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EXPERIMENTAL PROPOSAL FOR GSI-SIS

SEARCH FOR DEEPLY BOUND PIONIC STATES BY USING ^{208}Pb(d,^{3}He) REACTIONS

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Summary:

We propose to measure ^{208}Pb (d, ^{3}He) spectra in the $E_x = 130 - 140$ MeV region to search for deeply bound pionic states using a deuteron beam from the GSI-SIS heavy-ion synchrotron. The beam energy to be used is 600 MeV and 1200 MeV. From recent DWIA calculations we expect "quasi-substitutional" states, $(2p)_\pi(3p_{1/2})_n^{-1}$ and $(2p)_\pi(3p_{3/2})_n^{-1}$, to be populated at $T_d = 600$ MeV, while at $T_d = 1200$ MeV the $(1s)_\pi(1i_{13/2})_n^{-1}$ and $(2p)_\pi(1i_{13/2})_n^{-1}$ states will be populated predominantly. We will use the Fragment Separator (FRS) which will serve as a high-resolution spectrometer at 0 degree to achieve a mass resolution better than 0.5 MeV. Based on a simulation we request a beam time of 18 shifts as the first step to identify the "quasi-substitutional" states at $T_d = 600$ MeV with a beam intensity of 5×10^{10} d/sec, and then proceed to further experiments later.

1. INTRODUCTION

Recently Toki and Yamazaki [1] clarified that the pionic atoms in heavy nuclei have narrow discrete levels down to the 1s state due to the halo nature of the Coulomb-assisted bound states and that they can be populated by "pion-transfer" reactions. Those deeply bound pionic states constitute a special family of Gamow-Teller type nuclear resonance states at excitation just below the pion mass. As a series of experimental search for deeply bound pionic states in heavy nuclei [1,2] we propose to study (d,^{3}He) reactions by using the deuteron beam from SIS18 of GSI. A few years ago we proposed experiments of high-resolution spectroscopy using the nuclear reactions of inverse kinematics, namely, d(^{208}Pb,π^{-208}Pb)^{2}He, d(^{208}Pb, π^{-207}Pb)^{3}He, with a cooled beam and an internal target in the ESR [3,4]. While the proposed experiment needs more detailed consideration of beam conditions and experimental arrangements to achieve the required luminosity [5], and is thus to be realized in the future, we consider it urgent to make an exploratory experiment with the ^{208}Pb(d,^{3}He) reaction at medium resolution, since no experimental information is known to date.

Toki *et al.* [6] have studied proton-pick-up reactions such as (n,d) and (d,^{3}He). The diagram and the momentum transfer are presented in Fig.1 and Fig.2, respectively, and the cross sections of the elementary reactions, $p+p \to d+\pi^+$ and $d+p \to t+\pi^+$, are presented in Fig.3. These cross sections can be converted to the ones for $n+n \to d+\pi^-$ and $d+n \to {}^3\mathrm{He}+\pi^-$. The (n,d) and (d,^{3}He) reactions on ^{208}Pb are found to be suitable for the population of the 1s and 2p states with a neutron hole of j_n with configurations of $[(1s)_\pi \cdot j_n^{-1}]J$ and $[(2p)_\pi \cdot j_n^{-1}]J$ when the momentum transfer q matches the required angular momentum transfer, namely, $J \sim qR_o$. When the matching condition is fulfilled, the distortion effect is not too large. In the (n,d) and (d, ^{3}He) reactions the momentum transfer can be tuned by selecting the incident energy. The cross sections were calculated [6] for various pionic states on the low-lying neutron hole states in ^{208}Pb (see Fig.4). The optimum energy for (d,^{3}He) leading to the $(1s)_\pi(i_{13/2})_n^{-1}$ states is 600 MeV/u. On the other hand, at 300 MeV/u, where the momentum transfer is small, special pionic states of "substitutional" configurations, such as $(2p)_\pi(3p)_n^{-1}$, are preferentially populated.

A few years ago, an experiment to measure the ^{208}Pb(n,d) spectrum at excitation energies in the pion-mass region at $T_n = 400$ MeV was carried out at TRIUMF [7], which showed up a large continuum characterized by the quasi-free production of π^- on a smooth background of 300 μb/sr$\cdot$MeV, as shown in Fig.5. In addition, a significant bump below the π^- emission threshold is observed. The integrated cross section over the bound π^- region is about 800 μb/sr, which is comparable with the predicted cross section. The expected spectrum in the bound π^- region is also shown in Fig.5. Thus, this experiment gives the first experimental indication of the formation of deeply bound π^- states, but the statistics and resolution obtainable with the secondary neutron beam were not sufficient to resolve discrete peaks of the deeply-bound π^- states. To obtain further information with sufficient statistics the use of an alternative reaction (d, ^{3}He) is most desirable. The expected spectra including the quasi-free continuum have been calculated by Hirenzaki and Toki [8].

Recently, a test experiment of the ^{208}Pb(d, ^{3}He) reaction was carried out at Saturne [9], where the SPES1 spectrometer system was used to detect ^{3}He particles. Although the ^{3}He particles were well identified and discriminated from other particles such as p, d and ^{4}He, the detection of (d, ^{3}He) spectrum at small angles (<3.5 deg) was prevented by a huge (d, ^{3}He) background caused by beam particles hitting the spectrometer wall. This background at small angles was difficult to suppress because the SPES1 spectrometer has a single-bend structure, while the formation cross section of deeply bound pionic states is forward peaked. It is indispensable to use a spectrometer with two (or more) bending magnets. Thus, we propose to measure the (d,^{3}He) reaction spectra on ^{208}Pb using the Fragment Separator (FRS) [10] in combination with a deuteron beam from the SIS18 heavy-ion synchrotron of GSI.

