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Strangeness -2 Hypernuclei

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Abstract

Approaches to the problem of observing hypernuclei containing two lambda particles (double hypernuclei) are discussed. Existing data and its implications are examined. The relationship of double hypernuclei to other $S \leq -2$ systems is considered.

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1. Introduction

Two units of strangeness may exist in a nucleus in the form of a pair of Λ particles or a Ξ particle. If the H particle exists,[1] H-hypernuclei[2] must also be considered. The three kinds of hypernuclei thus constituted ($_{\Lambda\Lambda}{}^{A}Z$, $_{\Xi}{}^{A}Z$, and $_{H}{}^{A}Z$) are very closely related and can transform into one another through the strong interaction.

This paper will deal primarily with hypernuclei containing two Λ particles and will emphasize experimental detection. Some new approaches to the problem will be suggested. Other $S \leq -2$ systems will be discussed in the context of their relationship to $\Lambda\Lambda$ hypernuclei. Ξ^- in nuclei can serve as a doorway to produce $\Lambda\Lambda$ hypernuclei; the H particle if it exists may affect their formation or decay.

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A pair of Λ particles is 25 MeV lighter than Ξ^-p, too great a mass difference to be overcome by any possible differences in binding. Therefore, Ξ^- in nuclei decay into $\Lambda\Lambda$ with a width characteristic of the strong interaction. The maximal isospin states Ξ^-n and Ξ^-nn are stable against conversion of the Ξ^- but are probably not bound. Several Ξ^- hypernuclei have been observed in emulsion experiments, and the subject has been reviewed by Dover and Gal.[3]

Double hypernuclei provide a means of studying the interaction between two Λ particles. As will be discussed later, the weak interaction between two Λ particles may be studied as well as their strong interaction. Interest in double hypernuclei has been stimulated by proposals for new particles and states of matter containing two or more units of strangeness. The H particle is of particular relevance as it has the same quantum numbers as a pair of Λ particles in the ground state of a double hypernucleus.

The H particle consists of 2 u, 2 d, and 2 s quarks in a spin and isospin singlet state. Based on the Pauli exclusion principle and simple considerations of QCD, it is the lowest-lying 6-quark state. However, the question of whether the mass of the H is below the mass of two Λ particles is unresolved. The state of the theory is such that a definitive answer cannot be expected from calculations in the near future.

In addition to the H particle, there have been several proposals for new states of matter containing two or more units of strangeness. In the conventional picture of hadrons, double hypernuclei are stable on the time scale of the strong interaction. They thus provide a cornerstone for understanding exotic systems with $S \leq -2$.

In 1979 Chin and Kerman[4] proposed that multiquark states with strangeness per baryon number $S/A = -2$ and $A>10$ would be metastable, decaying by the weak interaction. Only the volume term was included in these bag model calculations. These states would be negatively charged. In 1984 Witten[5] proposed that quark matter with $S/A = -1$ might be absolutely stable. Strange quark matter rather than normal hadrons would then be the ground state of

QCD. Farhi and Jaffe[6] shortly thereafter found that for a wide range of reasonable parameters, quark matter and multiquark states with $-.5 > S/A > -1$ would be stable. The states have an anomalously small charge to mass ratio and are positively charged.

All these proposals are based on a very simple underlying observation. Because of the exclusion principle, the energy of a system of u and d quarks can be lowered by converting some of the constituents to s quarks. Even at nuclear matter densities, the energy gained by lowering the Fermi level may be greater than the mass difference $m_s - m_{u,d}$ and may be enough to bind the system when interactions between quarks are taken into account.

2. Existing Data on Double Hypernuclei

In the 1960's there were two reports of events identified as double hypernuclei in photographic emulsion experiments. No further observations have been reported. Let us consider these events and their implications in detail.

