INS--866

JP9107234

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INS-Rep.-866
February 1991

Invited talk at the 19th INS International Symposium on Cooler Rings and their Applications, Nov. 4-8, 1990, Tokyo

HIGH-RESOLUTION SPECTROSCOPY OF DEEPLY-BOUND PIONIC ATOMS IN HEAVY NUCLEI BY PION-TRANSFER REACTIONS OF INVERSE KINEMATICS USING THE GSI COOLER RING ESR

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1. INTRODUCTION

Recently Toki and Yamazaki [1] clarified that deeply bound π^- states in heavy nuclei may exist as narrow states due to the repulsive nature of the strong interaction. Using the conventional pion-nucleus optical potential which reproduces both pionic atom data and pion scattering data Toki *et al.* [2] calculated level structures of π^- bound by ^{208}Pb, as shown in Fig.1. Even the ground 1s states are found to be narrow. This theoretical result appears to be in contrast to what people usually believe, but the reason for this situation is clear from Fig.2; the π^- forms a halo around the nucleus, trapped in a Coulomb pocket produced jointly by the Coulomb attraction and by the repulsive strong interaction, thus reducing the absorption by the nucleus. This situation was pointed out by Friedman and Soff in their theoretical study of pion bound states in superheavy nuclei [3]. This type of bound state is typical of Coulomb-assisted hybrid bound states considered by Yamazaki *et al.* [4] for Σ^- hypernuclei.

Obviously, these inner bound states of π^- cannot be reached by the x-ray cascade in pionic atoms, simply because the π^- is destined to die at an outer orbital, where the strong interaction width becomes larger than the radiative width. The treasure of inner world is guarded by the wall of "last orbital", which lies at a radius 10 times the nuclear radius.

Toki and Yamazaki [1] proposed to use the charge-exchange reaction such as (n,p) to populate the deeply bound pionic states. The vertex $n \to p\pi^-$ does not occur in free space, but in a reaction with a heavy target the pion is transferred from the virtual

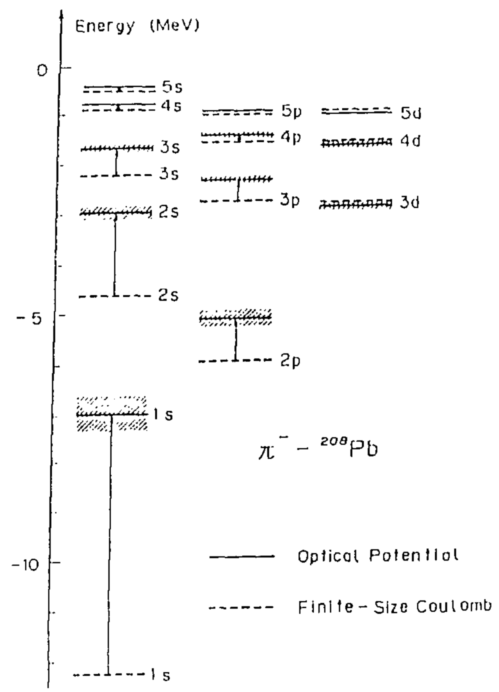

Fig.1 The calculated energy levels of π^- atom in ^{208}Pb [1,2].

state in the incoming neutron to a real bound state with a momentum transfer $\vec{q} = \vec{p_i} - \vec{p_f}$ (see Fig.3).

An attempt to measure (n,p) spectra in the pion mass region with a medium resolution around 1 MeV has been carried out at the TRIUMF CHARGEX facility [5]. Because of using a secondary neutron beam the *(n,p) experiment* has an inherent *limitation on* the *resolution* and the counting rate. The observed (n,p) spectrum at $T_n = 420$ MeV shows a flat continuum of cross section 0.8 mb/sr/MeV, but no distinct structure of statistical significance. They set an upper limit on the peak cross section to be 0.35 mb/sr, which is consistent with the DWIA calculation [5,6].

An alternative way is to employ the (d, ^{2}He) reaction at intermediate energy, which has been used at Saclay to study both the Gamow-Teller excitation and the Δ excitation. An experimental proposal for SATURNE at Saclay [7] is being carried out; a mass resolution around 1 MeV will be achieved by using the SPES-4 spectrometer which accepts two protons emitted in a (d, ^{2}He) reaction.

