CONF-850921--7

HYPERNUCLEAR GAMMA RAYS

BNL--37316

BNL 37316

DE86 005050

M. MAY

Brookhaven National Laboratory, Upton, New York, 11973, USA

Received by OSTI

JAN 1 6 1986

1. INTRODUCTION

The observation of hypernuclear γ rays provides a method of determining the spin dependence of the Λ-nucleon interaction with a sensitivity not approachable by other means in the forseeable future. The transitions of primary interest are those between states that differ only in the orientation of the spin of the Λ particle with respect to the angular momentum of the nuclear core. The effective Λ-nucleon interaction can be specified by a small number of γ-ray measurements. A program of experiments directed at this goal is in progress at Brookhaven National Laboratory. This paper will review the status of the subject with emphasis on the recent experiment[1] to measure ground state doublet splittings using germanium γ-ray detectors.

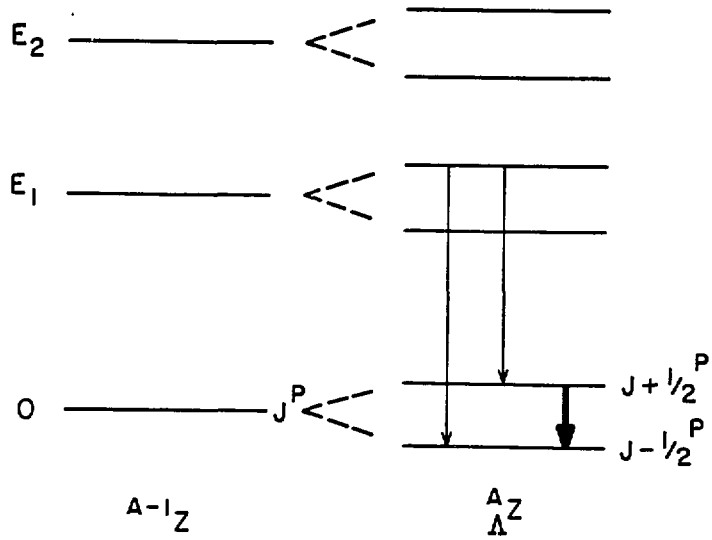
Hypernuclei are formed using the strangeness exchange reaction on a nuclear target forming a hypernucleus in an excited state ($K^- + {}^{A}Z \rightarrow {}_{\Lambda}{}^{A}Z^* + \pi^-$). The hypernucleus decays by γ emission which in many cases precedes the weak decay of the hypernucleus. The γ is detected using sodium iodide or germanium depending on the experimental requirements. Magnetic analysis of the formation reaction can give energy resolution of 2 MeV; sodium iodide resolution is typically 100 keV and germanium resolution 2 keV, a thousand-fold improvement. The γ rays are observed in coincidence with hypernuclei which have been positively identified through their formation reaction, giving an enormous suppression of background. The excitation energy of the hypernucleus is known from the magnetic analysis, and the requirement that a γ ray be seen only in coincidence with the appropriate excitation energy region is a powerful check on the origin of the γ rays.

Gamma-ray transitions in hypernuclei occur only in Λ hypernuclei. In general, the particle stable excited states are those in which the Λ is in an S-state and the nuclear core is in its ground state or excited states. The states of the core give rise t doublets (see Fig. 1) with small spin dependent splittings; observation of γ-ray transitions between core excited states shows that the inter-doublet spacing reflects the excitation energy of the core states. The doublet splittings directly measure the spin dependence of the Λ interaction. Since the doublet splitting results from the interaction of an

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

FIGURE 1

Schematic illustration of the doublet states of Λ hypernuclei formed by coupling the s-shell Λ to the states of the core nucleus ^{A-1}Z.



$s_{1/2}$ Λ with the valence nucleon, the splitting will decrease by several orders of magnitude from the lightest to the heaviest system[2]. However, since the electromagnetic lifetime of the state varies inversely as the cube of the transition energy, for small splittings the weak decay of the Λ competes with the electromagnetic decay of the state. It may be possible in the future to measure the ratio of the weak to the electromagnetic lifetimes through a systematic study of this competition.

