Nuclear Molecular Halo: Threshold Effect or Soft Dipole in $^{11}\text{Li}$?  

Moshe Gai

Dept. of Physics, U46, University of Connecticut, 2152 Hillside Rd.,
Storrs, CT 06269-3046, USA; gai@uconnvm.uconn.edu; http://www.phys.uconn.edu

The observation of large E1 strength near threshold in the electromagnetic dissociation of $^{11}\text{Li}$ poses a fundamental question: Is the large E1 strength due to the threshold or is it due to a low lying E1 state? Such molecular cluster states were observed in $^{18}\text{O}$ and in several nuclei near the drip line. We discuss the nature of the "threshold effect" as well as review the situation in Molecular (and Particle Physics) where such Molecular States are observed near the dissociation limit. We suggest that the situation in $^{11}\text{Li}$ is reminiscent of the argon-benzene molecule where the argon atom is loosely bound by a polarization (van der Waals) mechanism and thus leads to a very extended object lying near the dissociation limit. Such states are also suggested to dominate the structure of mesons [$a_0(980)$, $f_0(975)$] and baryons [$\Lambda(1405)$] with proposed Kaon molecular structure (e.g. by Dalitz) near threshold. The inspection of such states throughout Physics allows us to gain insight into this phenomenon and suggest that a new collective Molecular Dipole Degree of Freedom plays a major role in the structure of hadrons (halo nuclei, mesons and baryons), and that quantitative tools such as the E1 Molecular Sum Rule are useful for elucidating the nature of the observed low lying E1 strength in halo nuclei.

1 Introduction: Dipole (E1) Strength in $^{11}\text{Li}$

A measurement of the electromagnetic dissociation of $^{11}\text{Li}$ was performed at GSI from which the electric dipole (E1) strength shown in Fig. 1 was extracted.

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This measurement poses a fundamental question: Is the large E1 strength just above 1 MeV in $^{11}\text{Li}$, see Fig. 1, due to the kinematics (a "threshold effect") or is it due to the structure of $^{11}\text{Li}$ (a "low lying dipole state")? In this talk we examine these questions, we define and test the concept of a "threshold effect", as well as examine molecular structure in molecular and particle physics near threshold. We show that quantitative tools exist that allow us to examine this question in details.

The possibility of such a low lying dipole state was suggested by the RIKEN data on proton scattering off $^{11}\text{Li}$ where a peak was observed at approximately 1.3 MeV. The poor resolution of this experiment however does not permit a determination of the intrinsic width of such a state or to disintangle it from an underlying broad background. The possibility of a low lying dipole state is also given credence by the previous RIKEN data on the pion double charge exchange off $^{11}\text{B}$ where an $\ell = 1$ state at approximately 1.2 MeV in $^{11}\text{Li}$ was suggested. The pion data were given (some) credence recently. However the MSU group has recently proposed a "nuclear shakeoff mechanism" that explains this bump without invoking a low lying dipole state in $^{11}\text{Li}$. In such
a mechanism the proton (as well as the photon) imparts its momentum to the $^9Li$ core, and thus "shaking off" the two neutrons. Such a mechanism leads to a strength with a maximum at 1.3 MeV and a high energy tail, as observed in the low resolution experiment at RIKEN. The MSU group states: "In conclusion, there does not seem to be any compelling evidence from the proton scattering experiments of Korsheninnikov et al. for a 1.3 MeV excited level in $^{11}Li$.

To examine the "nuclear shakeoff mechanism" one obviously needs a probe that is strongly surface interacting. In this case the momentum could not be solely transferred to the $^9Li$ core and necessarily involves the "halo" neutrons at the surface. Such a probe is the pion (as well as other probes) and we conclude that the double pion scattering data of the RIKEN group pose some difficulty to the "nuclear shakeoff mechanism".

2 Threshold Effect: Photodisintegration of the Deuteron and $^8Li$

The photodisintegration of the deuteron shown in Fig. 2, provides a vivid example of a "threshold effect".

![Photodisintegration of the deuteron](image)

**Fig. 2:** The photodisintegration of the deuteron.
Namely, the peak shown in Fig. 2 at approximately 4.4 MeV does not correspond to a state in the proton-neutron system and arise from the kinematics as we discuss below.