A double hypernucleus identified as ${}_{\Lambda\Lambda}{}^{10}$Be was observed by Danysz and his collaborators[7] in 1963. The event was produced by 1.5 GeV/c K^- interacting in a photographic emulsion. A Ξ^- was produced which stopped and was captured on one of the light constituents of the emulsion (C, N, or O) producing ${}_{\Lambda\Lambda}{}^{10}$Be. The sequential decay of the double hypernucleus was observed.

$$\Xi^- + (\mathrm{C,\ N\ or\ O}) \rightarrow {}_{\Lambda\Lambda}{}^{10}\mathrm{Be}$$
$${}_{\Lambda\Lambda}{}^{10}\mathrm{Be} \rightarrow {}_{\Lambda}{}^{9}\mathrm{Be} + p + \pi^-$$
$${}_{\Lambda}{}^{9}\mathrm{Be} \rightarrow \alpha + \alpha + p + \pi^-$$

The experimenters were extremely fortunate to observe this event in an exposure of 10^5 interacting K^-. This exposure could be expected to result in 4 stopping Ξ^-.[8] In order for one of these stopping Ξ^- to result in the observed event, several steps had to occur.

(1) Capture on a light element: the light nuclei in photographic emulsion (C, N and O) comprise 10% of its mass. Capture on a light element is expected to occur for 30-40% of the stopping Ξ^-.[8]

(2) Formation of the double hypernucleus: the Ξ^- interacts with a proton in the nucleus to form two Λ particles. The Λ particles may appear in a double hyperfragment, in single hyperfragments, or as free Λ particles.

(3) Decay of both Λ particles by negative pion emission: the probability that both Λ decays are accompanied by pion emission may be estimated to be 4%.

(4) Decay with no neutral products: all decay products were charged so that a determination of the binding energy was possible.

This event was subject to intense scrutiny both by members of the collaboration who discovered it and by physicists outside the collaboration. A set of photographs of the event taken with varying depths of focus to display the various tracks and vertices is still in existence.[8]

A double hypernucleus identified as ${}_{\Lambda\Lambda}{}^{6}He$ was reported by Prowse[9] in 1966. The event resulted from the interaction of 4 GeV/c K^- with photographic emulsion. A Ξ^- was produced which stopped and was captured on a ${}^{12}C$ nucleus in the emulsion. The following sequence was observed

$$\Xi^- \, {}^{12}C \rightarrow {}_{\Lambda\Lambda}{}^{6}He + {}^{7}Li$$
$$\Lambda\Lambda{}^{6}He \rightarrow {}_{\Lambda}{}^{5}He \; p\pi^-$$
$$\Lambda\Lambda{}^{5}He \rightarrow \alpha p\pi^-$$

The exposure in this case was to 10^6 interacting K^-.

In both of the above cases the double hypernucleus was produced by a stopping Ξ^- capturing on a light nucleus. This may serve as a guide to future experimental searches. The signature is a three star event: a star occurs at the formation vertex, the double hypernucleus travels a short distance and

stops. Its decay produces a second star. A single hypernucleus recoils and stops; its decay produces the third star. Both decays are accompanied by π^- emission. The single hyperfragment recoils with a fraction of the energy liberated by the decay of the first Λ resulting in an extremely short track. In the ${}_{\Lambda\Lambda}{}^{10}$Be event, the ${}_{\Lambda}{}^{9}$Be track length was 2.5 ± 1 μm. In the ${}_{\Lambda\Lambda}{}^{6}$He event, the ${}_{\Lambda}{}^{5}$He track length was 2.1 μm. Only photographic emulsion has sufficient position resolution to utilize this short a track length as a signature.

The existence of double hypernuclei in which the Λ particles decay sequentially has important consequences (apart from any quantitative measurements of their properties). It bears directly on the existence of the H particle. If the mass of the H is less than the mass of two Λ particles, how can the sequential decay be explained? Why don't the two Λ particles fuse to form an H particle?

There are several domains in which the existence of the H with $m_H < 2m_\Lambda$ can be reconciled with the observed sequential decays:

1) Binding effects may make it energetically impossible for two Λ's to form an H in a nucleus. This occurs if

$$B_{\Lambda\Lambda} > m_H - 2m_\Lambda + B_H$$

where B_H is the binding energy of an H to the nucleus and $B_{\Lambda\Lambda}$ is the energy required to separate both Λ's from the hypernucleus.