The detection of deeply bound pionic states has various aspects of scientific importance. In medium and heavy atoms these states cannot be populated by deexcitation of more weakly bound atomic states. The obvious incapability of pionic x-ray spectroscopy for deeply bound states seems to have caused misunderstanding of the situation; namely, people tend to believe that those inner states do not exist due to the strong nuclear absorption. Nevertheless, based on the presently known pion-nucleus potential these "hidden" states are predicted to be narrow enough so as to exist as discrete states, accommodated by the Coulomb force and the repulsive strong interaction [1], and to be populated by special type of nuclear reactions ("pion-transfer" reactions).

The detection of so far unobserved deeply bound pionic states is very interesting and exciting by itself, because they will give the first evidence for the existence of narrow nuclear excited states in the pion mass region. This will create a new field of nuclear spectroscopy. The measurement of the binding energies and the widths will yield totally new knowledge on the pion-nucleus interaction as seen from the bound pion. The knowledge to be accumulated will eventually make it possible to answer the important question regarding the effective mass of pion in nuclear medium. Such a question (in general, hadrons in nuclear medium) has been raised theoretically, but no experimental information exists so far. The deeply-bound pion spectroscopy will also give information on the distribution of neutrons or the neutron skin, as discussed by Toki *et al.* [11].

2. PRINCIPLE

The (n,d) and (d,^{3}He) reactions can populate pionic states of configuration $[(n\ell)_\pi j_n^{-1}]JL$ with pionic quantum number $(n\ell)_\pi$ on a neutron-hole state of orbital j_n. Hereafter we assume the multiplet of a given configuration to be degenerate. Toki *et al.* [6] calculated the effective number $N_{\rm eff}$ in the expression

$$\frac{d\sigma}{d\Omega} = N_{\rm eff}\left(\frac{d\sigma}{d\Omega}\right)_{{\rm nd}\to\pi^{-\,3}{\rm He}}, \qquad (1)$$

by using the Eikonal approximation for the distortion. The effective number $N_{\rm eff}$ involves spectroscopic information depending on the momentum transfer and the state configuration to be formed. At 300 MeV/u, where the momentum transfer is small, the reaction predominantly populates "quasi-substitutional states" which are characterized by $L = 0$, such as $(2{\rm p})_\pi({\rm np})_n^{-1}$. At 600 MeV/u, on the other hand, the momentum transfer is large and the ground 1s orbital based on the neutron hole $i_{13/2}$ can be populated. See Fig.4.

The charged-particle induced reaction (d, ^{3}He) is experimentally much easier than the (n,d) reaction, though the (d, ^{3}He) cross sections are expected to be reduced by an order of magnitude. The elementary cross section for nd $\to \pi^{-\,3}$He has been obtained from the measurement of $p + d \to t + \pi^+$ at SATURNE [12] in the energy range of present interest. It is shown in Fig.3.

(d+ ^{208}Pb) → (^{3}He+ ^{207}Pb)+π^-

The Q value of the (d, ^{3}He) reaction is

$$
\begin{aligned}
-Q &= \omega + S_n(j_n) - [M_n + M_d - M(^3\text{He})] \\
&= m_\pi - B.E.(\pi^-) + S_n(j_n) - 6.787 \text{ MeV}, \qquad (2)
\end{aligned}
$$

where ω is the excitation energy of the pionic state with respect to the neutron-hole j_n and $S_n(j_n)$ is the neutron separation energy. The four neutron orbitals, $p_{1/2}$ ($S_n = 7.367$ MeV), $f_{5/2}$ ($S_n = 7.937$ MeV), $p_{3/2}$ ($S_n = 8.246$ MeV) and $i_{13/2}$ ($S_n = 9.000$ MeV) are taken into account. Hereafter, the π^- binding energy will be defined with respect to the ground state of ^{207}Pb, and thus it corresponds to the (d, ^{3}He) reaction Q value as :

$$-Q = 140.147 \text{ MeV} - B.E.(\pi^-) \qquad (3)$$

The expected line profiles at various angles of the ^{208}Pb(d,^{3}He) reaction at $T_d = 600$ MeV with an instrumental resolution of 50 keV FWHM are shown in Fig.6. They have a steep angular dependence, peaked at 0 degree. Above the π^- emission threshold there appears a quasi-free continuum, while discrete states are expected below the threshold. The constant background of ^{208}Pb (n,d) which does not contribute to the pion production has recently been measured at TRIUMF to be 300 μb/sr/MeV [7]. So, we have assumed the constant background for (d,^{3}He) to be 40 μb/sr/MeV without angular dependence. There is no experimental information yet on this background in the case of (d, ^{3}He).

The (d, ^{3}He) reaction has a very good intrinsic calibration coming from the two-body final state p(d, ^{3}He)π^0 when a target including hydrogen is used; the (d, ^{3}He) spectrum on a $(CH_2)_n$ target exhibits a distinct peak in the same momentum region as in the ^{208}Pb(d, ^{3}He) reaction. The position of this peak moves with the angle of ^{3}He. In the high acceptance FRS mode we have $\Delta\theta \sim \pm 40$ mrad, and hence, the ^{3}He momentum is distributed from 1670 to 1600 MeV/c, while the beam momentum is 1616 MeV/c and the central spectrometer momentum is 1682 MeV/c.

3. PROPOSED EXPERIMENT

We propose to measure the (d, ^{3}He) reaction spectra at $T_d = 600$ and 1200 MeV. The relevant kinematical quantities are shown in Table 1.

