A critical analysis on deeply bound kaonic states in nuclei and the KEK experiment

E. Oset and H. Toki
1 Departamento de Física Teórica and IFIC, Centro Mixto Universidad de Valencia-CSIC, Institutos de Investigación de Paterna, Aptd. 22085, 46071 Valencia, Spain
2 Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan

Abstract. We critically discuss the theoretical developments that led to predictions of very deeply bound kaon states and then revise the data of the KEK experiment from where claims for evidence of deeply bound kaon atoms in nuclei were made. We conclude that the peaks seen in the experiment correspond to the absorption of kaons by a pair of nucleons leading to $\Sigma p$ and $\Lambda p$ and leaving the daughter nucleus as a spectator. These conclusions have been reconfirmed by a recent experiment at FINUDA.

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1 Introduction

The success of the theoretical predictions and posterior finding of deeply bound pionic atoms lead to a search for other possible deeply bound states in nuclei. The case of deeply bound kaons was a good candidate since from data on kaon atoms it was known that the strong interaction of negative kaons with nuclei was attractive. This was in spite of the fact that the low density theorem $\pi NN = 4\rho$ gives repulsion since the isoscalar $K^-N$ amplitude at threshold is repulsive. The consideration of Pauli blocking in intermediate states was shown to be responsible for this change of sign in the interaction [1] although further considerations of self-consistency in the calculations led to a much weaker attraction than that produced by Pauli blocking alone [2,3]. These latter works were performed within the context of chiral unitary theory and all them led to moderate potentials of the order of 50 MeV attraction at normal nuclear matter density. By means of these, deeply bound $K^-$ states could be accommodated in medium and heavy nuclei with a binding of about 30 MeV, but unfortunately a very large width of the order of 100 MeV, which would make the spectroscopy of such states a hopeless task. It was then a surprise that a theoretical paper appeared predicting a much larger kaon attraction in nuclei with three and four nucleons with 108 MeV binding in $^3He$ with $I = 0$ [5]. Inspired by this prediction an experiment was done at KEK with $K^-\Lambda$ absorption at rest leading to proton emission. A peak in the proton momentum spectrum was found, but if it were interpreted as corresponding to a bound kaon atom the binding energy would have been 195 MeV and the isospin would be $I = 1$. In view of the clear discrepancy from the predictions a paper was published claiming the discovery of a strange tribaryon [6]. This experimental finding stimulated further work and the authors of [5] made some corrections to their earlier work from where they found a stronger potential of 618 MeV attraction in the center of the nucleus due among other rough approximations to allowing the nucleus get compressed to ten times the nuclear matter density [7]. From that moment on the KEK work was presented in conferences as an evidence for deeply bound kaons in nuclei. In a posterior paper [8], the authors of the present work made a critical review of the theoretical approach of [5] and found a natural interpretation for the peaks seen in [6], the essence of which we present here, together with further developments spurred by that publication.

2 Criticism of the theoretical potential leading to deeply bound kaon atoms

In [8] we make a thorough discussion of the calculations involved in the chiral models [2,3] which serves as a basis of discussion for the differences and deficiencies of the work of [5]. Limitation of space only allows here a brief description of these deficiencies:

1) In the chiral models a coupled channel approach is made which contains the channels $KN, \pi \Sigma, \pi \Lambda, \eta \Sigma, \eta \Lambda, K \Xi$. In the work of [5] only the $KN, \pi \Lambda, \pi \Sigma$ channels are considered but the couplings of $\pi \Lambda$ and $\pi \Sigma$ to themselves is neglected in spite of their large strength obtained from chiral Lagrangians. This restriction prevents the authors to get two $\Lambda(1405)$ states which are strongly supported experimentally now [9].
2) The authors of [5] assume the \( A(1405) \) to be a bound state of \( KN \), while in chiral theories the two poles are a complicated mixture of coupled channels. These assumptions lead to a \( KN \) amplitude below threshold that goes from a factor two about 50 % larger than chiral models depending on the model.

3) One of the most serious problem in the approach of [5] is the lack of selfconsistency. In the chiral calculations the \( K \) potential is obtained and inserted in the \( K \) propagators of the loops and the procedure is iterated till convergence is found. This is a must in the calculations because of the presence of the \( A(1405) \) resonance close to threshold. Indeed changes in the masses of the particles move the resonance up and down and one goes easily from attraction to repulsion of the \( K \). Needless to say that with a potential of 618 MeV attraction as in [7] the selfconsistent consideration its absolutely necessary, but it is not done in [7]. This lack is sufficient too make the results unreliable.

4) Since not enough attraction is obtained to get deep and narrow states the nuclear matter is compressed to ten times nuclear matter density in [5]. We consider this utterly exaggerated.

3 Discussion on the KEK experiment

On the basis of the discussion in the former section it is quite clear that the KEK experiment [6] could not be interpreted in terms of the creation of deeply bound kaonic states. From this perspective we would like to interpret the meaning of the peak seen there. The experiment is

\[ \text{stopped } K^- + {}^4\text{He} \rightarrow S + p \]  

where \( S \) has a mass of about 3115 MeV, and has the quantum numbers of \( YNN \) with zero charge whereas \( Y \) is a S=1 hyperon. The state \( S \) would have \( I_J = -1 \) and hence cannot be \( I = 0 \) as predicted originally in Ref. [7], which was already noted in Ref. [8]. The peak is also quite narrow, around or smaller than 20 MeV. In [5] a discussion is made of possible mechanisms producing the peak and all them are eliminated for inconsistencies with other data. Only one possible reaction passed all the experimental tests and we describe it below.