2) If the H particle binds to nuclei to form H hypernuclei, and the mass of the H is such that the decay[10] $H \rightarrow \Lambda p \pi^-$ can occur, then an H-hypernucleus can undergo a sequential decay which cannot readily be distinguished from the decay of a double hypernucleus. Because the mass of the H is at least twice the mass of a nucleon, a small attractive potential is sufficient to bind H-hypernuclei.[2]

If the decay of an H-hypernucleus is mistaken for the decay of a double hypernucleus, then the apparent binding energy of the double hypernucleus is

$$B_{\Lambda\Lambda} = m_H - 2m_\Lambda + B_H$$

3) In general, for $B_{\Lambda\Lambda} < m_H - 2m_\Lambda + B_H$ the strong conversion $\Lambda\Lambda \to H$ proceeds much more rapidly than the weak decay of the Λ.

However, there may be mechanisms[11] which suppress the strong conversion. Kerbikov has calculated the width for ${}^{6}_{\Lambda\Lambda}He \to H + \alpha$ and found

$$\Gamma_S \propto \sqrt{Q}\ e^{-aQ}$$

where Q is the energy released in the decay. For small Q the decay is suppressed by the phase space factor $\sqrt{Q}$. Dover has pointed out that for very large Q the decay is suppressed by the exponential factor. Dominance of the weak decay in this limit probably pertains only for m_H slightly above the mass of two nucleons.

For the observed two events, $B_{\Lambda\Lambda}$, the energy required to separate the two Λ's from the hypernucleus has been derived from an analysis of the energy released in the decay of the double hyperfragments. The separation energy[12] is much better determined in the ${}_{\Lambda\Lambda}{}^{10}Be$ event:

$$B_{\Lambda\Lambda}\ ({}^{10}_{\Lambda\Lambda}Be) = 17.7 \pm .1\ \text{MeV}$$

$$B_{\Lambda\Lambda}\ ({}^{6}_{\Lambda\Lambda}He) = 10.9 \pm .5\ \text{MeV}$$

The binding energy of a single Λ to the nuclear core is well determined from studies of single hypernuclei[12]

$$B_\Lambda\ ({}^{9}_{\Lambda}Be) = 6.71 \pm .04\ MeV$$

$$B_\Lambda\ ({}^{5}_{\Lambda}He) = 3.12 \pm .02\ MeV$$

Thus the part of the binding energy resulting from the interaction of the two Λ particles can be defined

$$\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda} - 2B_\Lambda$$

$$\Delta B_{\Lambda\Lambda}\ ({}^{9}_{\Lambda\Lambda}Be) = 4.29 \pm .1\ MeV$$

$$\Delta B_{\Lambda\Lambda}\ ({}^{6}_{\Lambda\Lambda}He) = 4.68 \pm .5\ MeV$$

The near equality of $\Delta B_{\Lambda\Lambda}$ for the two species suggests that the energy of interaction between the two Λ particles is the same in both cases. This is rather puzzling. In view of the measured values of $B_\Lambda\ ({}^{A-1}_{\Lambda}Z)$, it can be stated that the Λ particles are much less tightly bound to the nuclear core in ${}^{6}_{\Lambda\Lambda}He$ than in ${}^{10}_{\Lambda\Lambda}Be$. This implies a lesser overlap of the wave function of the two Λ's and hence the expectation for a smaller interaction energy between the two Λ's. This qualitative expectation is confirmed by the calculation of Bodmer and his collaborators.[13] In a cluster model which treats ${}_{\Lambda\Lambda}{}^{6}He$ as $\alpha + 2\Lambda$ and ${}^{10}_{\Lambda\Lambda}Be$ as $2\alpha + 2\Lambda$, they have failed to find a $\Lambda\Lambda$ potential which is consistent with both the reported events. Thus there appears to be an inconsistency, in the conventional picture, between the values of $B_{\Lambda\Lambda}$ reported.

