Nuclear dynamics in the analysis of possible exotic states: K NNN system

E. Oset, V. Magas and A. Ramos

Brief review of deeply bound Kaon atoms

Analysis of the FINUDA data claiming a bound KNNN system

Three body dynamics

Learning more on K absorption

Brief history of deeply bound Kaonic atoms

T Suzuki et al. Phys Lett. B (2004) find peak in p spectrum following K^- absorption in 4He
→ K^- bound in a trinucleon with 195 MeV binding

E. Oset, H. Toki (Phys. Rev. C (2006)) interpret the peak as due to absorption of K with nucleon pairs $K^- NN \rightarrow p\,\Sigma$. The width is not calculated.
Predict peak to appear narrower in bigger nuclei and gradullay disappear as A becomes larger.
Predictions confirmed by FINUDA (proton spectra), Agnello Nucl. Phys A (2006)
In 6Li. The peak nearly fades away in 12C.

FINUDA makes another experiment looking at K absorption in light nuclei looking at Λ p in coincidence. They claim evidence for a K^- bound in the pp system with 115 MeV binding and width 67 MeV.

Magas, Oset, Ramos, Toki, Phys. Rev. C (1006) interpret the peak as
$K^- pp \rightarrow p\,\Lambda$ followed by rescattering of p or Λ in the nucleus.

Akaishi, Yamazaki criticize approach of Oset, Toki and Magas, Oset, Ramos, Toki In Nucl. Phys. A (2007), in particular “the small width” of the peak in Oset and Toki which was never calculated, nor quoted.

Magas, Oset, Ramos, Toki strike back and rebute criticisms: three papers

1) Unconstraint reply (Oset style) in nucl-th/0701023
2) Politically correct, referee filtered, contribution to the Hypernuclear Conference Mainz, 2006, published in the Proceedings.
3) Professional style in Nucl. Phys A 804 (2008) 219

New result: the width of p spectra corresponding to the KEK experiment is calculated. It is not narrow, rather broad, around 70-80 MeV/c

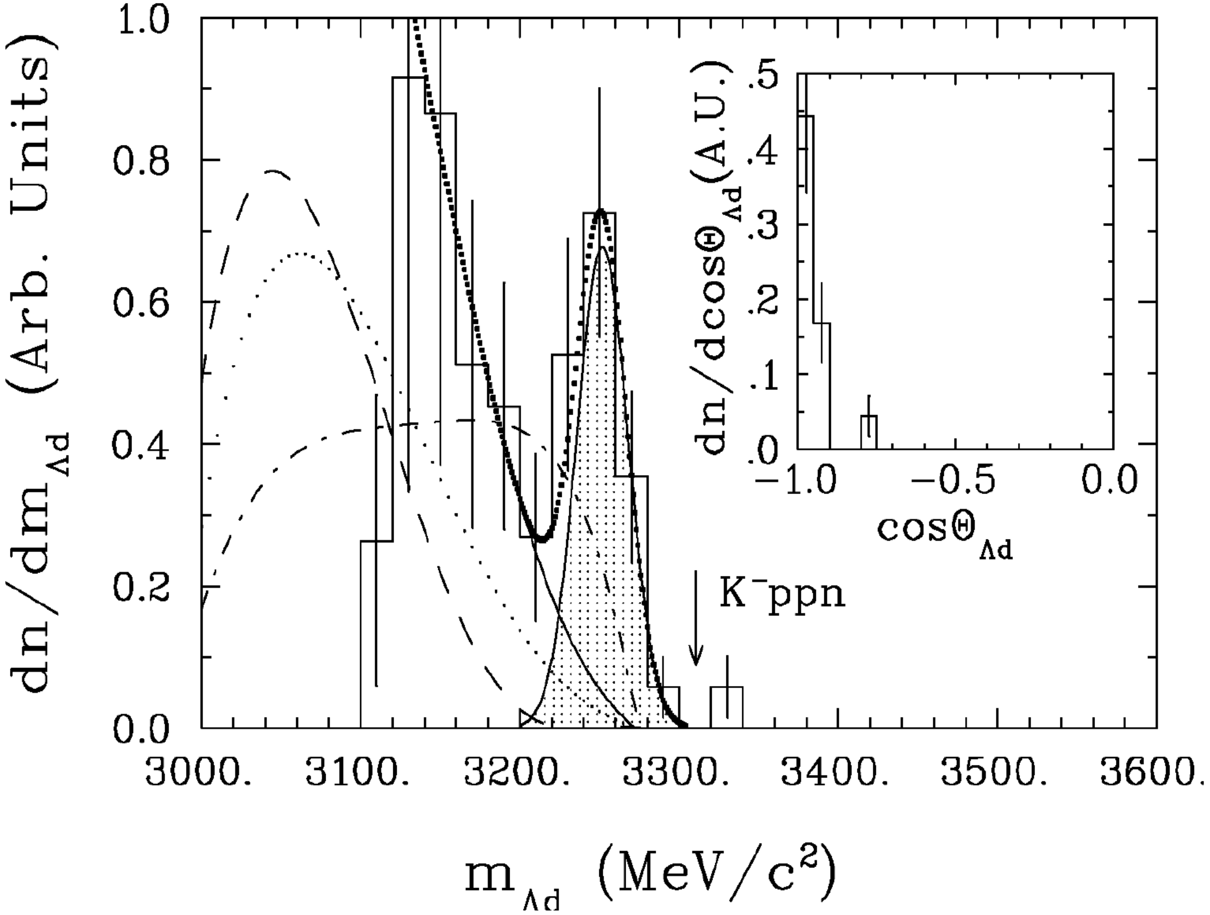
Sato et al repeat KEK experiment, Phys Lett B (2008). The initial narrow peak disappears and is substituted by a broad bump, in agreement with the previous theoretical predictions in Nucl. Phys. A804 (2008) 219.