We will use the FRS system [10] with which we will measure the momentum of ^{3}He in the range around 1.68 and 2.67 GeV/c. The layout of FRS is shown in Fig.7. The FRS will be operated in a special mode in which the first part will serve as a high-resolution spectrometer and the second part as a separator for ^{3}He particles, after the introduction of specific energy loss by mid-plane detectors and absorbers. Since FRS is composed of 4 bending magnets, most of the background events caused by the incident deuteron beam inside the first bending magnet will be eliminated already at the intermediate focal plane, where particle tracking drift chambers (DC1 and DC2) and scintillation counters are placed to provide informations on $p/Z, \Delta t$ and $\Delta E/\Delta x$. Two sets of high-rate drift chambers (100 mm vertical × 240 mm horizontal area with 2.5 mm drift distance in the horizontal and ± 15 degrees tilted directions) will give information on the angle of the particles. The particles with p/Z in a momentum bite Δp pass through these counters and are refocussed again in the final focal plane after the 3rd and 4th bending magnets. Because of the different energy loss in the detectors and the absorbers placed at the intermediate focal plane the ^{3}He particles can be separated and tagged at the final focal plane. The p/Z as well as the trajectory of each particle are precisely determined by using the information from the DC's at the middle focal plane. At the final focal plane additional scintillation counters are placed. The combined information of the time of flight Δt and $\Delta E/\Delta x$ for given p/Z is sufficient to identify individual particles, as shown in Fig.8.

A special mode for the operation of FRS [14] (large acceptance $\sim$ 3 msr and large mid-plane dispersion $\sim$ 4.2cm/%) will be used. The overall momentum resolution of FRS including the beam momentum spread may be achieved to be 2×10^{-4}, but here, it is safely assumed to be

$$\frac{\delta p}{p} = 5 \times 10^{-4}. \tag{4}$$

This corresponds to the energy resolution in the final state after (d,^{3}He) as follows,

$$\begin{aligned} \delta\omega &= (p_{He})^2/E_{He} \times (\Delta p/p)_{He} \\ &= 0.43 \text{ MeV for } T_d = 600 \text{ MeV} \\ &= 0.90 \text{ MeV for } T_d = 1200 \text{ MeV} \end{aligned} \tag{5}$$

The resolution is deteriorated by the energy loss of the ^{3}He particle in the target. The FWHM width due to this effect is estimated to be

$$\Delta E = 6.4 \text{ keV/mg/cm}^2 \tag{6}$$

in the case of $T_d = 600$ MeV. For instance, $\Delta E = 0.32$ MeV for a 50 mg/cm^2 target. So, using this thickness, we can obtain an overall energy resolution of 0.5 MeV FWHM for $T_d = 600$ MeV. For a better resolution we have to use a thinner target at the expense of a lower event rate.

We simulated expected spectra for a typical instrumental resolution of 0.5 MeV FWHM, as shown in Fig.9. The yield estimate assumes:

$$\begin{gathered} I_d = 5 \times 10^{10} \text{ /sec}, \\ N_{\text{target}} = 1.5 \times 10^{20} \text{ atoms/cm}^2 \ (50 \text{ mg/cm}^2\ {}^{208}\text{Pb}), \\ \Omega = 3 \times 10^{-3} \text{ sr } (\Delta\theta_x \sim \pm 40 \text{ mr}, \Delta\theta_y \sim \pm 20 \text{ mr}), \\ \text{momentum bite } \frac{\Delta p}{p} = 0.032. \end{gathered} \tag{7}$$

Since the differential cross section decreases rapidly with angle, the cross section was calculated by integrating the differential cross section over the spectrometer acceptance $A(\theta_x, \theta_y)$ as

$$\sigma = \int \frac{d\sigma}{d\Omega} A(\theta_x, \theta_y) d\Omega. \tag{8}$$

They are shown in Fig.9 (upper). Typically, $\sigma = 0.1 - 0.2$ μb/MeV.

The event rate was calculated as

$$R = I_d \times N_{target} \times \sigma. \tag{9}$$

The typical value in the above condition is .

$$R = 0.75 \sim 1.5 \text{ events/MeV/sec.} \tag{10}$$

The simulation presented in Fig.9 assumes a 24-hour beam time. When the beam intensity (or equivalently, the spectrometer efficiency, or the calculated cross section) is less than the assumed one, we have less statistics accordingly. We show such cases, too.

The energy band corresponding to the momentum bite $\Delta p/p = 0.032$ is

$$\begin{aligned} \Delta\omega &= 26 \text{ MeV for } T_d = 600 \text{ MeV} \\ \Delta\omega &= 54 \text{ MeV for } T_d = 1200 \text{ MeV.} \end{aligned} \tag{11}$$

This is very suitable in covering the energy region of present interest. We obtain 20—40 events/sec over the 26 MeV bite, which can be acquired by the present data taking system, when only the ^{3}He events were selected to trigger.

The background from break-up protons is most serious, since the field value p/Z for ^{3}He is very close to $p_d/2$, the momentum of protons from deuteron break-up. Its yield was estimated by using the double differential cross sections given by Jafar *et al.* [15]. It is also forward peaked, and the same procedure as above was taken to calculate the expected yield. The total cross section integrated over the momentum byte of the spectrometer is 50 mb. This background gives a huge counting rate in a middle-plane scintillation counter of as much as 4×10^5/sec. Taking into account the macroscopic duty factor of SIS ($\sim$0.5) we estimate the instantaneous intensity to be nearly $\sim$1 MHz.