2. SPIN DEPENDENCE

For the core excited states of hypernuclei in the p shell, the interaction of the $s_{1/2}$ Λ particle with the p nucleons has been analyzed by Gal, Soper and Dalitz[3] in terms of four two-body spin terms. Out of these, only three depend on the Λ spin: the spin-spin, spin-orbit, and tensor terms denoted Δ, s_Λ, and T. In the case where the Λ is in a p orbit, there is a one-body spin-orbit interaction $\vec{\sigma}_\Lambda \cdot \vec{\ell}_\Lambda$ which can be characterized by the energy splitting ε_p between $p_{1/2}$ and $p_{3/2}$ shells; ε_p is directly related to the two-body spin-orbit term $s_\Lambda = \vec{\sigma}_\Lambda \cdot \vec{\ell}_{N\Lambda}$ being equal to 1/6 S_Λ. Millener, Gal, Dover, and Dalitz[4] have recently revised and extended this analysis based on new data. The spin-spin and spin-orbit interactions are constrained by data, but no data exists on the tensor interaction.

3. SPIN-SPIN INTERACTION

For mass 4 hypernuclei all baryons are in s states, so the only spin dependent interaction is the spin-spin interaction. Gamma rays from the first excited states of $_\Lambda^4$He and $_\Lambda^4$H were observed by Bejidian et al.[5] in

coincidence with the pion from decay of the hypernucleus. The energies of the γ rays are 1.14 and 1.04 MeV, respectively. The result was confirmed at Brookhaven where we observed a 1.1 MeV γ-ray peak following fission of ${}_{\Lambda}^{7}$Li. The ground state spin for mass 4 hypernuclei is known from the analysis of the decay of the hypernucleus in emulsion. Thus it appears that we have an attractive spin-spin force of known strength. However, calculations of the spin-spin interaction in hypernuclei, based on what is known about the free Λ-nucleon system, give an interaction with the opposite sign[6]. Gibson[6] resolves this through the mechanism of Σ-Λ conversion. However, this leads to the conclusion that the splitting in mass 4 is only in part due to a two-body spin-spin interaction. Bodmer[7], considering the three-body interaction, attributes part of the splitting in mass 4 to a three-body interaction with Σ intermediate states. So, the interpretation of the splitting in mass 4 is not yet clear.

4. SPIN-ORBIT INTERACTION

The first indication that the ΛN spin-orbit interaction was small came from an analysis of the spectrum of ${}_{\Lambda}^{16}$O taken at CERN[8]. The present best value comes from an experiment[9] on ${}_{\Lambda}^{13}$C performed at Brookhaven. ${}_{\Lambda}^{13}$C is an especially favorable case for studying the ΛN spin-orbit interaction because of the singlet nature of the ground state of the ^{12}C core.

Figure 2 shows the spectrum of hypernuclear states observed[9] in ${}_{\Lambda}^{13}$C using the (K^-,π^-) energy difference technique. The threshold for ${}_{\Lambda}^{13}C \rightarrow \Lambda + {}^{12}C$ is at 11.7 MeV excitation. The peak labeled "3" in Fig. 2 has dominant composition $(p_{1/2})_{\Lambda}$ with the ^{12}C core in its ground state. In a spectrum taken at 15° which results in momentum transfer near the maximum of the L=2 transition