The photo nuclear cross section is derived using standard notation from detailed balance:

$$\sigma(\gamma, n) = \frac{(2J_1 + 1)(2J_2 + 1)}{2(2J_3 + 1)} \sigma(n, \gamma)$$

$$= \frac{(2J_1 + 1)(2J_2 + 1)}{2(2J_3 + 1)} \frac{\mu c^2 E_{\gamma}}{E_{\gamma}} \sigma(n, \gamma)$$

$$= \frac{(2J_1 + 1)(2J_2 + 1)}{2(2J_3 + 1)} \frac{\mu c^2}{\frac{E_{\gamma}}{E_{\gamma}} - \frac{Q}{E_{\gamma}}} \sigma(n, \gamma)$$  \hspace{1cm} (equ. 1)

where the factor of 2 in the denominator arises from the two polarization states of a real transverse photon and Q = 2.223 MeV, is the one neutron separation energy in deuterium. The kinematical factor $\frac{E_{\gamma} - Q}{E_{\gamma}}$ produces a peak at 2Q in the $\sigma(\gamma, n)$ cross section even in the absence of a peak (e.g. a state) in the $\sigma(n, \gamma)$ cross section. And we conclude that the peak at 4.4 MeV ($= 2Q$) in the photodisintegration of the deuteron is solely due to that kinematical factor and we define it as a "threshold effect". But we note that in the electromagnetic dissociation of $^{11}$Li one observes a peak at approximately 1.2 MeV, see Fig. 1, which is four times the two neutron separation in $^{11}$Li (Q = 300 keV), and hence this peak in $^{11}$Li can not arise from the above kinematical factor (of equ. 1) alone.

The capture of slow neutrons by nuclei is well understood and can be expanded in terms of the neutron velocity ($v$):

$$\sigma(n, \gamma) = (\sigma E^{1/2})_0 [E^{-1/2} + \alpha + \gamma E^{1/2} + ...]$$

$$= (\sigma v)_0 \left[ \frac{1}{v} + \alpha + \gamma v + ... \right]$$ \hspace{1cm} (equ. 2)
Fig. 3: The photodisintegration of the deuteron as described by the second term ($\alpha$) of equ. 2.

The photodisintegration of $^8Li$ represents yet another good example of a threshold effect. In Fig. 4 we show these data as deduced from the direct capture of neutrons on $^7Li$. The interaction of the low energy neutrons is indeed dominated by s-waves and the cross section of the $^7Li(n,\gamma)^8Li$ follows the $1/v$ law, as shown in Fig. 4. The photodisintegration cross section is given by the first term of equ. 2, with $(\sigma v)_0 = 7.3 \times 10^{-6} \times 40 = 0.29 \mu bc$. Note the observation of (an interfering) $3^+$ state on top of a threshold effect.

Fig. 4: The photodisintegration of $^8Li$, derived from direct capture data, as described by the first term of equ. 2—the $1/v$ law.
3 The Photodisintegration of $^{11}\text{Li}$

The photodisintegration of $^{11}\text{Li}$ below 1.0 MeV yields two low energy neutrons with velocities that may differ. But the two neutrons are in fact observed to emerge with almost identical energies (see Fig. 10 of [1]), as one may expect for halo neutrons. Hence we make the assumption that the two neutrons are emitted with the same velocity (but not implying a physical di-neutron object) and we use this velocity in the paramaterization of equ. 2. For these low energy neutrons (approx. 300 keV) we also expect the $1/v$ law, as discussed above. In contrast the GSI data can not be described by the $1/v$ law, or any of the terms of equ. 2, as shown in Fig. 5. In particular the third term in equ. 2 (for $\gamma = 0.6$) does not yield a peak at 1.2 MeV. However the shape of the spectrum is sufficiently uncertain that we can not rule out a "threshold effect" and this analysis thus calls for more accurate data on the shape of the spectrum, so as to test the validity of "threshold effect". Note that for a single step capture of two neutrons with two different velocities, the low velocity neutron tends to push the shape to lower energies, considerably below $4Q = 1.2$ MeV, as discussed above.

![Fig. 5: Electromagnetic dipole (E1) strength of $^{11}\text{Li}$](image)

The ubiquitous occurrence of molecular states near threshold in Physics may indeed allow for insight into the structure of $^{11}\text{Li}$ and other such "halo" nuclei. In Fig. 6 we show characteristic dimensions of the Ar-benzen molecule. The argon atom is loosely bound to the (tightly bound) benzen molecule by
a van der Waals polarization and thus this molecular state lies close to the
dissociation limit. We note that the relative dimension and indeed the very po-
larization phenomena are reminiscent of the structure of $^{11}\text{Li}$ where the argon
atom creates a "halo" around the benzene molecule.

![Diagram of Ar-benzene molecule]

Fig. 6: Characteristics dimensions of the Ar-benzene molecule, adopted from
Iachello and Levine.

