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AUTHOR(S) P. D. Barnes, UN-DO

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Los Alamos MASTER
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Search for the H particle: Its production and weak decay

Peter D. Barnes

Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
(For the BNL H Particle Collaboration [1], E-813)

Abstract

Jaffe has suggested that a six-quark state with the flavor content of two-lambda hyperons with all spins coupled to zero, the H particle, may be bound against strong decay. This particle has become the object of extensive discussion in the literature and of several experimental searches. We report here the present status of an investigation of the reaction: $(\Xi^-, d)_{\text{atom}} \rightarrow H + n$ in experiment E-813 at the BNL-AGS and describe plans for future running in 1992.

1. INTRODUCTION

The possible existence of multi-quark hadron states beyond $Q\bar{Q}$ and QQQ has been discussed for many years. Investigations of the role of the spin-spin interactions among the quarks has led to quantitative estimates of the baryon and meson masses and their properties. Of particular interest has been the six-quark state with the flavor content of two lambda hyperons but with the six spins recoupled to give the minimum mass. This state was originally discussed by Jaffe [2] in 1977 and labeled the "H particle." More recently, it has become the object of extensive discussion in the literature, both in terms of calculated properties and experimental searches. A new experimental search for this object has just begun taking data at the Brookhaven National Laboratory AGS. After a brief review of the properties of this particle, the present status of this measurement (E-813) will be discussed.

2. CALCULATIONS

In an investigation of low-mass six-quark states, Jaffe found that the system $uuddss$ can have especially low mass in a state with total spin zero, charge zero, isospin zero, and positive parity. The six quarks in the system have highly similar spatial wave functions (s-wave), and, in that respect, the system is rather *unlike* a deuteron or even a dihyperon. Among wave functions of six-quark systems, the H particle belongs to the 490 representation in the $SU(6)$ color-spin group and is a singlet in the $SU(3)$ flavor group.

From the perspective of constituent quark models, an essential ingredient in the binding of the H particle is the hyperfine interaction of the six quarks due to gluon exchange, which is parameterized as:

$$H_{\text{hfs}} = -c \sum_{i>j} \frac{(\lambda_i \cdot \lambda_j)(\sigma_i \cdot \sigma_j)}{m_i m_j} ,$$

where m_i , λ_i , and σ_i are quark masses and Gell-Mann and Pauli matrices summed over all pairs, and c is a constant that depends on the square of the wave function for a quark pair, evaluated at the origin. Thus, the H particle is the spin-zero state whose eigenvalue has the largest downward shift, Δ_H under the hyperfine interaction. In the flavor-SU(3) symmetric case, Δ_H for the H particle corresponds to about -450 MeV, and gives a binding energy in the constituent quark model of: $B_H = 2\Delta_\Lambda - \Delta_H = 150$ MeV. This reduces to about 50 MeV for the case [3] of heavy strange quark masses. Jaffe calculated the six-quark mass spectrum [2] in the bag model and obtain an H particle mass of 2150 MeV and thus a binding energy of about 80 MeV.

Since the original bag model calculations of the H particle mass by Jaffe, the properties of this state have been analyzed in calculations as varied as quark potential models to lattice gauge calculations. MIT bag model and cloudy bag model estimates generally tend to give a positive binding energy, B_H , although effects such as center-of-mass corrections and pressure from the pion cloud require special attention. Topological soliton (Skyrmion) models continue to give rather low masses. Oka [4,5] has shown that a nonrelativistic quark potential model calculation gives an H particle unbound by ~ 27 MeV. In a related calculation this has been confirmed by Silvestre-Brac et al. using a resonating group trial wave function and correctly treating the center-of-mass motion and the Pauli principle. They obtain $B_H = -70$ MeV. In 1985, Mackenzie and Thacker [6] reported a lattice gauge calculation in which the H particle was found to be strongly unbound. More recently, Iwasaki et al. [7] reported calculations on a much larger lattice in which they find the H particle strongly bound with a mass of about 1800 MeV. Recent calculations by Dover and Feshbach [8] based on the hyperon-nucleon interaction suggest that the H particle is unbound against strong decay.

The spin one excitation spectrum of the H particle has been investigated by G. Karl et al. [9] in a constituent quark model. For the case of broken SU(3) symmetry, they find a pair of spin one states with $I = 0$ and 1 at 180 and 240 MeV excitation energy, respectively.