The experimental Saga continues

M. Agnello *et al.* [FINUDA Collaboration], Phys. Lett. B **654** (2007) 80 [arXiv:0708.3614 [nucl-ex]].

Correlated Λd pairs emitted after the absorption of negative kaons at rest $K^-_{stop} A \to \Lambda d\, A'$

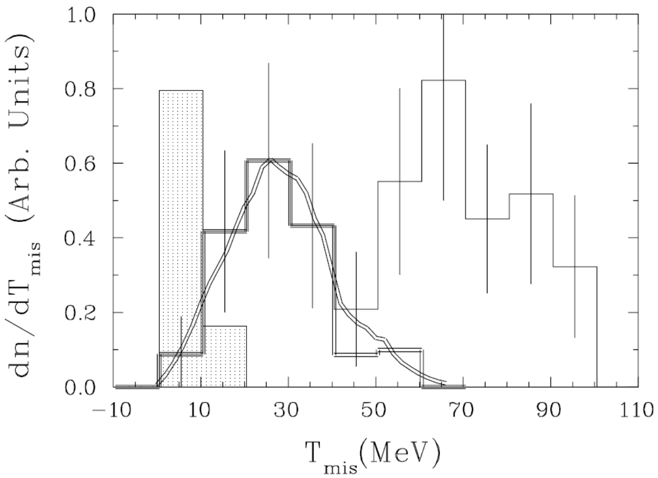
in light nuclei ^6Li and ^{12}C



Peak observed in Λ d invariant mass

Strong backward correlations of emitted Λ and d

Results interpreted as the formation of K- bound on a NNN system → Λ d



Missing kinetic energy distribution of the $^6Li(K^-_{stop}, \Lambda d)nd$ reaction (thin-line histogram)

$$T_{mis} = (m_{K^-_{stop}} + m_{^6Li} - m_\Lambda - m_n - 2m_d) - (T_\Lambda + T_d)$$

Such an occurrence can be explained by assuming the absorption process to start with the $\alpha(K^-_{stop}, \Lambda d)n$ reaction, where α is a substructure of $^6Li (\equiv \alpha + d_H)$

Reaction mechanisms to be considered in the process

V. Magas, E. Oset and A. Ramos, Phys. Rev. C 77 (2008) 065210

$$\Gamma \propto \int d^3\mathbf{r}|\Psi_{K^-}(r)|^2\rho^3(r)$$

To have Λ d the K^- needs to be absorbed by three nucleons. The K^- is absorbed from an atomic orbit

$$\rho(r) \;=\; 4\int \frac{d^3\mathbf{p}}{(2\pi)^3}\Theta(k_F(r)\;-\;|\mathbf{p}|)$$

$$\Gamma \propto \int d^3\mathbf{r}d^3\mathbf{p}_1 d^3\mathbf{p}_2 d^3\mathbf{p}_3|\Psi_{K^-}(r)|^2\times$$

$$V(r) = -\frac{k_F^2(r)}{2m_N}, \quad k_F(r) = \left(\frac{3\pi^2}{2}\rho(r)\right)^{1/3}$$

$$\times\,\Theta(k_F(r)-|\mathbf{p}_1|)\Theta(k_F(r)-|\mathbf{p}_2|)\Theta(k_F(r)-|\mathbf{p}_3|)$$