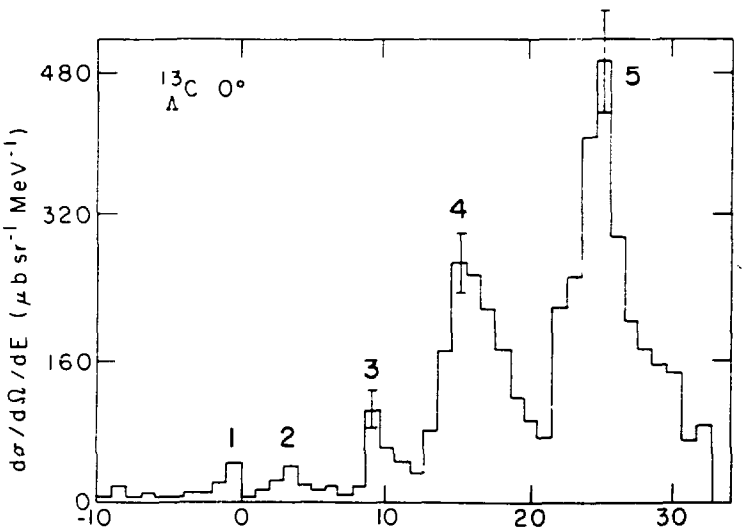
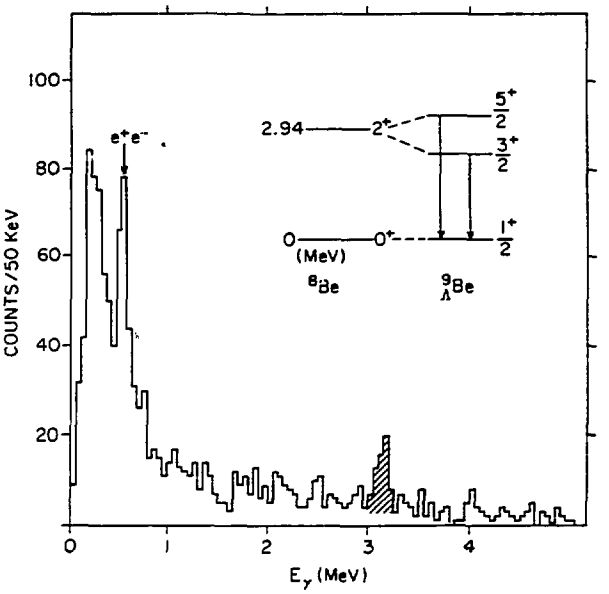


FIGURE 2

The excitation energy of ${}_{\Lambda}^{13}$C observed in the ${}^{13}C(K^-,\pi^-){}_{\Lambda}^{13}C$ reaction, with p_K = 800 MeV/c.

FIGURE 3

The γ-ray spectrum observed in coincidence with the bound state region of $_{\Lambda}^{9}Be$. The inset shows the known energy levels of the ^{8}Be core and the expected levels of $_{\Lambda}^{9}Be$.



amplitude, we observe another state with dominant composition $(p_{3/2})_\Lambda$ with the ^{12}C in its ground state. The difference in energy of these two states determines the Λ nucleus spin-orbit interaction $\varepsilon_p = \varepsilon(p_{1/2})_\Lambda - \varepsilon(p_{3/2})_\Lambda = .36 \pm .3$ MeV. A more rigorous analysis confirms that the splitting of these states is in fact due to only the spin-orbit interaction.

A comparable limit on the ΛN spin-orbit interaction is obtained from an experiment[10] on $_{\Lambda}^{9}Be$ using sodium iodide detectors. In coincidence with the bound-state region of $_{\Lambda}^{9}Be$, a γ-ray peak of energy 3.079 ± 0.040 MeV is observed (Fig. 3). We interpret this peak as being due to unresolved transitions from both members of the hypernuclear doublet built on the first excited state of ^{8}Be. Both members of the doublet are predicted to be excited with roughly equal intensity. Since we are, in this case, observing transitions from both members of a doublet to the ground state, the lack of apparent broadening of the peak from our known energy resolution gives an upper limit on the doublet splitting which is mainly due to the spin-orbit interaction.

We now know the spin-orbit interaction is small, but how small is it? We have only upper limits. We intend to perform an experiment a factor of 5 more sensitive. The $(p_{1/2})_\Lambda$ state and the $(p_{3/2})_\Lambda$ state in $_{\Lambda}^{13}C$ discussed above can be excited almost independently of each other by selecting the reaction angle. Each state decays to the hypernuclear ground state by emitting a ≈10 MeV γ ray. These γ rays can be detected with 300 keV resolution using sodium iodide. The centers of the full energy peaks can be determined to a small fraction of the resolution width.

How small should the ΛN spin-orbit interaction be? The smallness of the ΛN spin-orbit interaction is now understood in terms of one boson exchange models[11] and, because of the short-range nature of the spin-orbit interaction, in terms of quark models[12]. Both OBE and quark model calculations predict a ΛN spin-orbit interaction 20% of the nucleon-nucleon case, a result already hard pressed or ruled out by experiment.