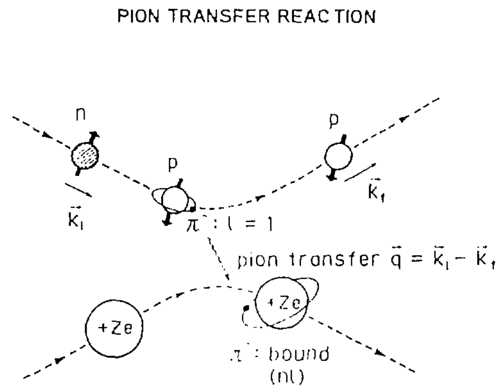

Fig.3 (n,p) reaction as a pion-transfer reaction.

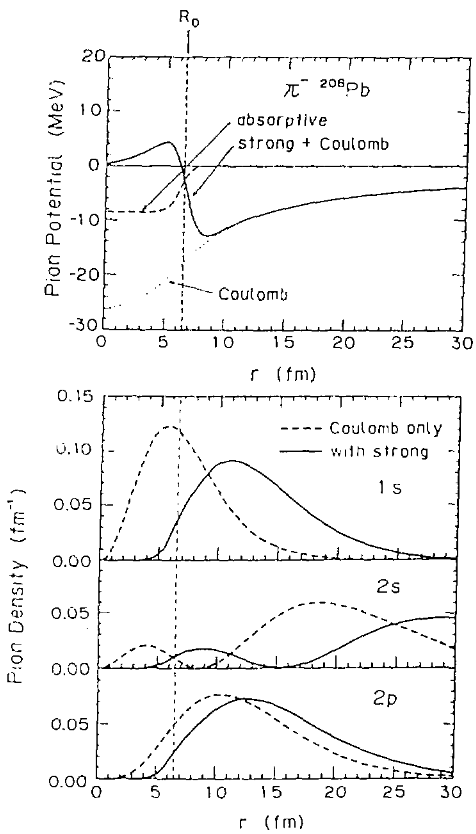

Fig.2 the π^--nucleus potential and the π^- densities of the 1s, 2s and 2p states in ^{208}Pb. Taken from Ref [2].

In addition to the (n,p) type reaction, which may suffer from a large distortion effect due to the large momentum transfer ($q \simeq 200$ MeV/c) for the formation of low-ℓ pionic states [4,6], other reactions are also being considered. Toki *et al.* [8] have proposed to use the proton-pick-up pion transfer reactions such as (n,d) and (d,^{3}He), where π^- states on a neutron hole with configurations $[(n\ell)_\pi \cdot j_n^{-1}]J$ are formed with large corss sections helped by the angular momentum matching ($qR_0 = L$). DWIA calculations have been performed in the case of ^{208}Pb.

The momentum transfer q depends on the incident energy, varying in the range $0 \sim 200$ MeV/c, as shown in Fig.4. There are two typical regions. At $T_p \sim 350$ MeV/u, where q is small, pionic states of "quasi-substitutional" configurations, such as $(2p)_\pi(3p)_n^{-1}$, are preferentially populated with (n,d) cross sections of $100 \sim 200$ μb/sr. On the other hand, at $T_p \sim 600$ MeV/u, where $q \sim 200$ MeV/c, the 1s and 2p pionic states with a $1i_{13/2}$ neutron hole are dominantly populated with (n,d) cross sections of 50 μb/sr. The corresponding (d, ^{3}He) cross sections are expected to be by one order of magnitude smaller than the (n,d) cross sections. The expected (d, ^{3}He) spectra based on the DWIA calculations [8] are shown in Fig.5. Very recently the ^{208}Pb (n,d) reaction has been studied at the TRI-

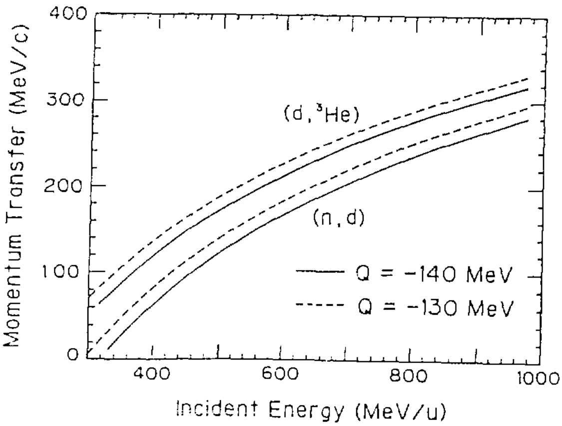

Fig.4 Momentum transfers in the (n,d) and (d, ^{3}He) reactions.