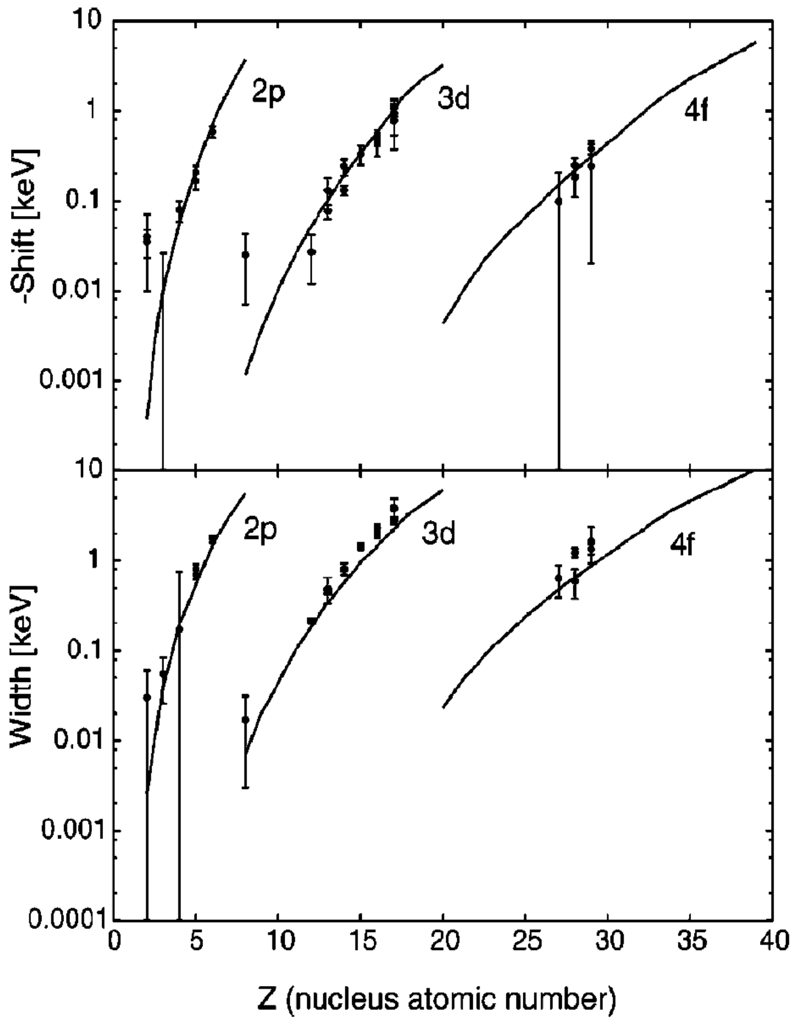
The nucleons move with a potential and have a gap Δ to be excited.
Δ is determined such as to satisfy the reaction threshold

$$m_{K^-}+M_{^6\mathrm{Li}}=m_{K^-}+3m_N-3\Delta+M_t$$

Where the three nucleons have been taken from the Fermi surface

$$\Delta \;=\; 7.8\;\;\mathrm{MeV}$$

From which orbit does the K^- get absorbed?



Hirenzaki, Okumura et al.
Phys Rev C (2000)

In 6He the K^- is absorbed from a 2p orbit

Kinematics of the reaction

$$E_{\Lambda d} = E_{K^- NNN} \equiv E_{K^-} + E_{N_1} + E_{N_2} + E_{N_3} \tag{5}$$
$$= m_{K^-} + 3m_N + \frac{\mathbf{p}_1^2}{2m_N} + \frac{\mathbf{p}_2^2}{2m_N} + \frac{\mathbf{p}_3^2}{2m_N} - 3\frac{k_F^2(r)}{2m_N} - 3\Delta \ ,$$

and the momentum from

$$\mathbf{P}_{\Lambda d} = \mathbf{P}_{K^- NNN} = \mathbf{p}_1 + \mathbf{p}_2 + \mathbf{p}_3 \ , \tag{6}$$

and, correspondingly,

$$M_{\Lambda d} = E_{\Lambda d} - \frac{\mathbf{P}_{\Lambda d}^2}{2E_{\Lambda d}} \ . \tag{7}$$