5. HYPERNUCLEAR GAMMA RAYS DUE TO LAMBDA SPIN FLIP

In a recent experiment[1] we have attempted to observe hypernuclear γ ray due to Λ spin flip, and thus directly measure the spin dependence of the Λ-nucleon interaction. The two hypernuclei studied were ${}_{\Lambda}^{10}B$ and ${}_{\Lambda}^{16}O$ (Fig. 4). In both cases we sought to observe the γ transition between the first excited state and the ground state of the hypernucleus using germanium detectors. In the case of ${}_{\Lambda}^{10}B$, the transition energy is approximately due to interaction of a $p_{3/2}$ neutron hole with the $s_{1/2}$ Λ particle; δ depends on s_{Λ}, Δ, and T (the spin-orbit, spin-spin, and tensor interactions) as shown in the figure, but the contribution of the spin-spin interaction is expected to dominate because of the small expected sizes of s_{Λ} and T. In the case of ${}_{\Lambda}^{16}O$, the interaction of a $p_{1/2}$ neutron hole with the $s_{1/2}$ Λ particle results in a ground state doublet splitting $\delta' = -1/3\Delta + 4/3s + 8T$. Because of the large coefficient of T, the Λ-nucleon tensor interaction, about which no experimental information exists, may make the dominant contribution to the ${}_{\Lambda}^{16}O$ doublet splitting.

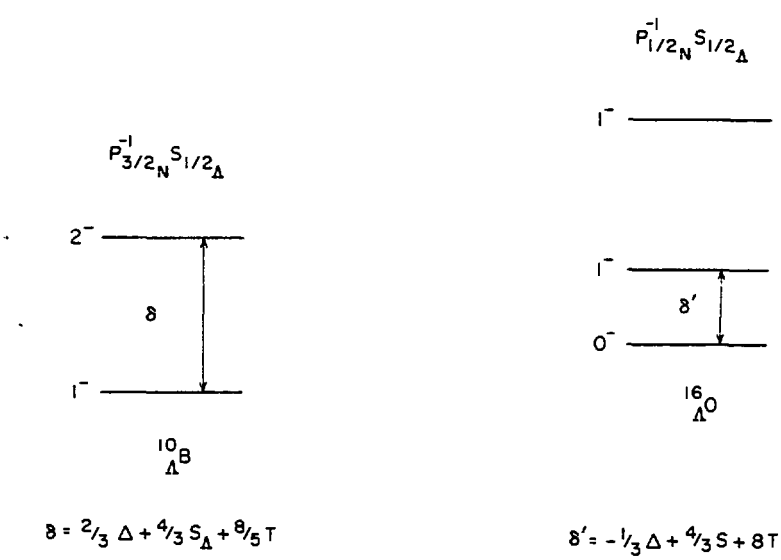
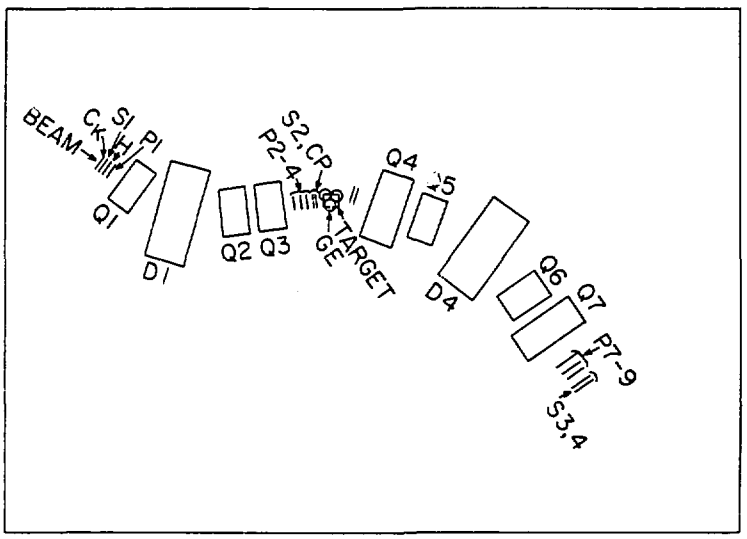


FIGURE 4

The ground state doublets in ${}_{\Lambda}^{10}B$ and ${}_{\Lambda}^{16}O$. The doublet splittings δ,δ' are given in terms of the spin-dependent components of the Λ-nucleon interaction.

FIGURE 5

The hypernuclear γ-ray experiment at Brookhaven. Germanium detectors (GE) are placed above and below the target. The formation reaction (K^-,π^-) is analyzed by quadrupoles Q1-Q7 and dipoles D1,D2. Particle tracking and identification is afforded by hodoscope H, drift chambers P1-P7, scintillation counters S1-S4, and Cerenkov counters CK and CP.