The observation of additional double hypernuclei would strengthen the conclusions drawn regarding the allowed mass range for the H particle and resolve the questions raised by the near equality of $\Delta B_{\Lambda\Lambda}$ for the two reported events.

3. Hybrid Emulsion Experiments

Since the two existing double hypernuclei were observed in photographic emulsion and since the three star signature can in most cases only be resolved in emulsion, further searches in this medium are clearly suggested. The use of fast electronic detection in conjunction with emulsion to select candidate events for scanning in the emulsion is highly desirable. In hybrid emulsion experiments the events in the fast detectors are correlated with the interaction in emulsion through spatial localization with an accuracy of 100 μm or better. This technique has been applied to the study of ν interaction and to the measurement of lifetimes of charmed particles and B-mesons.

The application of this technique to double hypernuclei was first suggested by Burhop[14] more than ten years ago. The experiment he suggested is as follows: A K^- beam is incident on an emulsion target. A K^+ leaving the target signals that two units of strangeness have been transferred to the target. Fast detectors identify and track the K^- and K^+. The emulsion is scanned at the K^-K^+ vertex which is well localized.

An experiment along these lines was proposed[15] at KEK in 1987 and is now underway. Silicon strip detectors are used to track the K^- and K^+. The emulsion will be scanned by tracing back the K^+ track. An exposure of 30 liters of emulsion is planned. This should result in 300 stopping Ξ^-.

Based on the expectation that large amounts of strangeness could be produced in heavy ion collisions, hypernuclei have been searched for in a hybrid emulsion exposure made in connection with experiment NA34 at the CERN SPS. In the experiment an emulsion was exposed to 225 GeV/c beams of ^{16}O and ^{32}S. Events with high transverse energy or high multiplicity could be selected for scanning in the emulsion. A search for Λ hypernuclei was envisioned if copious production of single hyperfragments were observed. Slow single hyperfragments have been observed but not in sufficient numbers to suggest that double hyperfragments could be expected. Analysis of the data for other kinematic regions is in progress.[16]

4. New Approaches to Detecting Double Hypernuclei

Can double hypernuclei be detected without the use of emulsion? A reaction where the double hyperfragment is produced in a two body final state would provide a clean signature.

The reaction

$$K^- + Z \rightarrow {}_{\Lambda\Lambda}(Z - 2) + K^+$$

has been discussed[17] in the literature. Unfortunately, a two step process with large momentum transfer is required and the cross sections are correspondingly small.

A more promising approach is to stop Ξ^- in a nuclear target. An experiment using the reaction

$$\Xi^- \, {}^6Li \rightarrow {}_{\Lambda\Lambda}{}^6He + n$$

is under active consideration.[18] Observation of the monoenergetic neutron with kinetic energy of approximately 30 MeV identifies the formation of ${}_{\Lambda\Lambda}{}^6He$. This hypernucleus consists of two neutrons, two protons and two lambda particles all in s states.

Like the α particle it is expected to be particularly stable. The small energy release in the reaction, together with the strong binding of the hyperfragment lead to the expectation of a significant branching ratio.[19]

This experiment would

(1) Confirm the existence of double hypernuclei and strengthen conclusions based on the existence of the previously reported emulsion events; improve the measurement of $B_{\Lambda\Lambda}({}_{\Lambda\Lambda}{}^6He)$.

(2) Provide a measurement of the production rate of double hypernuclei. Suppression or enhancement of the production rate due to the existence of the H particle could be determined.

(3) Provide a source of double hypernuclei for study of their properties, for example their weak decays.

The Ξ^- is formed in the reaction

$$K^- p \rightarrow \Xi^- K^+$$

The cross section for this reaction peaks at $p_{K^-} = 1.8$ Gev/c. A new, high intensity K^- beam is being built at Brookhaven. It is optimized for Ξ^- production with design momentum at the peak of the production cross section. By identifying and momentum analyzing the K^- and K^+, Ξ^- of known momentum can be selected. The momentum of the Ξ^- is minimum if the reaction takes place at 0°. Since the minimum Ξ^- momentum is approximately 550 MeV/c, a high density degrader is required to bring it to rest in the ^{6}Li target where the double hypernucleus is formed.