Indeed the structure of baryons and mesons near threshold was suggested
to be governed by a molecular degree of freedom. The $\Lambda(1405)$ that lies close
to the N + Kbar threshold (1435 MeV) was proposed by Dalitz to be an s-
wave NKbar molecule. And similarly the scalar meson $a_0(980)$ and the $f_0(980)$
meson that lie near the KKbar threshold at 995.4 MeV, were proposed by
Weinstein and Isgur to have the structure of a KKbar molecule, and a
signature for such a molecular structure was suggested to be given by the
ratio of the branching ratios of the radiative decay of the $\phi$ meson to the $a_0$
and the $f_0$ mesons.

## 5 The Molecular Degree of Freedom and Molecular Sum Rules

A molecular degree of freedom is characterized by excitations that involves
the relative motion of two tightly bound objects and not the excitation of
the objects themselves. Hence it is associated with a polarization vector known
as the separation vector. Such a vector can be described geometrically in
three dimensions or by using the group $U(4)$ and the very successful Vibron
model of molecular Physics. This model has two symmetry limits that
corresponds to the geometrical description of Rigid Molecules, the $O(4)$ limit,
or Soft Molecules, the $U(3)$ limit.

The polarization phenomena associated with a molecular state implies that
it should be associated with dipole excitations of the separation vector. In this
case expectation values of the dipole operator do not vanish as the center of mass and center of charge of the polarized molecular state do not coincide. Hence molecular states give rise to low lying dipole excitations. While the high lying Giant Dipole Resonance (GDR) is associated with (a Goldhaber-Teller) excitation of the neutron distribution against that of the proton, a molecular excitation involves a smaller fraction of the nucleons at the surface and is thus expected to occur at lower excitation; i.e. a soft dipole mode.

The GDR excitation exhausts the (TRK) Energy Weighted Dipole Sum Rule:

\[
S_1(E_1; A) = \frac{9}{4\pi} \frac{N^2}{A} \times \frac{e^2\hbar^2}{2m}
\]  
(equ. 3)

And for a molecular state Alhassid, Gai and Bertsch derived sum rules by subtracting the individual sum rules of the constituents from the total sum rule:

\[
S_1(E_1; A_1 + A_2) = S_1(A) - S_1(A_1) - S_1(A_2)
\]

\[
= \frac{Z_1A_2 - A_1Z_2}{A_1A_2} \times \frac{e^2\hbar^2}{2m}
\]  
(equ. 4)

\[
S_1(E_1; \alpha + A_2) = \frac{(N-Z)^2}{A(A-4)} \times \frac{e^2\hbar^2}{2m}
\]

\[
S_1(E_1; n + A_2) = \frac{Z^2}{A(A-1)} \times \frac{e^2\hbar^2}{2m}
\]

\[
S_1(E_1; 2n + A_2) = \frac{2Z^2}{A(A-2)} \times \frac{e^2\hbar^2}{2m}
\]  
(equ. 5)

Note that the sum rule for two neutrons molecular states, \(S_1(2n + A_2)\), is the same whether one assumes a "di-atomic" nuclear molecule (\(^9\)Li + a dineutron), or a "tri-atomic" nuclear molecule (\(^9\)Li + n + n). And the sum rule (as a kinematical model) does not allow us to distinguish between the two molecular cases. These molecular sum rules (equ. 4,5) were shown to be useful in elucidating molecular (cluster) states in \(^{18}\)O where the measured B(E1)'s and B(E2)'s exhaust 13% and 23%, respectively, of the molecular sum rule. Similarly, these molecular states in \(^{18}\)O have alpha widths that exhaust 20% of the Wigner sum rule. The branching ratios for electromagnetic decays in \(^{18}\)O were also shown to be consistent with predictions of the Vibron model in the U(3) limit. Indeed the manifestation of a molecular structure in \(^{18}\)O has altered our understanding of the coexistence of degrees of freedoms in \(^{18}\)O.

The dipole strength at approximately 1.2 MeV in \(^{11}\)Li, shown in Fig. 1, exhausts 20% of the two neutrons molecular sum rule, and the total strength integrated up to 5 MeV exhausts 100% of that sum rule. We emphasize that the experimental efficiency at for example 6.0 MeV is very large (30%) but no strength is found at higher energies beyond 100% of the molecular sum rule. These two facts strongly suggest the existence of a low lying soft dipole mode in \(^{11}\)Li.
6 Conclusion

In conclusions we demonstrate that quantitative tools exist to test the validity of the "threshold effect" and the "soft dipole mode" interpretation of the dipole (E1) strength in $^{11}$Li. More precise data are needed to rule out one or the other interpretation and this paper may serve as an impetus for such data. Current interpration is consistent with the existence of a low lying dipole mode in $^{11}$Li at approximately 1.2 MeV, and may pose difficulties to other interpretations.

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