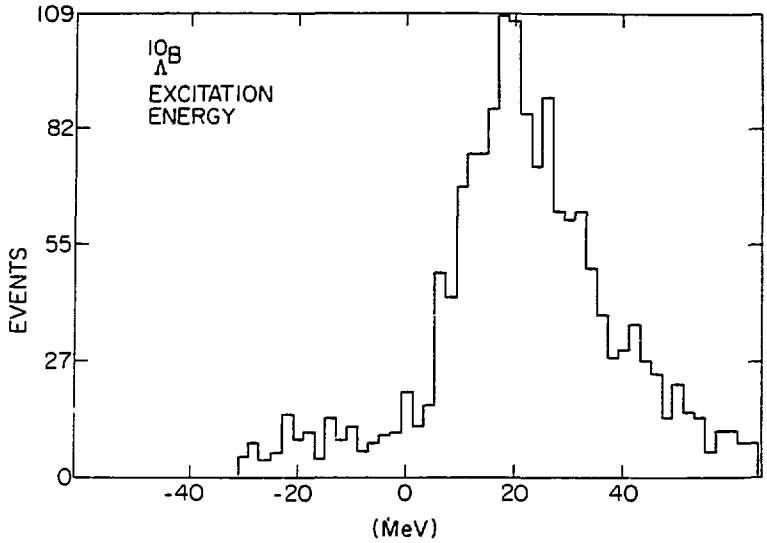


Prior to the experiment, the ground state doublet splittings for hypernuclei other than mass 4 were not known, nor was it known in general which doublet member is the ground state and which the excited state. In general, because of angular momentum and parity considerations, only one member of a doublet is excited directly to any significant degree in the (K^-,π^-) reaction, so that the possibility that the excited state will not be populated adds an additional uncertainty to planning an experiment. In this regard, ${}_\Lambda^{10}B$ and ${}_\Lambda^{16}O$ are favorable cases. For ${}_\Lambda^{10}B$, there is indirect evidence from emulsion experiments that the ground state is 1^-. For ${}_\Lambda^{16}O$, an excited 1^- state at approximately 6 MeV excitation energy is strongly populated in the (K^-,π^-) reaction and decays to both members of the ground state doublet.

Figure 5 shows the apparatus used in the experiment. Two focussing magnetic spectrometers are instrumented with drift chambers and a hodoscope for trajectory analysis and with scintillation counters and Cerenkov counters for particle identification. The experiment was performed in low-energy separated beam I at the Brookhaven National Laboratory AGS. The kaon flux at the target was 10^5 per AGS pulse. The pion from hypernuclear formation was detected in a spectrometer with 23 msr acceptance. The mean angle between incoming kaon and

FIGURE 6

The thin target (3 gm/cm^2) excitation spectrum of $_\Lambda{}^{10}B$. The hypernuclear ground state is at 0 MeV.



outgoing pion was 5°. The intrinsic resolution of the spectrometers in the determination of the energy of a hypernuclear state is 3 MeV but was limited in this experiment by target thickness effects. Six coaxial n-type intrinsic germanium detectors were placed above and below the target at a distance of 10 cm. The detectors, which are 5 cm in diameter and 4 cm deep, have an intrinsic efficiency which is close to 1 down to 20 keV decreasing to 1/3 at 500 keV. The energy resolution of the detectors was 2.5 keV full width half maximum. The targets used were a) B isotopically enriched to 93% of ^{10}B, 12 gm/cm^2, and b) ^{16}O in the form of water, 10 gm/cm^2. The preliminary results for $_\Lambda{}^{10}B$ are presented here.

The excitation spectrum of $_\Lambda{}^{10}B$, measured in the experiment using a thin (3 gm/cm^2) target, is shown in Fig. 6. A region from $E_{ex} = -12$ to $E_{ex} = +6$ contains the bound states of $_\Lambda{}^{10}B$. It is only in coincidence with this region that the ground state doublet γ ray can occur. Figure 7 shows the γ-ray spectrum in coincidence with this region. The only significant peak, aside from the ubiquitous 511 keV positron annihilation γ is at 157 keV. The γ-ray spectrum in the vicinity of 157 keV is shown with expanded scale.