To get angular correlations and missing mass one needs further information

$$\mathbf{p}_\Lambda^{CM} = p_\Lambda^{CM}(\sin\Theta\cos\phi, \sin\Theta\sin\phi, \cos\Theta)$$
$$\mathbf{p}_d^{CM} = -\mathbf{p}_\Lambda^{CM} ,$$

with

$$p_\Lambda^{CM} = \frac{\lambda^{1/2}(M_{\Lambda d}^2, m_\Lambda^2, M_d^2)}{2M_{\Lambda d}} ,$$

Knowing Λ d invariant mass Λ and d are generated randomly in their CM frame

Then the momenta are boosted to the lab frame

$$\mathbf{v} = \mathbf{P}_{\Lambda d}/(m_\Lambda + M_d)$$

$$\mathbf{p}_\Lambda = \mathbf{p}_\Lambda^{CM} + m_\Lambda \mathbf{v}$$
$$\mathbf{p}_d = -\mathbf{p}_\Lambda^{CM} + M_d \mathbf{v}$$

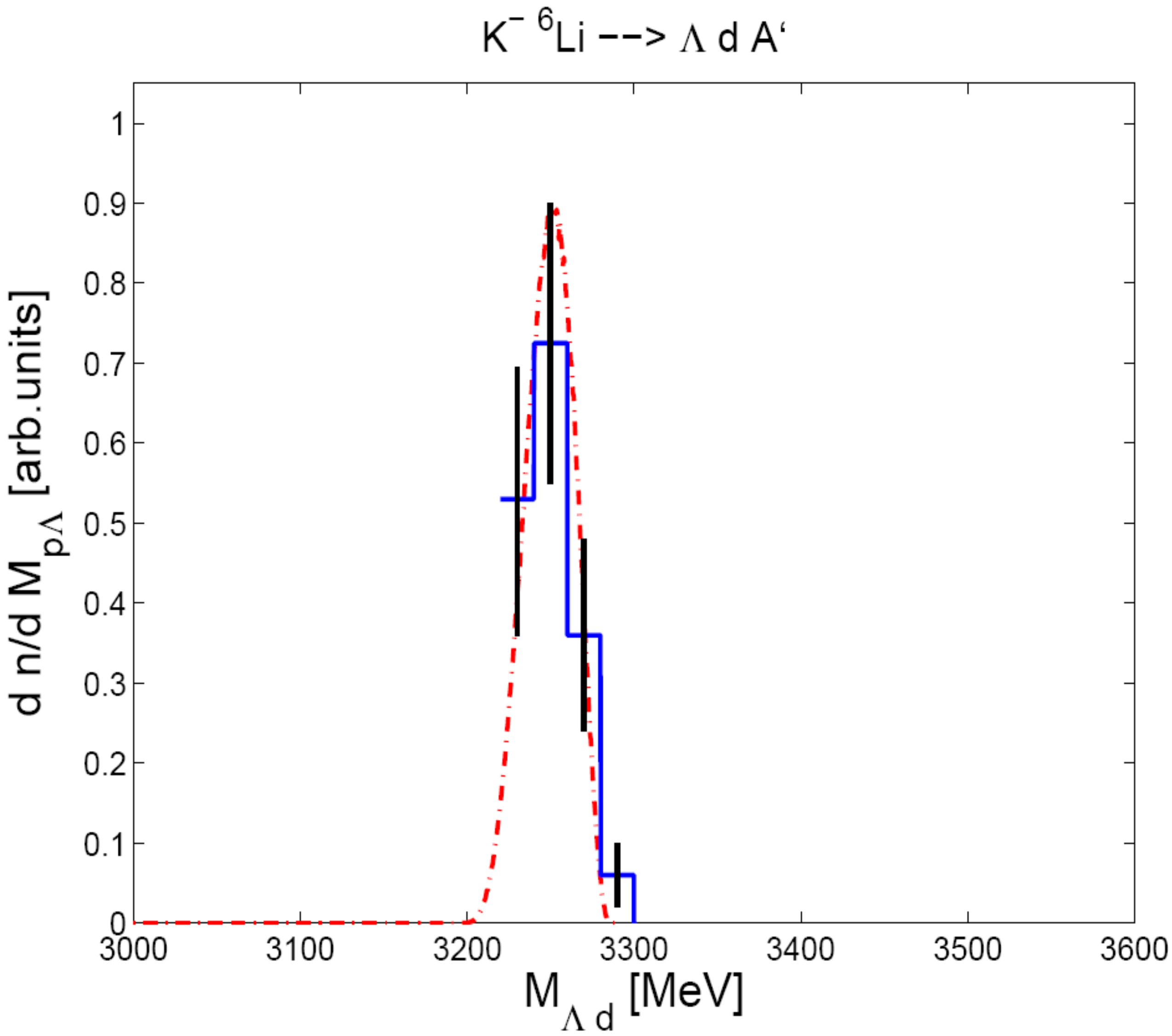
This gives angle between Λ and d

$$\int d\cos\Theta \int d\phi \int d^3\mathbf{r} d^3\mathbf{p}_1 d^3\mathbf{p}_2 d^3\mathbf{p}_3 |\Psi_{K^-}(r)|^2$$
$$\times\Theta(k_F(r) - |\mathbf{p}_1|)\Theta(k_F(r) - |\mathbf{p}_2|)\Theta(k_F(r) - |\mathbf{p}_3|)$$
$$\times\Theta(M^* - M_t) . \qquad (13)$$

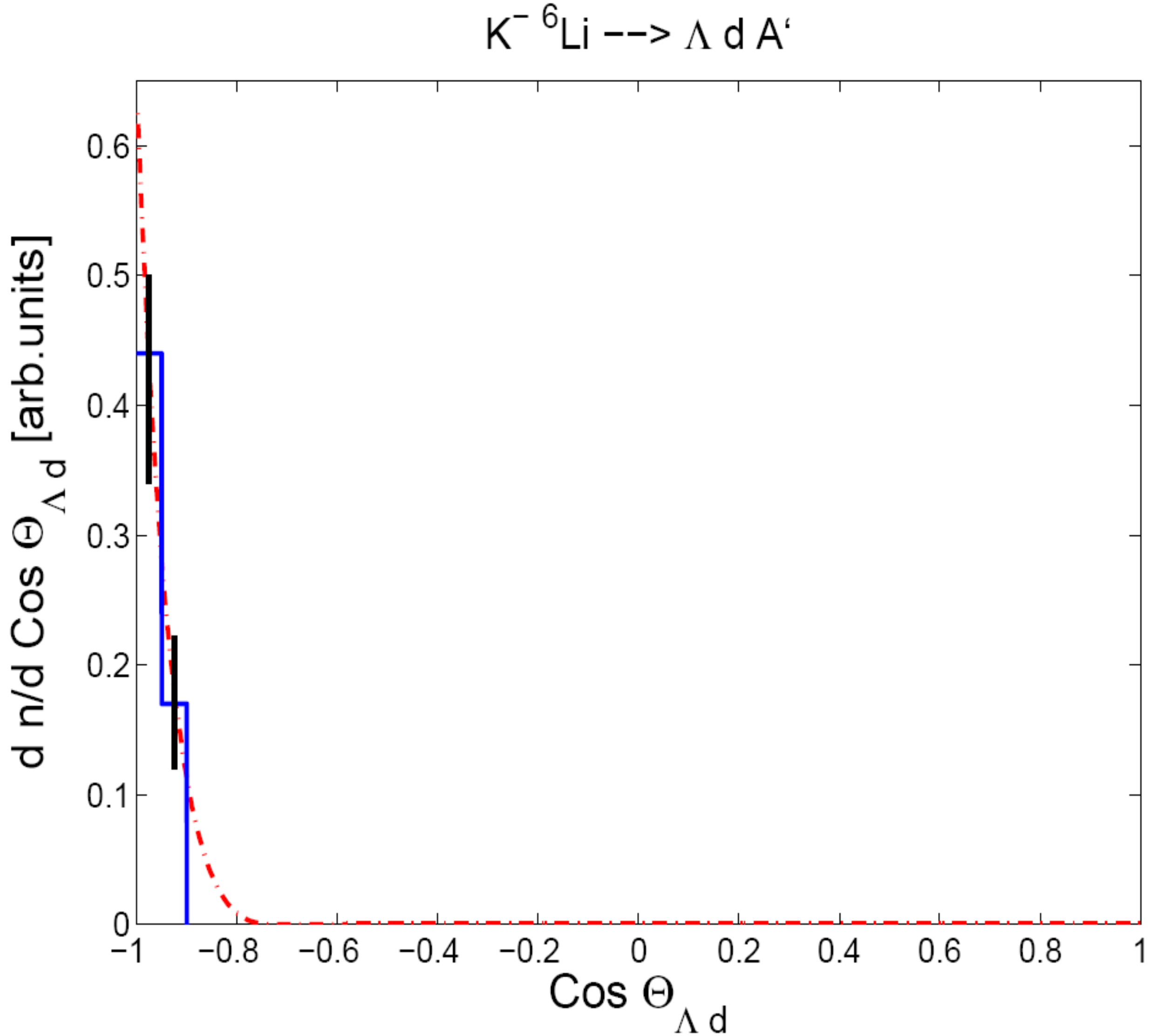
M* the energy of the 3N system

$$T_{miss} = m_{K^-} + M_{^6\mathrm{Li}} - m_\Lambda - m_n - 2M_d - (T_\Lambda + T_d)$$