The target is surrounded by wire chambers which track the charged decay products of the hyperfragments, and by neutron counters. The neutrons are detected by proton recoil in a scintillator and their energy is determined by time of flight. Observation of the charged decay products of the double hyperfragments can help suppress backgrounds, and is interesting in its own right as will be discussed later.

One source of neutron background is the decay of the Ξ^-

$$\Xi^- \rightarrow \Lambda \pi^-$$

followed by

$$\Lambda \rightarrow p \pi^-$$
$$\rightarrow n \pi^\circ$$

In addition to the neutron from Λ decay, the π^- may be captured in a nucleus giving rise to neutrons.[20]

This background can be reduced by excluding as many as possible of those Ξ^- which will not stop in the target. For Ξ^- produced on protons, the 2-body kinematics can identify those Ξ^- with the correct range to stop in the target. The observation of hypernuclear decay products can be used to exclude those Ξ^- which decay before stopping.

When a Ξ^- interacts with a proton in the ^{6}Li target, we have in the final state 2 Λ particles, an α particle, and a neutron. Only the desired reaction results in a monoenergetic neutron. Cases where neither, or only one Λ particle is bound to the α give rise to background

$$\Xi^- \, {}^6\mathrm{Li} \rightarrow \Lambda + \Lambda + \alpha + n$$

$$\Xi^- \, {}^6\mathrm{Li} \rightarrow \Lambda + {}_{\Lambda}{}^{5}\mathrm{He} + n$$

The resulting neutron spectra or end points are shown in figure 1 and are clearly separated from the reaction of interest.

Reactions which break up the α particle have a much lower q value and are therefore not a problem. For example,

$$\Xi^- \, {}^6\mathrm{Li} \rightarrow 2 \, {}_{\Lambda}{}^{3}\mathrm{H} + n$$

has a maximum neutron kinetic energy of only 1 MeV and is suppressed by phase space. Weak decays of hypernuclei will produce neutron background, but the neutron energies will be distributed over a broad range.

The detection of new decay modes which exist only in double hyperfragments may be sufficient in itself to identify double hypernuclei.[18] This is a second new approach.

The free lambda decays predominantly by

$$\Lambda \rightarrow p\ \pi^-$$
$$\Lambda \rightarrow n\ \pi^\circ$$

In a single hypernucleus, new modes result from the weak interaction of the lambda with nucleons. These are referred to as neutron stimulated and proton stimulated decays.

$$\Lambda n \rightarrow nn$$
$$\Lambda p \rightarrow np$$

In a double hypernucleus we may observe the weak interaction between two lambda particles.[21]

$$\Lambda\Lambda \rightarrow \Lambda n$$
$$\Lambda\Lambda \rightarrow \Sigma^- p$$
$$\Lambda\Lambda \rightarrow \Sigma^\circ n$$

Double hyperfragments may be identified through these characteristic decay modes. For example, in the decay

$$_{\Lambda\Lambda}{}^{6}He \rightarrow \Sigma^-\ \alpha\ p$$

the emission of a Σ^- is a highly unusual signature.