In view of the high counting rate ($\sim$ MHz) due to the break-up protons we will use high-rate drift chambers which have been successfully used for (π^+, K^+) spectroscopy at KEK [16], where the beam-line chambers are exposed to particles of 10^6/sec over a 10 cm $\times$ 24 cm area. In addition, we will make the scintillation counter at the mid-focal plane S2 divided into 8 pieces vertically to reduce the counting rates. Since the energy deposit of these break-up protons is a factor of 6 smaller than that for ^{3}He, we can discriminate these protons and the ^{3}He particles in the hard logic stage. Furthermore, the lower energy loss of the background protons compared to ^{3}He can be used to shift the protons out of the FRS (S2-S4) by putting a degrader at S2. The energy loss straggling in the detectors (and the degrader) at the mid-focal plane S2 can be tolerated, since the second part of FRS is only used for the identification of ^{3}He and the velocities of all relevant particles (except d and α) are clearly distinct (see Fig.8). In this way we are able to select ^{3}He particles out of a huge number of background protons.

4. BEAM TIME REQUEST

The case of $T_d = 600$ MeV

The energy resolution is expected to be as good as 0.5 MeV FWHM, where the presence of the main peaks, $(p_{1/2})_n^{-1}(2p)_\pi$ and $(p_{3/2})_n^{-1}(2p)_\pi$, will be firmly demonstrated in 24 hours at the beam intensity of 5×10^{10} d/sec. Assuming a reduction factor of 5 from various origins (for instance, lower beam intensity) we request 15 shifts for data taking and additional 3 shifts for tuning.

The case of $T_d = 1200$ MeV

With an expected resolution of 1.0 MeV FWHM the three groups (3d, 2p and 1s built on the $i_{13/2}$ neutron hole) will be identified. For a firm identification of the most important state (1s) we need a better statistics, and thus a longer beam time. The proposed experiment at $T_d = 1200$ MeV will be done as the second step and will be based on our finding in the first step of using $T_d = 600$ MeV.

5. CONCLUSION

We propose to investigate the ^{208}Pb(d, ^{3}He) reactions at $T_d = 600$ and 1200 MeV by using the Fragment Separator system at GSI-SIS18. From the simulation based on the DWIA calculations we expect to identify the 2p pionic bound states at $T_d = 600$ MeV. We intend to begin the study of pionic atoms with the search for these states at an incident energy $T_d = 600$ MeV, and later to extend it to the search for the 1s state at $T_d = 1200$ MeV.

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Table 1. Kinematical values for (d, ^{3}He) reaction at zero degree for two typical Q values, -140.147 MeV and -130.147 MeV, where the π^- binding energy is 0 and 10 MeV, respectively.

T_d (MeV)	600	600	1200	1200
Q (MeV)	140.147	130.147	140.147	130.147
p_d (MeV/c)	1616.0	1616.0	2440.0	2440.0
T_{He^3} (MeV)	460.2	470.2	1061.9	1071.9
E_{He^3} (MeV)	3268.4	3278.4	3870.1	3880.1
p_{He^3} (MeV/c)	1671.9	1691.4	2662.8	2677.3
q (MeV/c)	55.9	75.4	222.8	237.3
$(p/Z)_{He^3}$ (MeV/c)	836.0	845.7	1331.4	1338.7
$p_d/2$ (MeV/c)	808.0	808.0	1220.0	1220.0
β_d	0.652	0.652	0.792	0.792
β_{He^3}	0.511	0.516	0.688	0.690
$(Z^2/\beta^2)_p$	2.352	2.352	1.594	1.594
$(Z^2/\beta^2)_{He^3}$	15.318	15.023	8.451	8.402
$p^2_{He^3}/E_{He^3}$ (MeV/c^2)	855.2	872.6	1832.1	1847.4

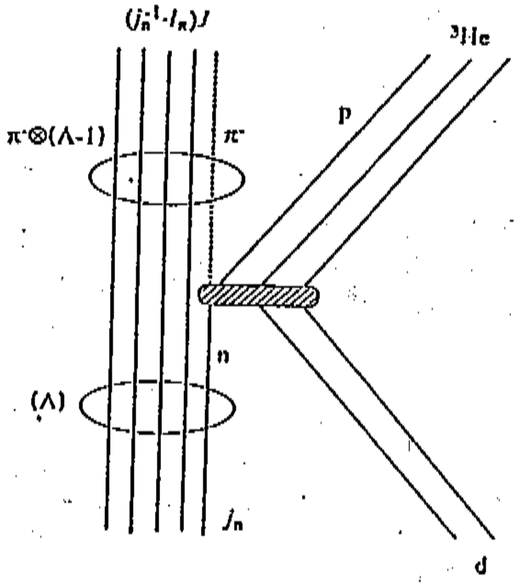


Fig.1 Diagram for the pion-transfer (d, ^{3}He) reaction.

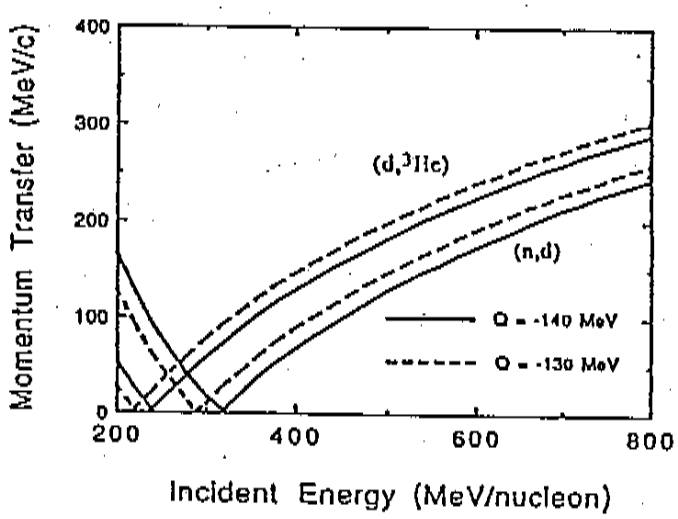


Fig.2 Momentum transfers of (n,d) and (d, ^{3}He) reactions as functions of the incident energy.