Red line are results. Black bars experiment



Red line are results. Black bars experiment



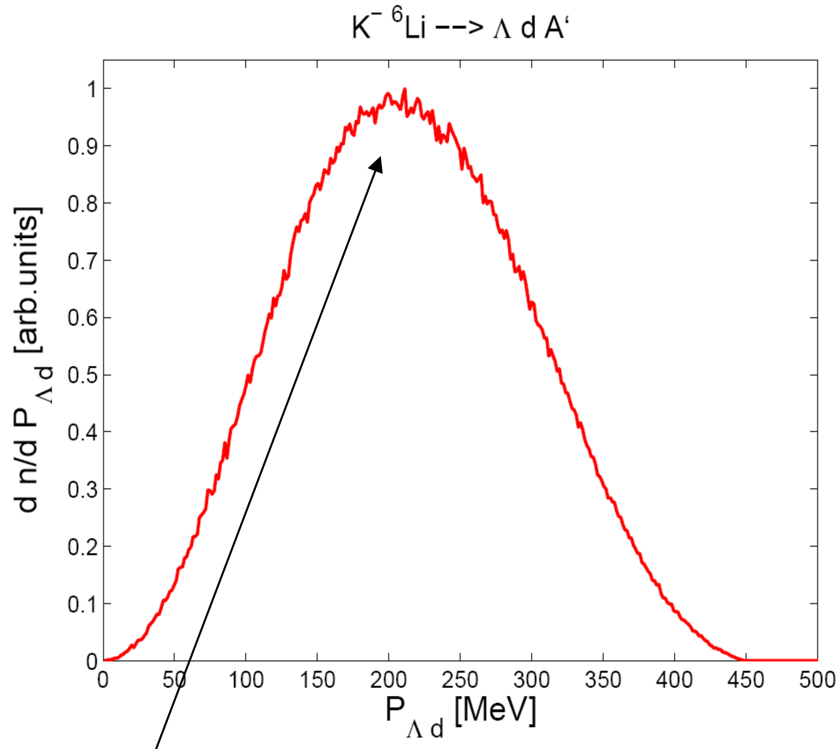
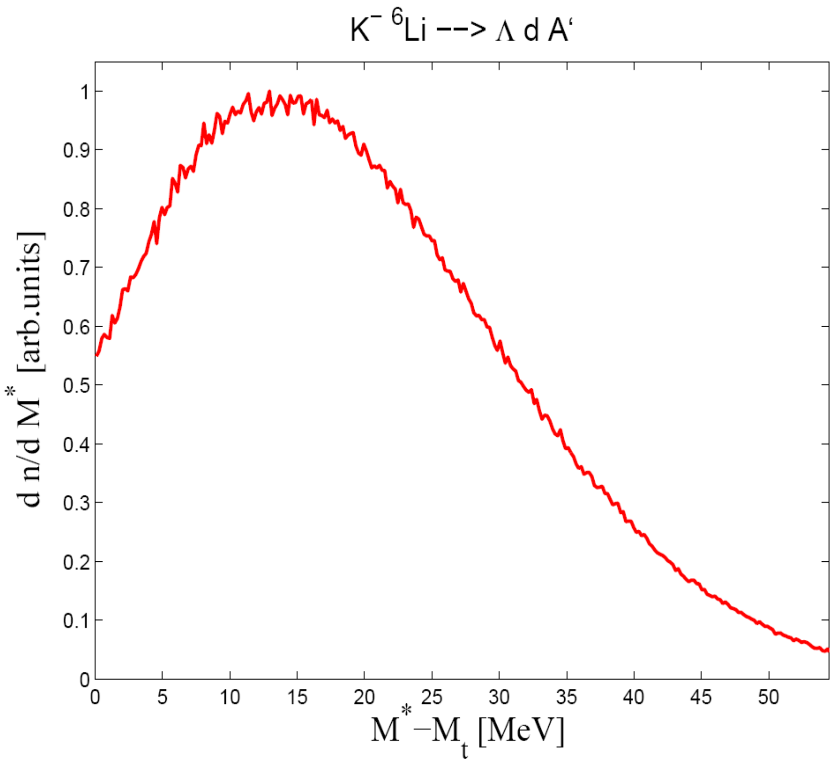