UMF CHARGEX facility [9]. The continuum cross section is found to be 400 μb/sr·MeV below the pion-emission threshold, above which a quasi-free pion-production bump is clearly seen. So, we have assumed 40 μb/sr·MeV for the background in the (d,^{3}He) reaction.

The natural widths as well as the level positions are important observables from which we can deduce unique information about the pion-nucleus interaction and also the nuclear surface structure (neutron skin) [10]. For this purpose, we need experimental resolution as high as possible (even 10 keV!). Needless to say, higher-resolution measurements assure better peak to background ratios. Thus, it is very important to extend those experiments so as to attain a better mass resolution, but it will be extremely difficult to achieve a resolution much better than 1 MeV.

In a recent paper we have discussed the possible use of the inverse kinematics in the charge-exchange pion-transfer reactions of (n,p) and (d,^{2}He) types to form deeply-bound pionic atoms in heavy nuclei [11]. It is shown that the recoil spectroscopy based on inverse kinematics in a reaction,

$$M_1(\text{projectile}) + m_2(\text{target}) \rightarrow m_3(\text{recoil}) + M_4(\text{pionic nucleus}), \qquad (1)$$

will permit a high-resolution measurement of narrow discrete states at 140 MeV excitation energy. This method will also make it possible to form pionic atoms on unstable nuclei. A high-quality medium-energy cooled beam to be produced in a heavy-ion cooler/synchrotron, such as the SIS/ESR ring of GSI Darmstadt [12], will be an ideal tool for this purpose.

In the following we describe how well we can apply the method of inverse kinematics to the case of (d,^{3}He) reactions [13]. The (d,^{3}He) reaction in inverse kinematics is feasible from practical viewpoints, as will be discussed in Section 3.

2. INVERSE KINEMATICS OF (d,^{3}He) REACTION

We consider the inverse kinematics in which a heavy-ion beam (*i.e.*, ^{208}Pb) of projectile kinetic energy T_p (MeV/u) hits a deuteron target and ejected recoil ^{3}He nuclei are measured in the forward direction. Following the formulation given in Ref.[11] we calculate the recoil momentum as a function of the Q value and the recoil angle. Suppose a heavy projectile of mass number A_p with kinetic energy T_p (in MeV per nucleon) which hits a light target nucleus of mass number A_t, as shown in Fig.6.

The velocity of the center of mass is

$$\beta = \frac{p_1}{E_1 + m_2}, \qquad \gamma = \frac{E_1 + m_2}{\sqrt{M_1^2 + m_2^2 + 2E_1 m_2}} \qquad (2)$$

and the total c.m. energy is

$$\sqrt{s} = E_{cm}^{tot} = \sqrt{M_1^2 + m_2^2 + 2E_1 m_2}, \quad \cong M_1 + \frac{E_1}{M_1} m_2, \qquad (3)$$

where

$$E_1 = M_1 + T_p \cdot A_p, \qquad p_1 = \sqrt{E_1^2 - M_1^2} \qquad (4)$$

The excess c.m. energy brought by the projectile is $m_2 T_1 / M_1 = A_t T_p$, namely, T_p times the *target mass number*.