Additional evidence for this candidate for the ground state doublet γ ray in $_\Lambda{}^{10}B$ comes from the fact that it does not appear in coincidence with other regions of hypernuclear excitation (Fig. 8) and from a study of the timing of the signal in the germanium detector. Because the germanium detectors were chosen to be efficient up to a considerably higher energy than the observed γ-ray energy, they are larger than optimum. A γ ray of energy 157 keV interacts close to the surface of the detector, whereas the background comes from γ rays which interact throughout the volume of the detector. The background,

FIGURE 7

The γ-ray spectrum observed in coincidence with the bound state region of $_{\Lambda}^{10}B$. The spectrum near 150 keV is shown on an expanded scale with a fitted background.

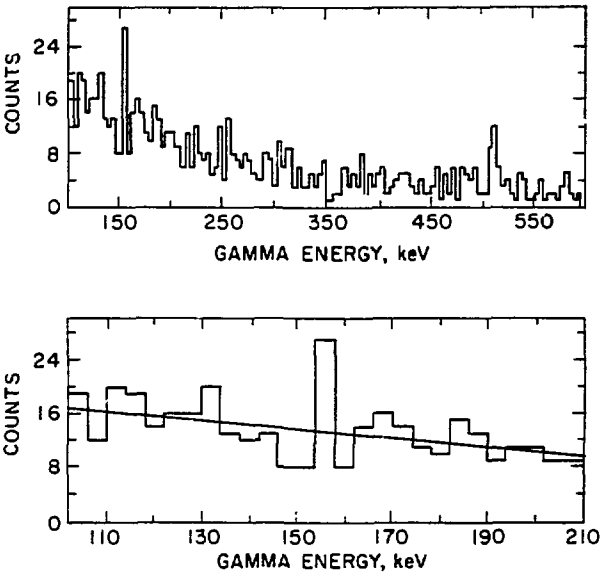


FIGURE 8

The γ-ray spectrum observed in coincidence with the unbound state region of $_{\Lambda}^{10}B$.

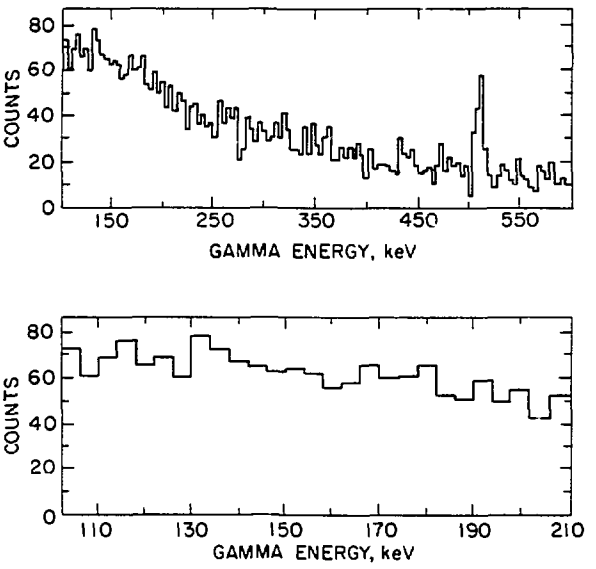
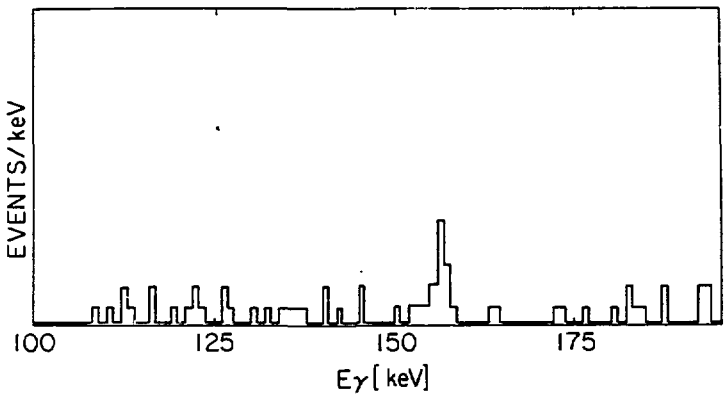


FIGURE 9

A spectrum for $_{\Lambda}{}^{10}B$ γ rays obtained by a time selection designed to enhance low-energy γ radiation absorbed near the detector front surface.



much of which is initiated by neutral pions, is mainly a result of high-energy γ rays which deposit a small fraction of their energy in the crystal by Compton scattering. This difference between signal and background is reflected in the rise time of the pulses in the germanium detector. An analysis utilizing this effect to suppress the background, though with significant loss in efficiency, results in the spectrum shown in Fig. 9.