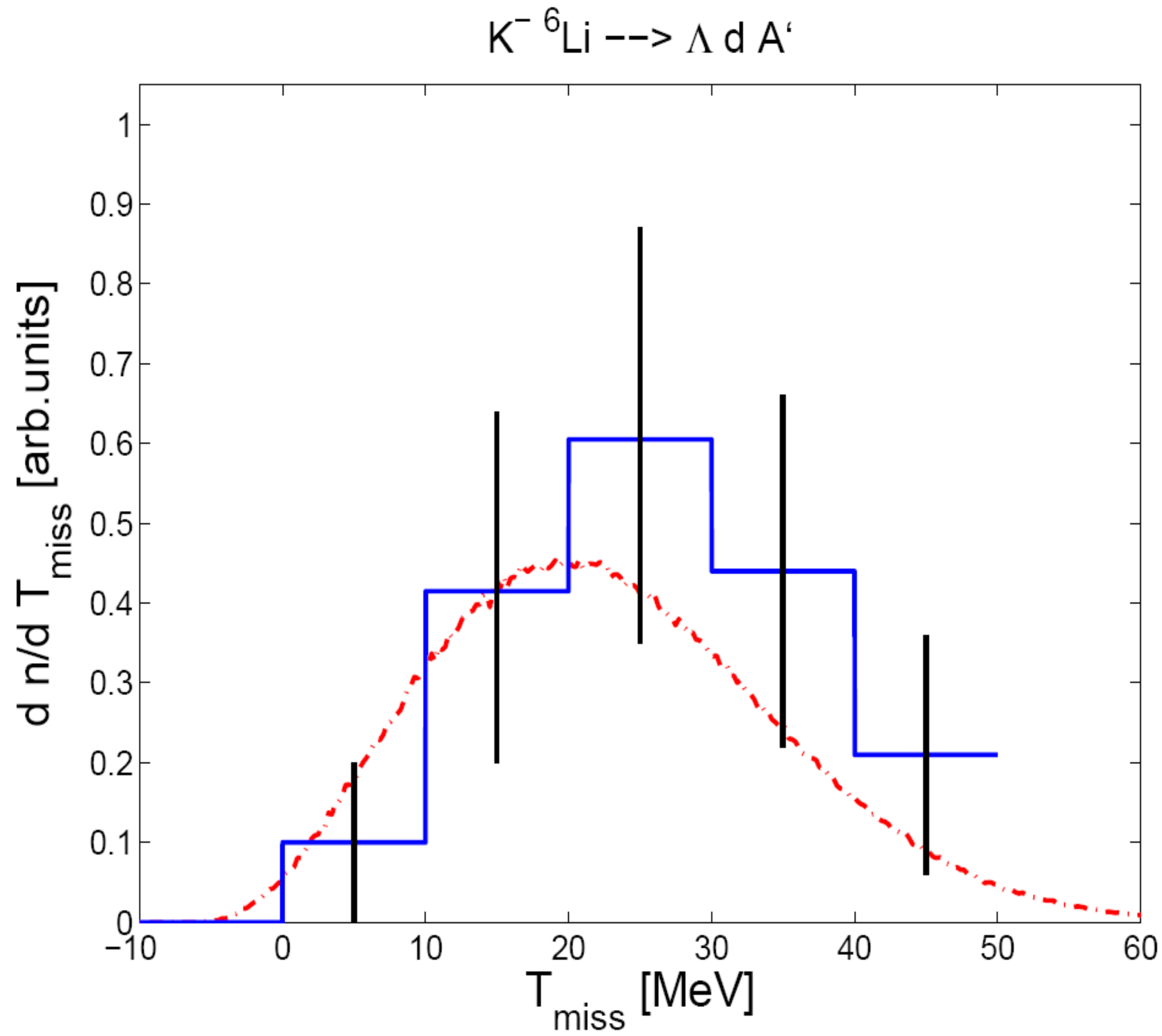


FIG. 3: (Color online) The Λd momentum distribution for the $K^-_{stop}A \to \Lambda d A'$ reaction. The calculation implements the cut 3220 MeV $< M_{\Lambda d} <$ 3280 MeV.