We take

$$M_1 = MASS\ (^{208}\text{Pb})$$
$$m_2 = MASS\ (\text{d})$$

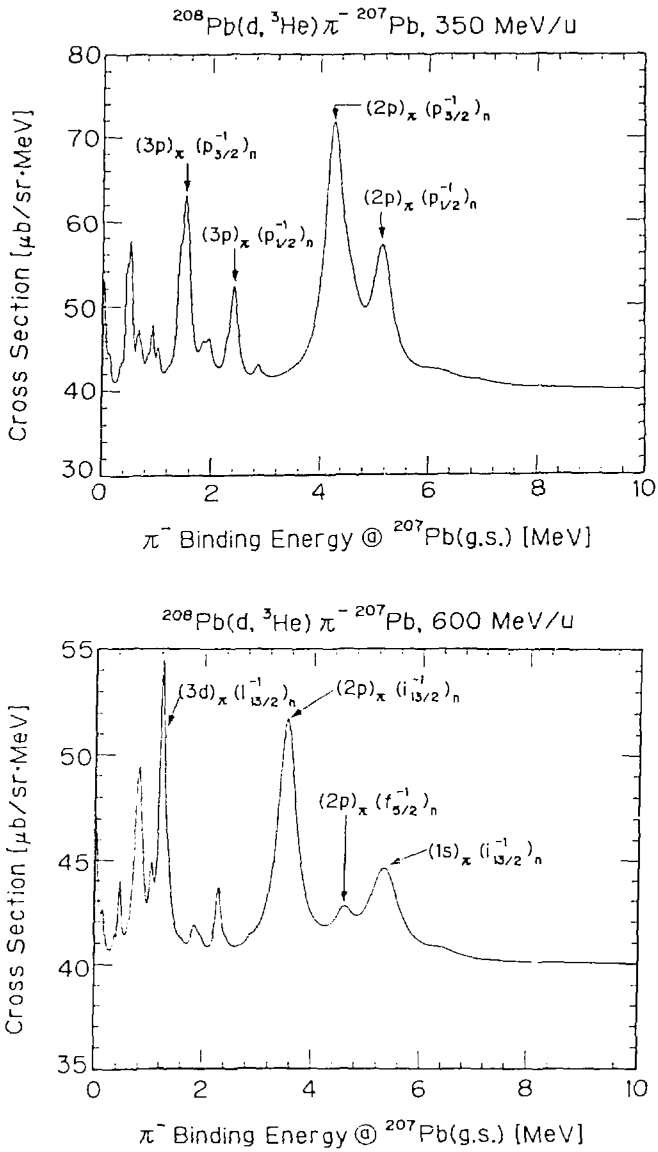

Fig 5 Calculated spectra of ^{208}Pb (d, ^{3}He) at $T_d = 350$ and 600 MeV/u. An instrumental resolution of 50 keV FWHM is assumed. The background for (d,^{3}He) is assumed to be 40 μb/sr·MeV.

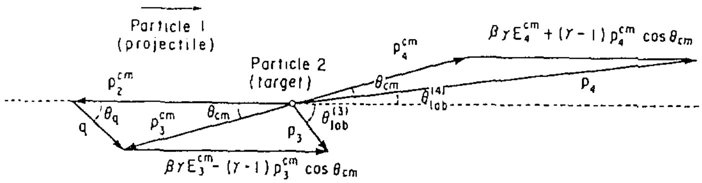

Fig.6 Relevant momenta in inverse kinematics.

$$m_3 = MASS\ (^3\mathrm{He})$$
$$M_4 = MASS\ (^{207}\mathrm{Pb},\ j_n^{-1}) + \omega$$
$$\omega = m_\pi c^2 - B.E.(\pi^-).$$

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

$$Q = \omega + S_n(j_n) - (M_n - M_d + B.E.(^3\mathrm{He}))$$
$$= m_\pi c^2 - B.E.(\pi^-) + S_n(j_n) - 3.519\ \mathrm{MeV} \quad (5)$$

where $S_n(j_n)$ is the separation energy of a neutron in a shell of j_n. In the case of ^{208}Pb $S_n(j_n)$= 7.367 MeV for $j_n = p_{1/2}$, 7.937 MeV for $f_{5/2}$, 8.264 MeV for $p_{3/2}$ and 9.000 MeV for $i_{13/2}$. The spectra in Fig.5 are expressed in the scale of $B.E.(\pi^-)$ with respect to the ground state of ^{207}Pb. So,

$$Q = 143.415\ \mathrm{MeV} - B.E.(\pi^-) \quad (6)$$

Fig.7 shows recoil momentum p_3 versus Q. The recoil momentum is around 600 MeV/c. The recoil momentum is linear versus the Q value, which means that the expected spectra as shown in Fig.5 are linearly mapped on recoil momentum spectra.