On both theoretical and experimental grounds it is quite interesting to investigate the decay properties of the H particle (see Fig. 1). For a moderately bound H particle, the available open channels consist of $\Delta S = 1$ transitions to ΣN and ΛN final states and $\Delta S = 2$ transitions to the NN system. One expects the decay to be dominated by nonleptonic weak processes very much like hyperon and hypernuclear decay [10]. As for most hypernuclear decay, the process could be nonmesonic. For the $\Delta S = 1$ transitions, Jaffe [2] took into account both the phase space available and the SU(3) couplings to get the relative branching ratios shown in Table 1 for $B_H = 0$.

Table 1
Relative branching ratios for H decay

Transition	Jaffe [2]	Donoghue [10]
$H \rightarrow \Sigma^- p$	50%	40%
$H \rightarrow \Sigma^0 n$	30%	45%
$H \rightarrow \Lambda^0 n$	20%	15%

More recently, Donoghue et al. [11] have made extensive calculations of both the $\Delta S = 1$ and 2 decay modes as a function of H particle mass. They find that because of the structure of the six-quark wave functions, $s \rightarrow d$ quark transitions are enhanced over $s \rightarrow u$ quark transitions. This is contrary to the usual case in nonleptonic weak hyperon decay and the

Decay Modes of H Particle

Figure 1. Two-baryon mass spectrum and decay modes of the H particle.

resulting dependence on the small pieces of the effective weak Hamiltonian leads to long predicted lifetimes. Data on kaon and hypernuclear weak decay indicate that $\Delta I = 1/2$ transitions are actually enhanced by a factor of twenty over $\Delta I = 3/2$ transitions leading to hyperon lifetimes of the order of 10^{-10} sec. In the Donoghue calculation [11] for decay of the H particle, the authors obtain (with $B_H = 0$) a longer lifetime, $\approx 10^{-8}$ sec, for transitions into the ΣN system and they predict that the $\Delta I = 3/2$ amplitudes will dominate the $\Delta I = 1/2$ amplitudes.

For H particle masses below the ΣN threshold (see Fig. 1) only the $\Delta I = 1/2$ transition into the ΛN system is allowed and the calculated lifetime grows by a factor of ten. At lower masses

NN is the only open channel and the lifetime grows to about 10^{+6} seconds for this $\Delta S = 2$ transition. Thus, these calculations predict a suppression of the usually strong $\Delta I = 1/2$ transition and, consequently, a rather long lifetime. This is interesting on theoretical grounds and also because of its implications for detection of the H decay in an experiment.

In summary, it is quite important to make an experimental verification of the existence of the H particle. It is intrinsically interesting as a new form of matter. Establishing its mass will set the mass scale for the six-quark spectrum. Moreover, an investigation of the H particle decay modes will test the special character of its wave function, test the relevance of the proposed effective weak interaction for nonleptonic decays, and finally, test the rather dramatic prediction of a significant violation of the $\Delta I = 1/2$ rule. What is needed is a high-sensitivity measurement in the region of the $\Lambda\Lambda$ mass and below. If this object is not found, it is important to set meaningful upper limits on its production cross section.

3. H PARTICLE SEARCH EXPERIMENTS

Two complementary experiments [1] to search for the H dibaryon are now under development or in progress at the AGS at BNL. The reactions used for each measurement are shown in Fig. 2. AGS experiment E-813 requires the formation of (Ξ^-, d) atoms leading to the reaction $\Xi^- + d \rightarrow H + n$. The experiment, shown schematically in Fig. 3, involves the

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

$$\Xi^- + (pn) \rightarrow H^0 + n$$

Figure 2. Two-step reaction processes used in the two BNL AGS experiments. Experiment E-813 uses cryogenic liquid targets of both hydrogen and deuterium. H particle production is induced by a Ξ^- bound in an atomic orbit of deuterium. Experiment E-836 uses a single ^3He target in which a virtual Ξ^- is produced and then combines with a proton to produce the H particle.