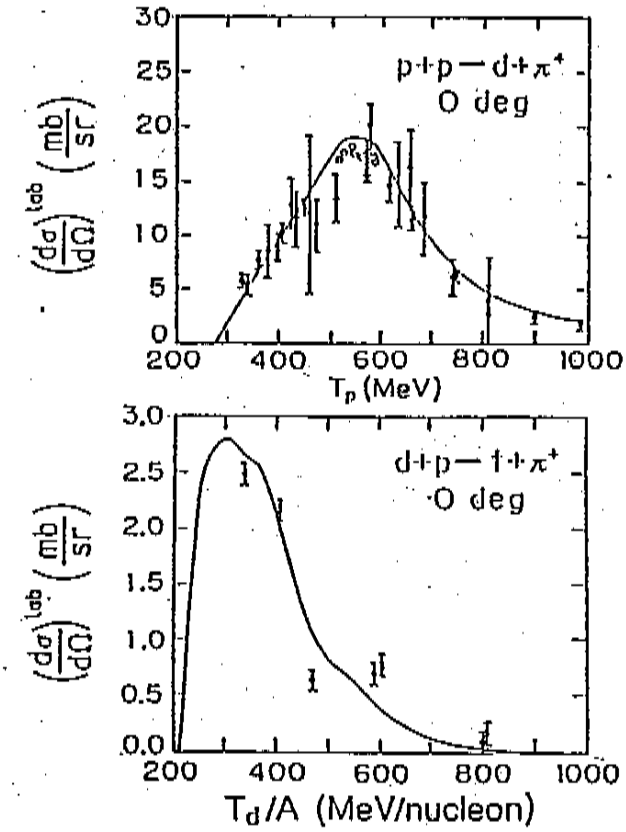


Fig.3 Elementary cross sections, a) pp→ π^+d and b) pd→ π^{+3}He [12]. From the compilation by Toki *et al.* [6].

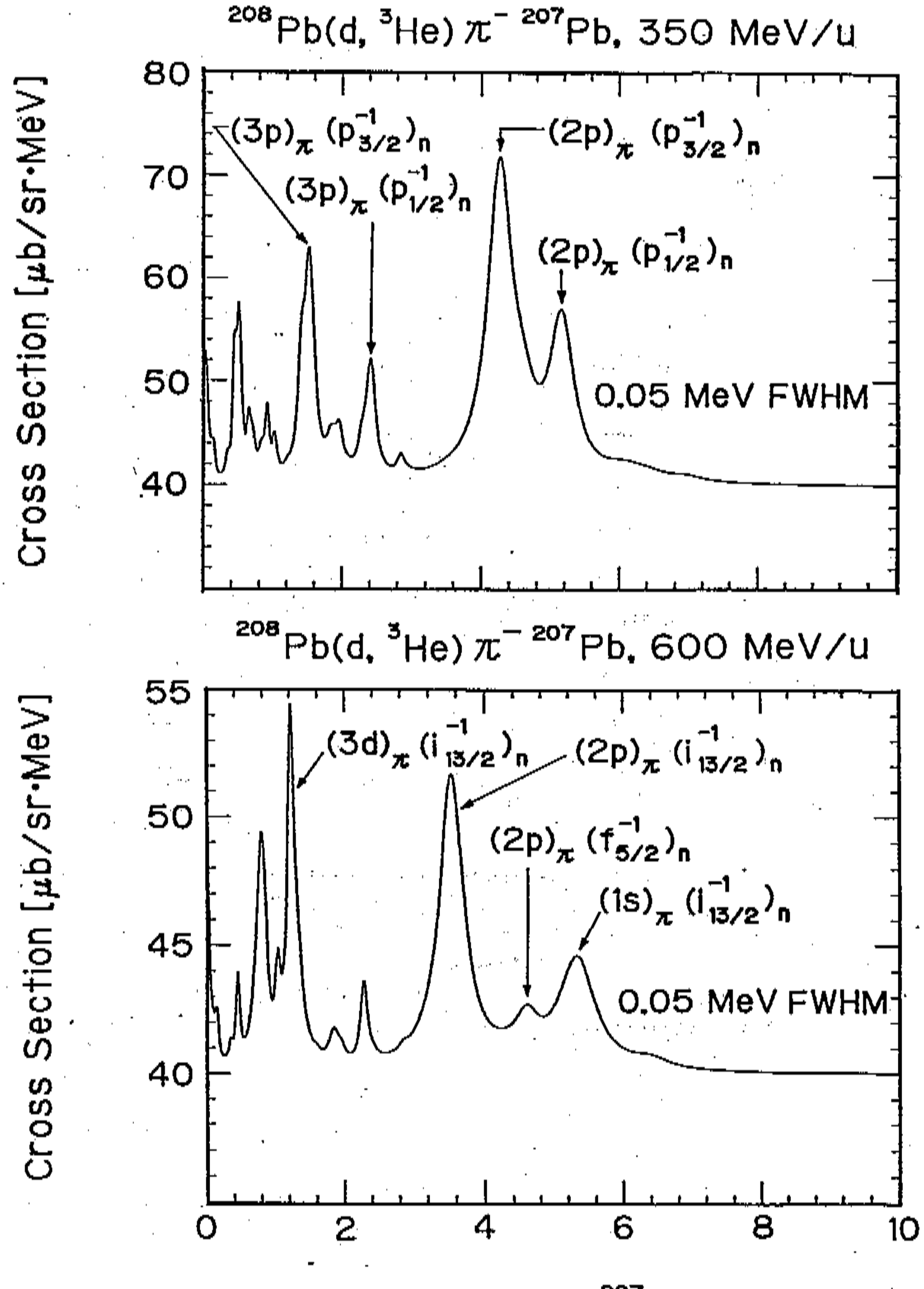


Fig.4 Calculated cross sections for ^{208}Pb(d,^{3}He) at T_d =600 and 1200 MeV with FWHM resolution of 50 keV. From Toki *et al.* [6].