The dependence of p_3 on Q in this region is

$$\frac{\Delta p_3}{\Delta Q} = 1.5\ \mathrm{MeV/c/MeV\ for}\ T_p = 350\ \mathrm{MeV/u},$$
$$= 1.1\ \mathrm{MeV/c/MeV\ for}\ T_p = 600\ \mathrm{MeV/u}. \quad (7)$$

Thus, to obtain $\Delta\omega$ = 100 keV, we need a momentum resolution of 0.15 MeV/c and 0.11 MeV/c, or $\Delta p_3/p_3 = 2.5 \times 10^{-4}$ and 1.7×10^{-4}, for T_p = 350

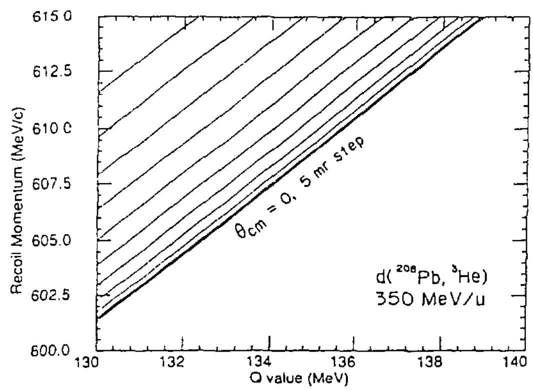

Fig.7 Recoil momentum of ^{3}He versus Q value in the case of d(^{208}Pb,^{3}He) at T_p = 350 MeV/u.

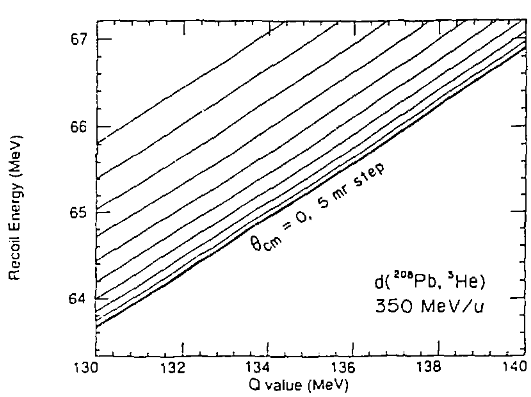

Fig.8 Recoil kinetic energy of ^{3}He versus Q value in the case of d(^{208}Pb,^{3}He) at T_p = 350 MeV/u.

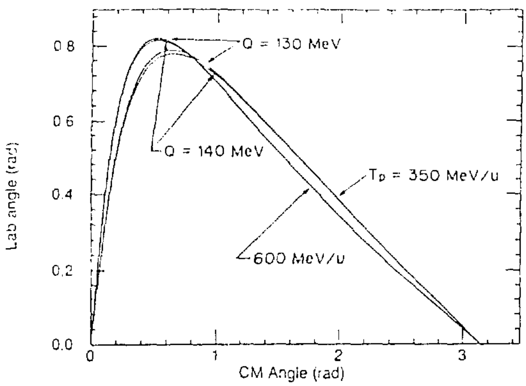

Fig.9 The laboratory angle versus c.m. angle.

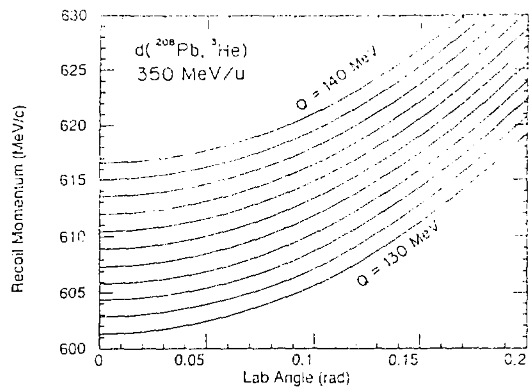

Fig.10 Dependence of recoil momentum on recoil angle.

MeV/u and 600 MeV/u, respectively. The recoil kinetic energy is in the range of 60 MeV, as shown in Fig.8. The energy resolution required for $\Delta\omega = 100$ keV is 32 keV and 25 keV, for $T_p = 350$ MeV/u and 600 MeV/u, respectively, which is possible with a solid state detector.

The laboratory angle versus cm angle is shown in Fig.9. The laboratory angle is about 3-4 times as large as the cm angle in the forward region.