Studies of the optimum selections of excitation energy, time, and other parameters are continuing so as to produce the best background suppression. The collaborators on this experiment are listed in ref. 1 below.

ACKNOWLEDGEMENT

Research has been performed under contract DE-AC02-76CH00016 with the U.S. Department of Energy.

REFERENCES

1) J. Derderian, R. E. Chrien, M. May, P. Pile, R. Sutter, P. Barnes, R. Eisenstein, G. Franklin, R. Grace, D. Marlow, R. Rieder, J. Seydoux, J. Syzmanski, W. Wharton, C. Chu, R. Hackenburg, E. Hungerford, T. Kishimoto, Y. Civelekoglu, M. Deutsch, J. Prater, B. Bassallek, T. Fukuda, M. Barlett, E. C. Milner, and R. L. Stearns. Columbia/BNL/CMU/Houston/MIT/New Mexico/Osaka/Texas/Vassar Collaboration.

2) J. D. Walecka, Ann. Phys. 63 (1971) 219.

3) A. Gal, J. M. Soper, and R. H. Dalitz, Ann. Phys. 113 (1978) 79.

4) D. J. Millener, A. Gal, C. B. Dover, and R. H. Dalitz, Phys. Rev. C31 (1985) 499.

5) M. Bedjidian, E. Descroix, J. Y. Grossiord, A. Guichard, M. Gusakow, M. Jacquin, M. J. Kudla, H. Piekarz, J. Piekarz, J. R. Pizzi, and J. Pniewski, Phys. Lett. 83B (1979) 252.

6) B. F. Gibson and D. R. Lehman, in Proceedings of the International Conference on Hypernuclear and Kaon Physics (Max-Planck Institut fur Kernphysik, Heidelberg, 1982), p. 161.

7) A. R. Bodmer, Q. N. Usmani, and J. Carlson, Phys. Rev. C29 (1984) 684.

8) W. Bruckner, M. A. Faessler, T. J. Ketel, K. Kilian, J. Niewisch, B. Pietrzyk, B. Povh, H. G. Ritter, M. Uhrmacher, P. Birien, H. Catz, A. Chaumeaux, J. M. Durand, B. Mayer, J. Thirion, R. Bertini, and O. Bing, Phys. Lett. 79B (1978) 157.

9) M. May, H. Piekarz, R. E. Chrien, S. Chen, D. Maurizio, H. Palevsky, R. Sutter, Y. Xu, P. Barnes, B. Bassalleck, N. J. Colella, R. Eisenstein, R. Grace, P. Pile, F. Takeutchi, W. Wharton, M. Deutsch, J. Piekarz, S. Bart, R. Hackenburg, E. V. Hungerford, B. Mayes, L. Pinsky, R. Cester, and r. L. Stearns, Phys. Rev. Lett. 47 (1981) 1106.

10) M. May, S. Bart, S. Chen, R. E. Chrien, D. Maurizio, P. Pile, Y. Xu, R. Hackenburg, E. Hungerford, H. Piekarz, Y. Xue, M. Deutsch, J. Piekarz, P. D. Barnes, G. Franklin, R. Grace, C. Maher, R. Rieder, J. Szymanski, W. Wharton, R. L. Stearns, B. Bassalleck, and B. Budick. Phys. Rev. Lett. 51 (1983) 2085.

11) R. Brockman, Phys. Lett. 104B (1981) 256; A. Bouyssy, Nucl. Phys. A381 (1982) 445; H. Bando, Prog. Theor. Phys. 66 (1981) 1349; C. B. Dover and A. Gal, Hyperon nucleus potentials, in: Progress in Particle and Nuclear Physics, Vol. 12, no. 3, ed. D. Wilkinson (Pergamon, Oxford, 1984).

12) O. Morimatsu, S. Ohta, K. Shimizu, and K. Yazaki, Nucl. Phys. A420 (1984) 573.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.