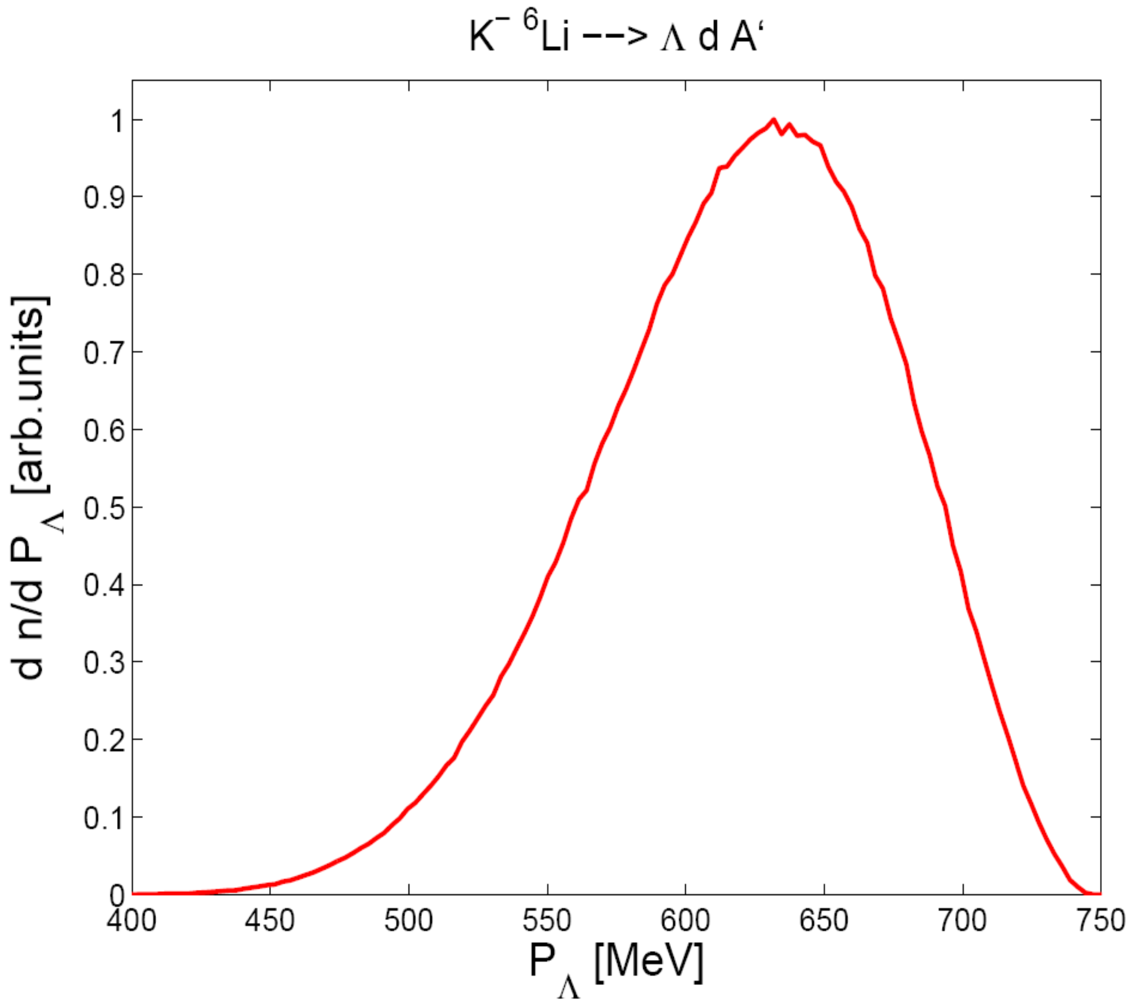


Experimental peak
appears at about 190 MeV/c

FIG. 5: (Color online) The invariant mass distribution of the residual system, Eq. (8), for the $K^-_{stop}A \to \Lambda d A'$ reaction.



Red line spreads a bit if convoluted by experimental resolution



Experimentally the Λ momentum peaks around 600 to 700 MeV/c

Conclusion:

The kinematics tied to the necessary three body absorption to make Λ d produces spectra and angular correlations identical to those observed in the FINUDA experiment

One does not need to invoke the formation of a bound eigenstate of the Hamiltonian of K^- NNN to produce the observed features.

On the positive side, we are learning about three body absorption now, and about two body absorption in former experiments.
The determination of the strength is also important. It goes beyond kinematics and allows to test dynamical theoretical models. Some work is already done. More is needed in the future.