As in the case of (n,p), it is important to determine the recoil angle as precisely as the momentum itself. The dependence of the recoil momentum on the recoil angle is shown in Fig.10. The sensitivity of the mass resolution on lab angle, $\delta\omega/\delta\theta_{lab}$, increases linearly with θ_{lab}, and is approximately given by

$$\begin{aligned}\frac{\delta\omega}{\delta\theta_{lab}} &= 1.3 \text{ keV/mr} \times \theta_{lab}(\text{in mr}),\\ &\quad \text{for } T_p = 350 \text{ keV/u},\\ &= 1.1 \text{ MeV/mr} \times \theta_{lab}(\text{in mr}), \quad (8)\\ &\quad \text{for } T_p = 600 \text{ MeV/u}.\end{aligned}$$

This sensitivity is much smaller than in the case of (d, ^{2}He) reaction, because the recoil momentum depends predominantly on the Q value, as shown below.

We can derive simple analytical expressions for inverse kinematics by employing the Lorentz-invariant momentum transfer q_L, which is defined as

$$q_L^2 = q^2 - (\Delta E)^2.$$

In the center of mass frame (nearly the at-rest frame of M_1) q is of order of 0-200 MeV/c and the energy transfer is $M - Q$, and thus

$$q_L^2 = q^2 - (M - Q)^2.$$

In the laboratory frame a target nucleus d at rest changes into a ^{3}He recoil which acquires a momentum p_3 and an energy $M + T_3$, and thus

$$q_L^2 = p_3^2 - (M + T_3)^2.$$

These two are equated and we obtain a crude estimate

$$p_3 \cong (3MQ)^{1/2}$$

as a leading term, which agrees well with the exact numerical values. It is to be noted that the recoil momentum depends predominantly on the excitation energy. This is why the recoil spectroscopy in inverse kinematics works for high resolution spectroscopy.

We have just shown that the recoil spectroscopy with inverse kinematics can be applied to the case of (d,^{3}He) reaction, which will yield high mass resolution as good as $\Delta\omega = 50$ keV. One can use a deuteron internal target in a cooled circulating beam. Precise determination of momentum and direction of recoil ^{3}He particles will be possible in various ways. The use of the (d,^{3}He) reaction will be easier than that of the (d,^{2}He) and (t,^{3}He) reactions also from practical reasons; in the (d,^{2}He) case one has to detect two protons which are divergently emitted in the inverse kinematics and in the case of (t,^{3}He) one cannot avoid using a radioactive target. Thus, the inverse (d,^{3}He) reaction appears to be most feasible from both physics and practical viewpoints.

3. EXPERIMENTAL SETUP IN THE FIRST STAGE

In Ref.[11] we have discussed various ways for the high-resolution recoil spectroscopy. Here, we discuss a simple detector configuration without using magnetic field, as shown in Fig.11. At 2 m downstream of a deuterium gas-jet target we place a detector assembly comprising position-tracking counters, ΔE counters and E counters in an annular configuration. The whole assembly can be decomposed into two parts, which should be movable according to the beam size that changes with time before and after beam cooling. The beam emittance after cooling is $0.2\ \pi$ mm·mr. So, we expect $\delta x = 0.5$ mm and $\delta\theta_{beam} = 0.5$ mr. This emittance which limits the ultimate resolution is taken into account in the following considerations

The detector will cover $\theta = 5$-25 mr. At $\ell = 2$m this corresponds to $r = 1.0$-5.0 cm. The 2-cm-dia. aperture is big enough for the beam and its halo so as to pass through the hole. Assuming an angular resolution as good as 0.5 mr, which corresponds to a 1.0 mm spatial resolution, we expect that the uncertainty in a mass determination is as good as 3.3 - 16 keV for $\theta = 5$-25 mr, respectively, which are well below the mass resolution arising from the detector energy resolution. The solid angle of the detector system mentioned above is

$$\Omega = \pi(\theta^2_{max} - \theta^2_{min}) = 1.8 \times 10^{-3}. \qquad (9)$$

The energy resolution with a 2.5-mm-thick Si detector will be 20 keV, which corresponds to a mass resolution of 30 keV. The identification of particles can be done by using i) ΔE, ii) total energy E, and iii) time of flight. The T.O.F. can be best obtained, if the internal beam is microscopically bunched. According to Franzke, a bunched and cooled internal beam of 27 MHz repetition (interval = 37 nsec) and width of 1 nsec will be achieved.