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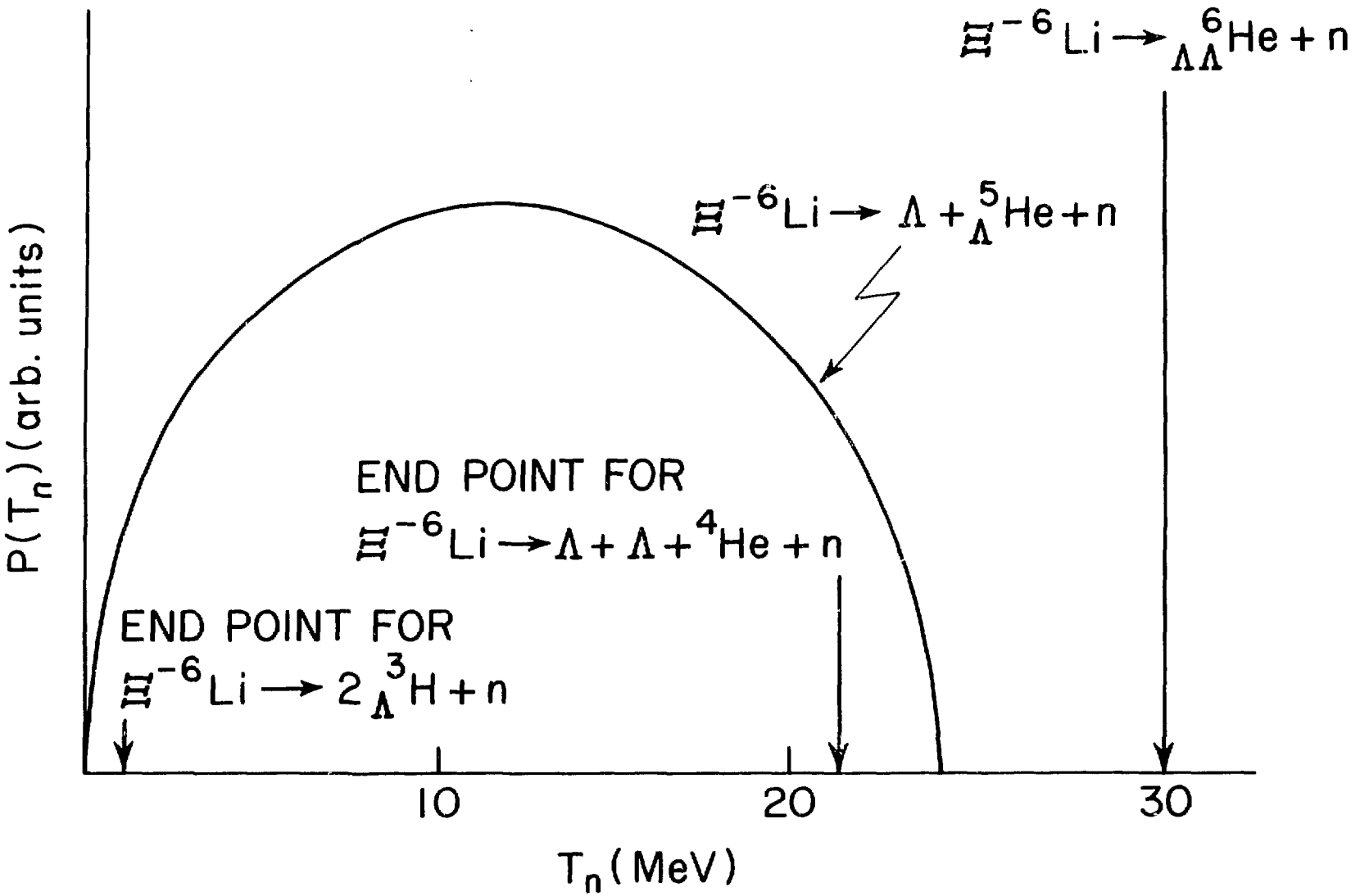
Figure Caption

Figure 1. Energies of neutrons emitted in various Ξ^{-6}Li reactions.


$\Xi^{-6}Li \rightarrow {}_{\Lambda\Lambda}^{6}He + n$
$\Xi^{-6}Li \rightarrow \Lambda + {}_{\Lambda}^{5}He + n$
END POINT FOR
$\Xi^{-6}Li \rightarrow \Lambda + \Lambda + {}^{4}He + n$
END POINT FOR
$\Xi^{-6}Li \rightarrow 2\,{}_{\Lambda}^{3}H + n$
$P(T_n)$ (arb. units)
10
20
30
T_n (MeV)