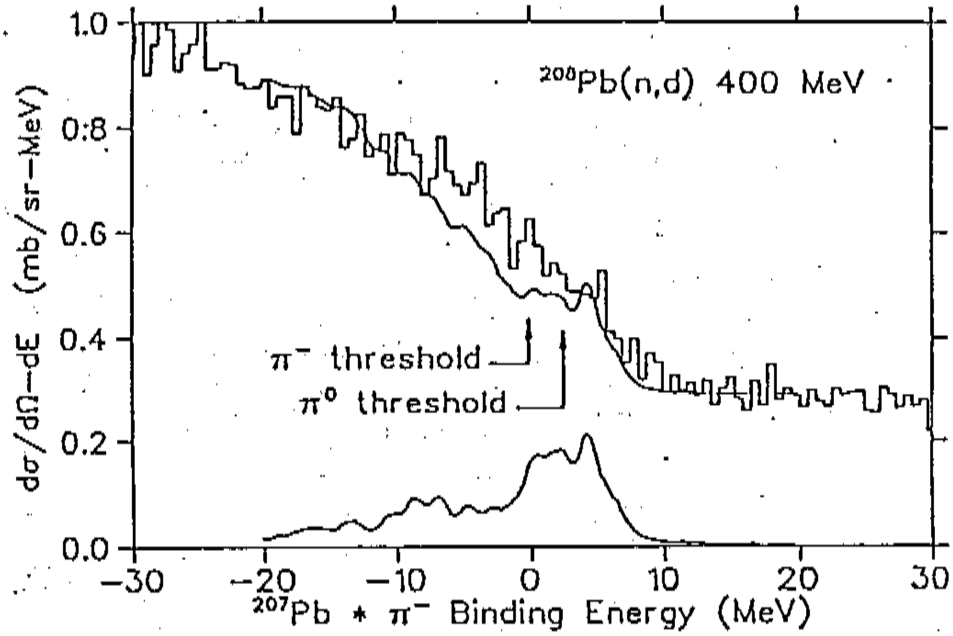
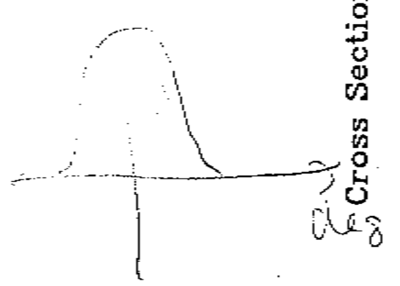


Fig.5 Inclusive deuteron spectrum from ^{208}Pb(n,d) at 0° and 400 MeV, obtained from the TRIUMF Experiment E628 by Trudel *et al.* [7]. The smooth curve is a calculation by Toki *et al.* [6] for ^{208}Pb(n,d) ^{207}Pb$\otimes\pi^-$ for the pionic bound states and the free pion continuum convoluted with 1.5 MeV FWHM resolution for comparison with the data. The lower curve shows just the bound state calculation.



