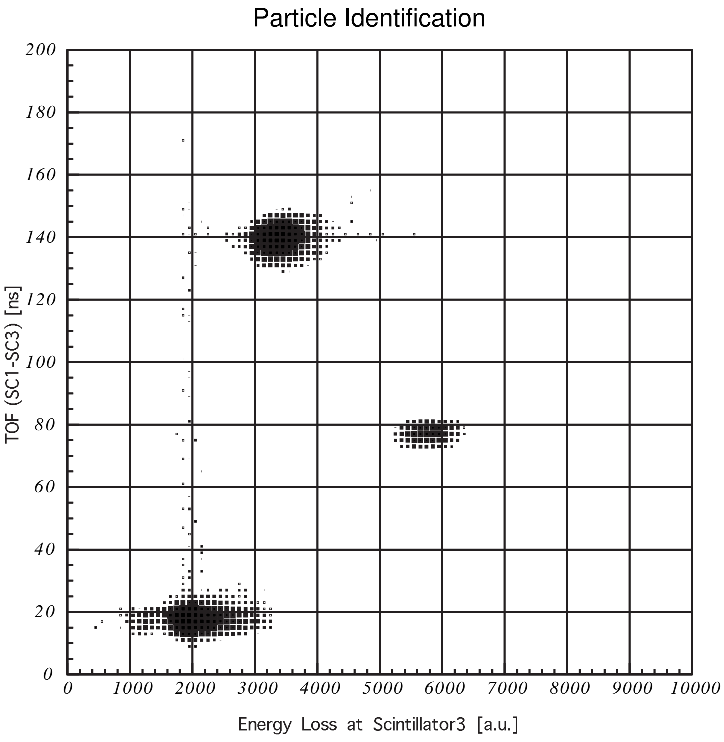

Figure 7: The measured time of flight between the focal planes F2 and F4 vs the energy loss in the scintillation counter at F4 in the previous S160 experiment.