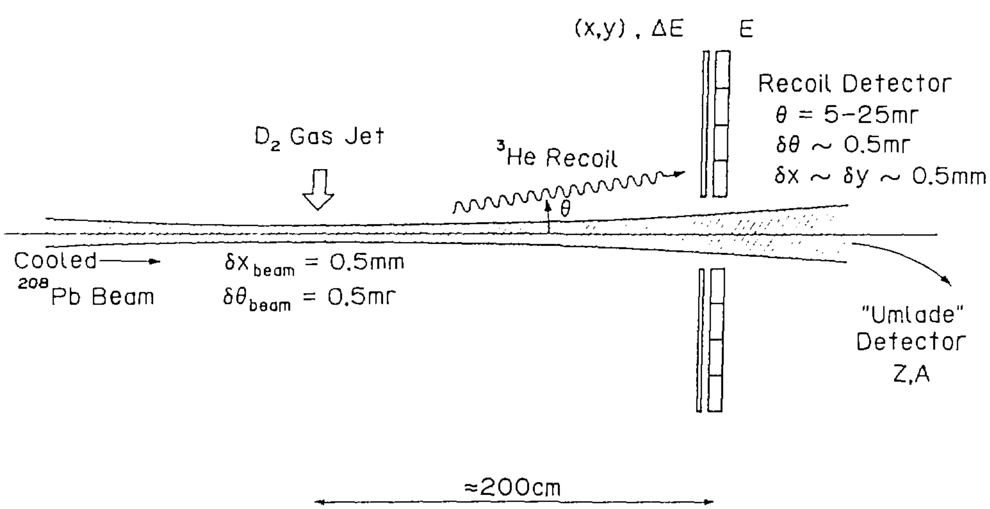

Fig.11 A schematic diagram for the proposed experiment (Phase I).

Since the flight time of a typical ^3He recoil of 600 MeV/c momentum is 32.6 nsec, particle identification in this energy range can be done easily by using the timing of such microscopic bursts. In the case that such microscopic bursts are not available, the timing signal can be obtained from a projectile-fragment detector (Umlade Detector) as described later.

Let us estimate the event rate and simulate the proposed experiment. We assume the following beam parameters.

Beam particle. $n_{beam} = 10^{10}$ ppp,
Revolution frequency: $f_{rev} = 2$ MHz,
Target density : $\rho_t = 5 \times 10^{13}$ cm^{-2}.

Then, the luminosity of this experiment is estimated as

$$L = f_{rev} n_{beam} \rho_t = 10^{30} \text{ cm}^{-2}/\text{sec}. \qquad (10)$$

The event rate is given by

$$R = \Omega \left(\frac{\theta_{cm}}{\theta_{lab}}\right)^2 \left(\frac{d\sigma}{d\Omega}\right)_{cm} L \qquad (11)$$

For a typical (d,^{3}He) cross section of 20 μb/sr in the center of mass we obtain

$$R = 3 \times 10^{-3}/\text{sec}. \qquad (12)$$

We thus expect 10 events per hour for a peak cross section of 20 μb/sr. Simulated spectra for a beam time of 400 hrs are shown in Fig.12. Here, the mass resolution is assumed to be 50 keV FWHM.

A serious background which is difficult to estimate at the present stage is the beam halo or δ-ray halo which will fire the detector system. The spread angle of δ-rays is quite large so that they may cause a serious background and worsen the energy resolution.