A.G.S. Experiment E 813

Figure 3. Schematic layout of the $(\Xi^-, d)_{\text{atom}}$ experiment, E-813. The detection of neutrons from the reaction $(\Xi^-, d)_{\text{atom}} \rightarrow \text{H} + n$ will be the signature of the H particle production.

creation of Ξ^- hyperons in a liquid hydrogen target with the reaction $K^- + p \rightarrow K^+ + \Xi^-$. The recoiling Ξ^- is then stopped in a liquid deuterium target. Monoenergetic neutrons from the two-body reaction $(\Xi^-, d)_{\text{atom}} \rightarrow \text{H} + n$ give a clear, unambiguous signature for the formation of the H particle. This version of the experiment was shown to be sensitive over a mass region from 20 MeV above the mass of two Λ hyperons ($B_{\text{H}} = -20$ MeV) to approximately 80 MeV below the mass of two Λ hyperons ($B_{\text{H}} = +80$ MeV) (see Ref. [12]).

Experiment E-836 requires the replacement of the two-component target used in the $(\Xi^-, d)_{\text{atom}}$ H search, with a single ^3He target used in the reaction $K^- + ^3\text{He} \rightarrow K^+ + \text{H} + n$ as either a coincidence K^+n measurement or an inclusive K^+ measurement. The similarity between the two reaction mechanisms is illustrated in Fig. 2. With the ^3He target, greater sensitivity to a more tightly bound H is achieved. In view of this complementary nature of the ^3He version of the H search, the experimental apparatus for each version was designed to be as compatible with the other as possible. Although this second measurement has the advantage of covering a wider mass region, it is technically more difficult due to the need to reject pion contamination in the initial or final state to better than $1:10^4$. It also has poor sensitivity in the region of small binding energy. However, this is the region in which the $(\Xi^-, d)_{\text{atom}}$ measurement has the highest sensitivity.

Except for targets, both experiments use the same apparatus as shown in Figs. 4 - 6. The incident beam channel utilizes momentum analysis and has three independent methods of rejecting the π^- contamination. Figure 4 shows the composite hydrogen/deuterium target designed for E-813. The outgoing K^+ mesons are momentum analyzed and again there are three independent methods of pion rejection (see Fig. 5). Figures 6 and 7 show the 100-element neutron detector around the cryogenic target and a simulated neutron TOF spectrum.

Target Geometry

Figure 4. Detailed drawing of the hydrogen/deuterium target. The Ξ^- passes through the tungsten degrader and the silicon detector before passing into the deuterium region, stopping, and forming the atomic system. This is one of twenty cells that make up the 60-cm target.

K^+ Spectrometer Elevation View

Figure 5. Layout of the K^+ spectrometer. Pions are rejected by two aerogel Cherenkov detectors, while recoil protons are identified by the Lucite Cherenkov detector. The K^+ survival factor to the TOF hodoscope is 43%.

Figure 6. The neutron detector consists of two fifty-element arrays on each side of the target, with about a 1-m flight path. The efficiency times solid angle is about 9%.

Schematic: Neutron TOF Spectrum

Figure 7. Schematic neutron time-of-flight spectrum, assuming the H particle binding energy is 10 MeV.

This apparatus has been installed at the AGS, tested with beam in the spring, 1991, and used in a first data run on experiment E-813. The goals of the run were to test the new 2.0-GeV/c beam line for intensity and purity, evaluate performance of the composite hydrogen/deuterium cryogenic target, including the silicon detector array, and to measure coincidence and background rates in the apparatus.

For the 2.0-GeV/c beam line [13], shown in Fig. 8, we obtained the kaon rates and π/K ratios versus momentum, shown in Fig. 9. During these measurements the electric field in the separator gap was limited to about 80% of the design goal. We believe this problem is now corrected and, in the next run, we expect to improve upon the 4:1 π/K ratio at 1.7 GeV/c and to lower the singles rates in the in-beam counters.

2.0 GeV/c Separated Beam Line

Figure 8. New 2.0-GeV/c beam line at the AGS with two stages of electrostatic separation.

During this initial run we obtained an integrated flux of $6 \times 10^{10} K^-$ on the hydrogen target. The mass distribution for the reconstructed tracks in the K^+ spectrometer are shown in Fig. 10. The intense proton peak is due to K^- elastic scattering at back angles from a proton. For the detected K^+ , the missing mass spectrum shows a clean Ξ peak, as shown in Fig. 11. With about 10% of the tapes analyzed, the projected integrated exposure of $6 \times 10^{10} K^-$ incident on the hydrogen target will generate about 4000 events in the Ξ^- missing-mass peak. This produces about 1880 coincidence events (Ξ^- 's and decay products) in the silicon detectors. A preliminary analysis of the time and energy deposited for hits in the silicon detectors is shown in Fig. 12. The plot illustrates the low accidental background for large pulse heights. The region where we expect to find Ξ hyperons that have a large probability of stopping in the liquid deuterium is indicated by the block outline. Analysis of the time-of-flight spectrum in the neutron detectors is in progress.