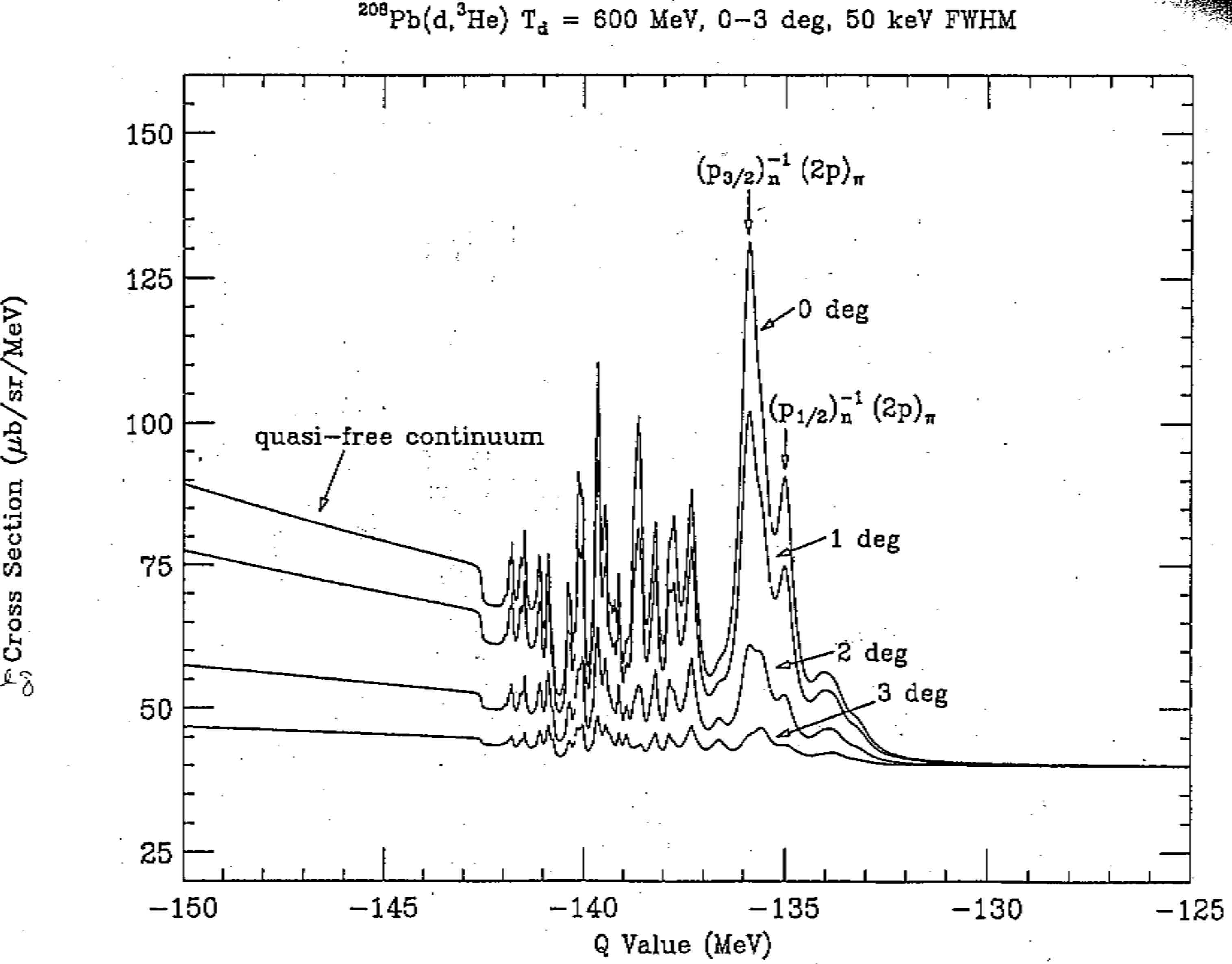


Fig.6 Expected spectrum including continuum part and its angular dependence for ^{208}Pb(d,^{3}He) at $T_d = 600$ MeV with FWHM resolution of 50 keV. From the DWIA calculation of Hirenzaki and Toki [13].

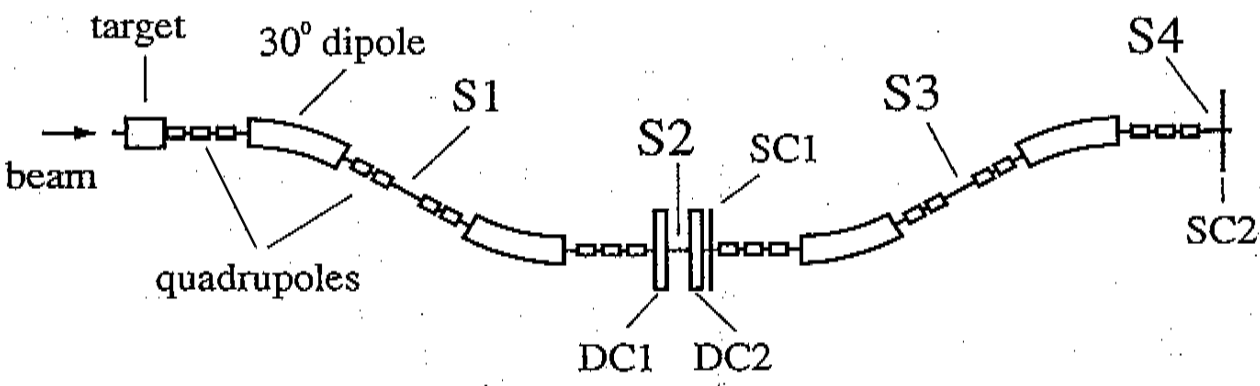


Fig.7 Layout of the experimental setup at the GSI Fragment Separator (FRS) system. The total length is 72 m. At the mid-focal plane (S2) two sets of drift chambers (DC1 and DC2) and a scintillation counter are placed. At the final focal plane another scintillation counter is placed. The detectors are not drawn with the correct scale.