We can acquire coincidence with outgoing residual nuclei which can be detected by the "Umlade Detector" located after the bending magnet of the ESR ring. The residual nucleus after the (d,^{3}He) reaction is ^{207}Tl*, which is one charge unit and one mass unit less than the beam particle ^{208}Pb. Since this is a pionic state with excitation energy of 140 MeV, the ^{207}Tl* will immediately decay into $^{207-x}$Tl. Thus, the tagging by the "Umlade Detector" will help select only the pionic states after

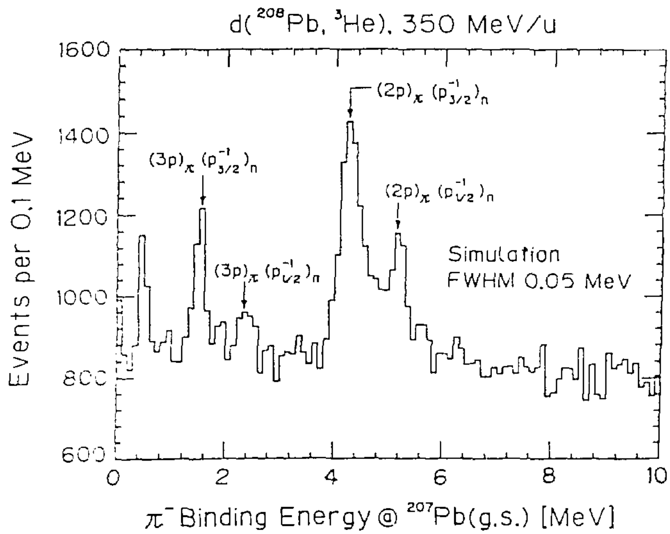

Fig.12 A simulated spectrum of d(^{208}Pb, ^{3}He) at T_p = 350 MeV/u with an instrumental resolution of 50 keV FWHM. A beam time of 400 hrs is assumed.

(d,^{3}He) reactions. Furthermore, the mass spectrum obtained from the "Umlade Detector" will tell us the distribution of nuclear mass after pion capture. The signal from the "Umlade Detector" also serves as a timing signal for time-of-flight measurements of recoil particles to be detected by the Si assembly.

Another possibility to reduce the physical background is to acquire coincidence with forward going neutrons after pion absorption by placing a neutron detection system. The neutron kinetic energy after pion absorption is 70 MeV on average and thus its momentum is 360 MeV/c. It is boosted in the laboratory frame. At T_p = 350 MeV/u the forward momentum of the neutron is 880 MeV/c so that its cone angle is θ_n = 0.4 rad. So, we can place an annular shaped neutron detection system in the downstream. The information on forward neutrons will be used as an additional information.

So far, we have considered the case of using a ^{208}Pb beam. A similar experiment can be done by using a ^{136}Xe beam of 350 MeV/u, which can preferentially populate the ground $(1s)_\pi$ state with a neutron hole at $3s_{1/2}$. In the case of ^{208}Pb there is no s-state hole near the Fermi surface, while in the $N = 82$ region the $3s_{1/2}$ is low lying.

In conclusion, we find that the (d,^{3}He) reaction in inverse kinematics will be promising in getting high-resolution spectra of deeply bound pionic atoms. This new spectroscopy can be started in the ESR ring with the gas-jet target system combined with a recoil detection system of solid-state detectors in the down stream.

The author would like to thank Professors P. Kienle, R.S. Hayano and H. Toki for the helpful discussions.

REFERENCES

[1] H. Toki and T. Yamazaki, Phys. Lett. B213 (1988) 129.

[2] H. Toki, S. Hirenzaki, T. Yamazaki and R.S. Hayano, Nucl. Phys. A501 (1989) 653.

[3] E. Friedman and G. Soff, J. of Phys. G11 (1985) L37.

[4] T. Yamazaki, R.S. Hayano, O. Morimatsu and K. Yazaki, Phys. Lett. B207 (1988) 393.

[5] M. Iwasaki *et al.*, Phys. Rev. C, in press.

[6] J. Nieves and E. Oset, Nucl. Phys. A518 (1990) 617.

[7] T. Yamazaki *et al.*, Saturne Proposal No.214 (1989).

[8] H. Toki, S. Hirenzaki and T. Yamazaki, Nucl. Phys., in press.

[9] A. Trudel, private communication (1991).

[10] H. Toki, S. Hirenzaki and T. Yamazaki, Phys. Lett. B249 (1990) 391.

[11] T. Yamazaki, R.S. Hayano, H. Toki and P. Kienle, Nucl. Instr. Meth. A292 (1990) 619.

[12] P. Kienle, Nucl. Phys. A478 (1988) 847c.

[13] T. Yamazaki, H. Toki and R.S. Hayano, Nucl. Instr. Meth., to be published.