If R is the branching ratio for decay of the Ξ^- deuterium atomic system into the neutron plus H particle final state [12], we estimate the number of neutrons in the H particle peak in the TOF spectrum (see Fig. 7) to be about $10R$ for this set of data.

Running will continue in the late spring, 1992. Our overall goal is to collect $10^{12} K^-$ on target, 2×10^5 events in the Ξ missing-mass peak, about 2000 stopped Ξ in deuterium, and to produce about $170R$ neutrons in the H particle peak (Fig. 7). As an indication of our sensitivity, if $R = 10\%$, we estimate, from measured background rates, that this will produce a 2.7 standard deviation effect.

Figure 9. Performance data for the 2.0-GeV/c beam line obtained in the spring, 1991, with the separators operating at about 80% of their design voltage.

Reconstructed Mass vs. Momentum

Figure 10. Reconstructed mass versus momentum for particles tracked through the K⁺ spectrometer at a scattering angle of 7 to 9 degrees. The large number of protons results from kaon-hydrogen elastic scattering at large kaon angles.

Missing Mass Spectrum

Figure 11. Preliminary missing-mass spectrum for K⁺ events in which the Ξ^- peak is clearly visible.

Figure 12. Comparison of time of arrival versus energy deposited in the silicon detectors for events in the Ξ^- missing-mass peak. The boxed region indicates candidate events for a Ξ^- that will stop in the liquid deuterium. Note the low accidental coincidence rate in this region.

It is intriguing to ask what experimental information we have in hand that would constrain the mass region in which to search for the H particle. Three cases are especially relevant. To what extent does the existence of nonstrange nuclei rule out the region below the two-nucleon mass? Ejiri [14] has pointed out that as a result of the search for double ρ decay, good measurements exist on the stability of certain nuclei. In favorable cases, these measured nuclear lifetimes are up to ten orders of magnitude longer than estimates for the transition rate $NN \rightarrow H$ using an effective weak Hamiltonian for this $\Delta S = 2$ process. Despite the known uncertainties in this type of weak decay calculation, this large factor would appear to exclude all masses more than a few MeV below the nucleon-nucleon mass.

The weak decay of Λ hypernuclei in which the strangeness is reduced by one unit has been studied for a number of years [10]. There is no experimental evidence for a strangeness increase in these decays, as for example, in the elementary process $\Lambda N \rightarrow H$, although this has not been carefully explored. Kishimoto [15] has estimated the partial width for the particular decay branch, $\Lambda p \rightarrow H\pi^+$, to be at the 0.5% level.

Finally, the existence of long-lived double Λ hypernuclei is unclear at this time, but it is of great relevance to H decay. One might look for the strong process $\Lambda\Lambda N \rightarrow HN$ as a rapid strong decay mode. Thus, evidence for the existence of long-lived $\Lambda\Lambda$ nuclei could be used to exclude a large region of mass for the H particle. There are currently two events reported in the literature as evidence for ${}_{\Lambda\Lambda}^6\text{He}$ and for ${}_{\Lambda\Lambda}^{10}\text{Be}$. This experimental evidence for long-lived double strange hypernuclei has been reviewed recently by Dalitz et al. [16]. They conclude that there appears to be little reason to question the interpretation of the single ${}_{\Lambda\Lambda}^{10}\text{Be}$ event. When the nuclear binding energies are taken into account, its existence would seem to exclude the mass region corresponding to $B_H \approx 15$ MeV and above.

Thus it becomes extremely important to confirm the existence of these doubly strange nuclei. There is currently in progress an experiment (E-176) at KEK [17] that could clarify this issue. It utilizes an emulsion stack bombarded by K^- mesons followed by downstream tracking and identification of K^+ emission. This external tracking is used to project into the emulsion to find the production vertex of a Ξ^- . Possible $\Lambda\Lambda$ hypernuclear events observed in these measurements have been reported in the literature [17] and will be reported at this conference.

In summary, there has been wide discussion about the possible existence of the H particle for more than ten years. While it is predicted to exist in most confinement models, its mass is uncertain. Although there is currently no experimental evidence for the H particle, several new searches with high sensitivity are now in progress.

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