In view of the previous unsuccessful trials it was concluded in [5] that the reaction which is most likely to happen is \( K^- \) absorption by two nucleons in \( {}^4\text{He} \) leaving the other two nucleons as spectators. This kaon absorption process should happen from some \( K^- \) atomic orbits which overlap with the tail of the nuclear density and hence the Fermi motion of the nucleons is small. Then we would have \( K^-NN \rightarrow \Lambda N \), and \( \Sigma N \), and the two baryons are emitted back to back with the momentum for the proton of 562, and 488 MeV/c respectively. These results are very interesting: the peak of the proton momentum in Ref. [6], before proton energy loss corrections, appears at 475 MeV/c (see Fig. 5 of this reference). This matches well with the 488 MeV/c proton momentum from a \( K^-NN \rightarrow \Sigma N \) event, and the proton would lose about 13 MeV/c when crossing the thick target. This energy loss is compatible with the estimate of about 30 MeV/c in Ref. [6], particularly taking the width of the peak also into account.

This suggestion sounds good, but then one could ask oneself: what about \( K^-NN \rightarrow \Lambda p \) ? Should not there be another peak around 550 MeV/c, counting also the energy loss? The logical answer is yes, and curiously one sees a second peak around 545 MeV/c in the experiment. The peak is clearly visible although less pronounced than the one at 475 MeV/c and it appears in the region of fast decline of the cross section.

There are other arguments supporting our suggestion. Indeed, as mentioned above, the pion momenta from \( \Lambda \) decay are smaller than those from \( \Sigma \) decay. As a consequence of this we should expect the peak associated with \( p\Lambda \) emission to appear in the low momentum side of the pion (the range of pion momenta is from 61 MeV/c to 146 MeV/c from phase space considerations). Actually, this is the case in the experiment of Ref. [6] as one can see in Fig. 5d of this reference, corresponding to the spectrum when the low pion cut is applied, where the peak of higher momentum stands out more clearly. On the other hand, by working out the phase space for \( \Sigma \) decay, the pion momenta range from 162 MeV/c to 217 MeV/c and the pion could be seen in the two regions of pion momenta of Ref. [6], as it is indeed the case (see figs. 5c, 5d of Ref. [6]).

One can even argue about the size of the peaks and their relative strength. For this the information of Ref. [10] is very useful. There we find the following results for events per stopped \( K^- \):

\[ \Sigma^- p d \quad 1.6 \% \quad (2) \]
\[ \Sigma^- ppn \quad 2.0 \% \quad (3) \]
\[ A(\Sigma^0) pnn \quad 11.7 \% \quad (4) \]

with errors of 30-40 %.

From these data and further analysis is was concluded in [5] that one could understand the larger strength of the peak coming from \( \Sigma p \) versus that from \( \Lambda p \). It was also suggested that because the \( \Sigma^- p d \) reaction leaves indeed the daughter nucleus \( (d) \) untouched, this channel is the best candidate to explain the peak caused by the \( \Sigma p \) emission, leading to a momentum of the proton of 482 MeV/c.

The hypothesis advanced should have other consequences. Indeed, this peak should not be exclusive of the small nuclei. This should happen for other nuclei. Actually in other nuclei, let us say \( K^- {}^7\text{Li} \), the signals that we are searching for should appear when a proton as well as a \( \Sigma \) or a \( \Lambda \) would be emitted back to back and a residual nuclear system remains as a spectator and stays nearly in its ground state. We would thus expect two new features: first, the two peaks should be there. However, since now the spectator nuclear systems remain nearly in their ground states, only about the binding energy of the two participant nucleons will have to be taken from the kaon mass, instead of the 28 MeV in \( {}^4\text{He} \) for a full break up, as a consequence of which the proton momenta should be a little bigger. We make easy estimates of 502 MeV/c for the proton momentum in the case of \( p\Sigma \) emission and 574 MeV/c for the case
of $p\Lambda$ emission. Curiously the FINUDA data \[11\] exhibits two peaks in $^7Li$ around 505 MeV/c and 570 MeV/c (see comments at the end about a recent publication).

There is one more prediction we can make. The process discussed has to leave the remnant nucleus in nearly its ground state. This means that one has to ensure that the nucleus is not broken, or excited largely, when the energetic protons go out of the nuclear system. Theoretically one devises this in terms of a distortion factor that removes events when some collision of the particles with the nucleons takes place. Obviously this distortion factor would reduce the cross sections more for heavier nuclei and, hence, we should expect the signals to fade away gradually as the nuclear mass number increases. This is indeed a feature of the FINUDA data \[11\].

Similarly, we can also argue that the spectator nucleus, with a momentum equal to that of the combined pair on which $K^−$ absorption occurs, will have smaller energies for heavier nuclei since their mass is larger. Hence, the spreading of the energy of the emitted proton should become narrower for heavier nuclei. This is indeed a feature of the FINUDA data \[11\].

This sequence of predictions of our hypothesis, confirmed by the data of \[6\] and \[11\], provides a strong support for the mechanism suggested of $K^−$ absorption by a pair of nucleons leaving the rest of the nucleons as spectators. Certainly, further tests to support this idea, or eventually refute it, should be welcome. An obvious test is to search for $\Sigma$ or $\Lambda$ in coincidence and correlated back to back with the protons of the peak.

4 Conclusions

In this paper we have made a thorough review of the theoretical developments that led to predictions of deeply bound kaonic atoms in light nuclei. We could show that there were many approximations done, which produced unreliably deep potentials. Three main reasons made the approximations fail dramatically: the problem of the coupled channels to produce the two approximations fail dramatically: the problem of the cou-