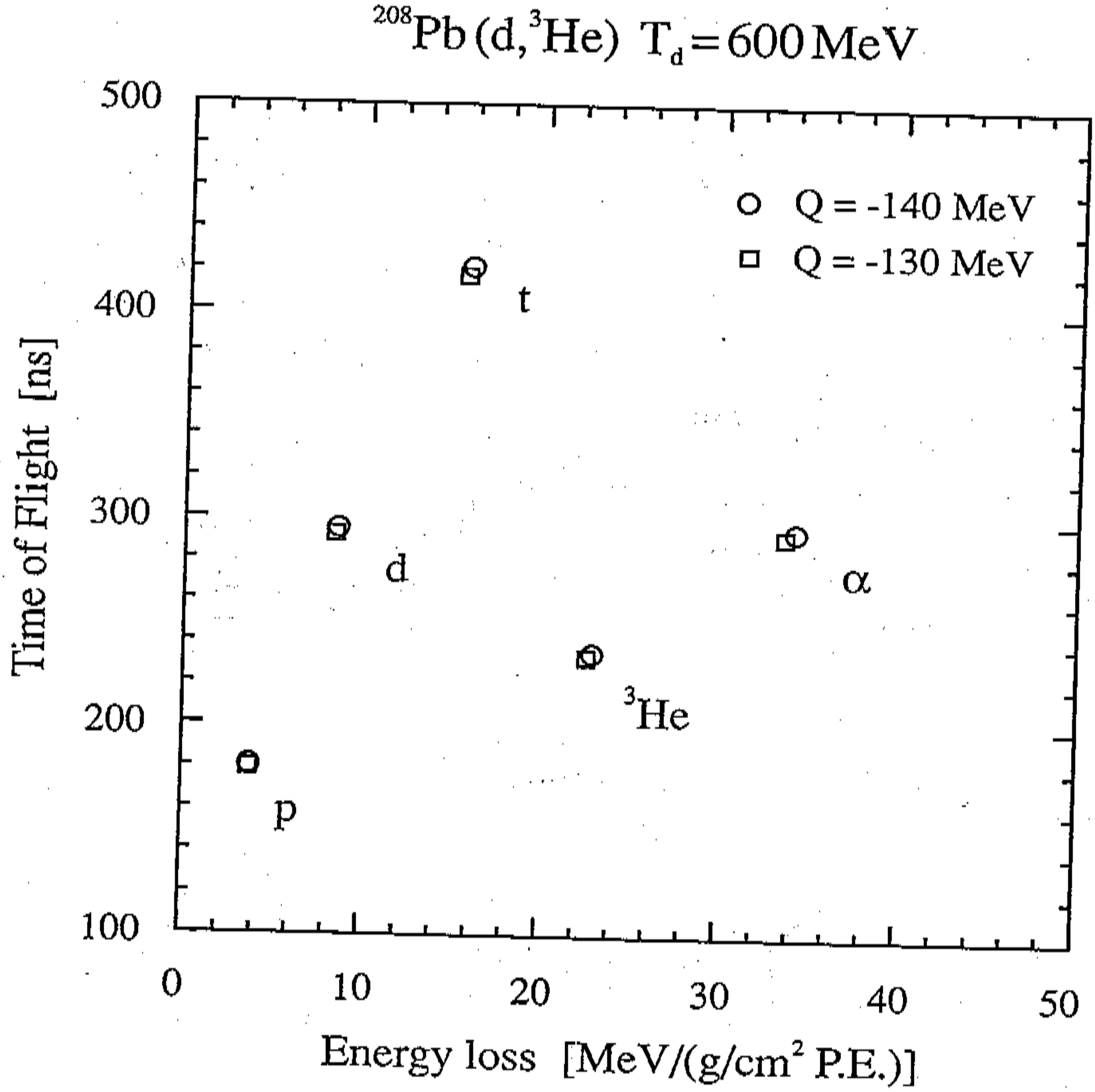


Fig.8 Time of flight (S2 → S4) versus $\Delta E/\Delta x$ in plastic scintillator of various particles for p/Z = 836 and 846 MeV/c (within a momentum bite, $\Delta p/p$ = 3.2%, centered at 841 MeV/c per charge).

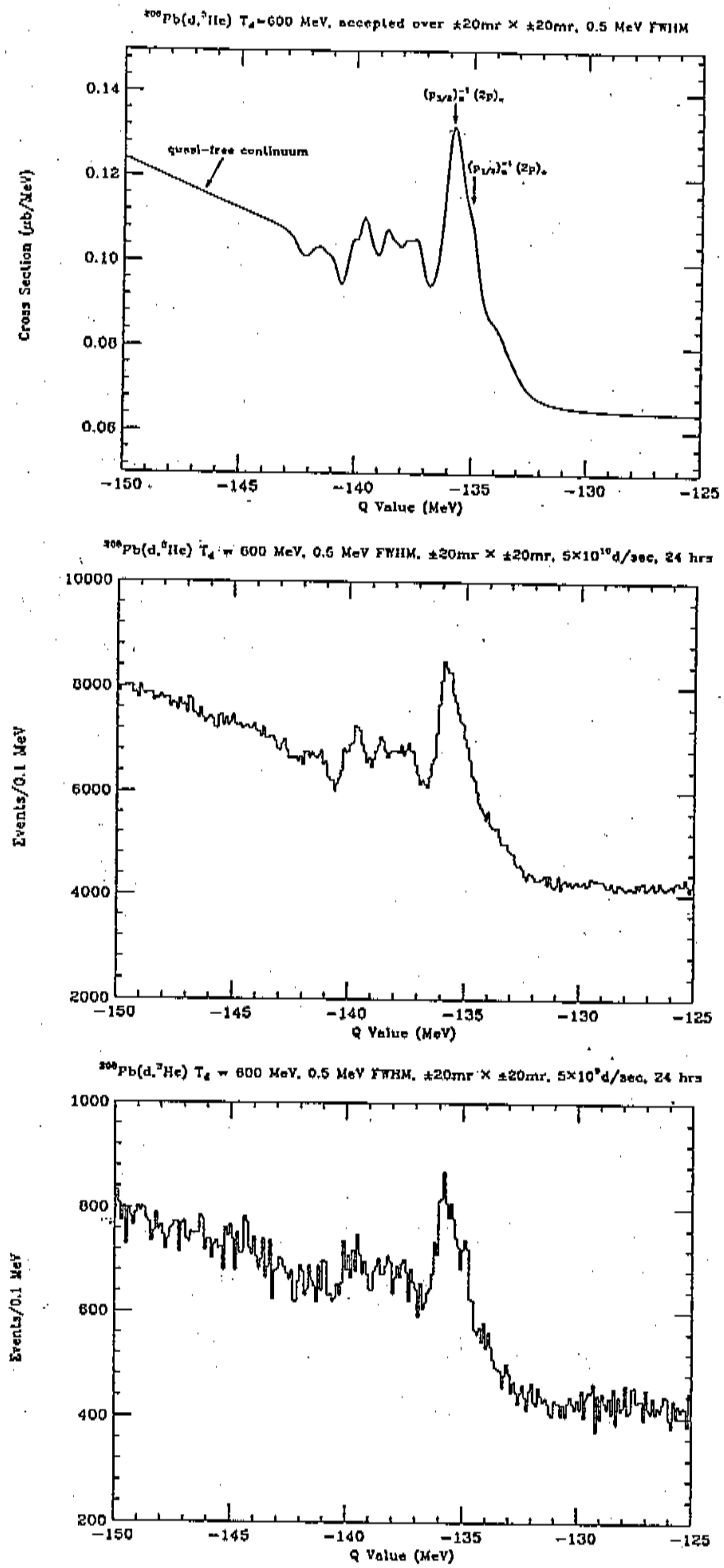


Fig.9 Simulated ^{208}Pb(d,^{3}He) spectrum at T_d=600 MeV. A FWHM resolution of 0.5 MeV is assumed.