Radiative Pion Capture in ^{6}Li[†]

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The photon spectrum from the reaction ^{6}Li(π^-, γ) was measured with high resolution in the 50- to 150-MeV region by using an electron-positron pair spectrometer. The total fraction of pions absorbed radiatively is 4.4 $\pm$ 0.6% with branching ratios to the ^{6}He ground state of 0.31 $\pm$ 0.04% and to the 1.8-MeV state of 0.15 $\pm$ 0.03%, in disagreement with previous experimental results, but in qualitative agreement with theoretical predictions. Evidence for higher excitations is observed in addition to quasifree capture accompanied by neutron emission.

I. INTRODUCTION

Within the last several years it has been realized that radiative pion capture provides a new probe of nuclear structure. Studies[1] on ^{12}C and ^{16}O have shown that the photon spectra in the 90- to 140-MeV region exhibit a fine structure, with resonance-like peaks that can be identified as enhanced transitions to known collective $T=1$ ($J^\pi = 1^-, 2^-$) excitation modes of the mass-12 and -16 systems. Such transitions were predicted by Delorme and Ericson[2] (1966), Anderson and Eisenberg[3] (1966), and Überall[4] (1966) prior to their direct observation by Bistirlich *et al.*[1] Calculations[5,6] based on an impulse-approximation Hamiltonian, with amplitudes deduced from the elementary capture process $\pi^- p \to n\gamma$, and on nuclear-model wave functions which were representations of the SU(4) classification of giant resonances, have resulted in qualitative agreement with the data.[1] For more quantitative studies a number of improvements must be made. First, pionic x-ray data indicate[7] that for light nuclei, $4 \lesssim A \lesssim 16$, the pion is absorbed by the nucleus predominantly from the $2p$ Bohr orbital, rather than the $1s$ orbit as many authors assumed. Thus, to deduce correct radiative branching ratios from the theoretical transition matrix elements one needs pion-capture schedules. These have just recently been published[7] for ^{6}Li and ^{12}C. Second, the theoretical calculations of Skupsky[8] (1971), Vergados and Baer[9] (1972), and Maguire and Werntz[10] (1972) have shown that for $2p$ capture, terms in the effective Hamiltonian dependent on pion momentum make sizeable contributions. Therefore the simple $(\vec{\sigma}\cdot\vec{\epsilon})e^{i\vec{k}\cdot\vec{r}}$ operator employed in nearly all earlier calculations is inadequate. Third, there has been the experimental problem that, even with 2-MeV resolution at 130 MeV, the measurements[1] have not been able to isolate transitions to individual nuclear states which could serve as test cases. The present work, in measuring the $\pi^- + {}^{6}\mathrm{Li}(1^+) \to \gamma + {}^{6}\mathrm{He}(0^+$, g.s.) transition, achieves this.

Much of the interest in the above transition centers on the fact that it might be used to test the hypothesis of partially conserved axial-vector current (PCAC) and soft-pion limit for complex nuclei. The approach based on these assumptions[11] (referred to in the literature as the elementary particle treatment of nuclei) permits one to determine the radiative π-capture rate from the $1s$ Bohr orbital, shown to be a matrix element of the axial-vector current, from the rates of other weak and electromagnetic processes involving the same states or their analogs in the isobaric multiplet. The transition $^{6}\mathrm{Li}(1^+) \to {}^{6}\mathrm{He}(0^+)$ is particularly well suited for this type of study since the β-decay[12] and μ-capture[13] rates are known and the 0^+ analog in ^{6}Li at 3.562 MeV[12] has a well-measured γ-decay width. In addition the inelastic electron scattering to this state has been measured by several groups.[14] Using the experimental rates, Delorme,[15] Fulcher and Eisenberg,[16] Pascual and Fujii,[17] and Griffiths and Kim[18] have used the elementary particle approach to predict the radiative π-capture rate for $^{6}\mathrm{Li}(1^+) \to {}^{6}\mathrm{He}(0^+)$. It is of considerable interest to test these predictions as well as others based on nuclear-model wave functions, such as those by Vergados and Baer,[9] and Roig and Pascual.[19] Comparison with the theoretical calculations of Maguire and Werntz,[10] who use the impulse-approximation Hamiltonian but relate the nuclear matrix elements to other measured quantities, is also of interest. The only experimental value for the branching ratio of this transition was that of Deutsch *et al.*[13] (1968), which was thought to be

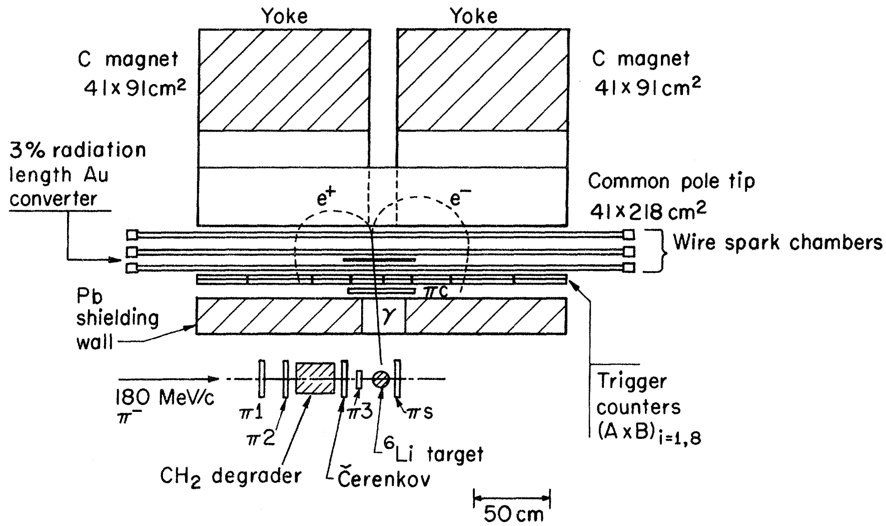

FIG. 1. The electron-positron pair spectrometer and range-telescope geometry. The trigger for an event was $\pi 1 \times \pi 2 \times \pi 3 \times \bar{c} \times \overline{\pi s} \times \overline{\pi c} \times (A\times B)_i \times (A\times B)_k,\ i \neq k, k \pm 1$.

in agreement with theory. However, the more recent calculations, when combined with the improved x-ray data, are lower by factors of 2 to 3 from this experimental result. Thus it seemed important to remeasure this quantity which has been cited as evidence for the validity of the PCAC and soft-pion theorem approaches.

II. EXPERIMENT

The experiment was carried out in the stopped pion beam of the Lawrence Berkeley Laboratory 184-in. cyclotron. The experimental setup is shown in Fig. 1. The incoming pions pass a beam telescope, which includes a Lucite Čerenkov detector to discriminate against electrons and a CH_2 degrader. The pions are brought to rest in a 7.6-cm-diam by 9-cm-high cylinder of 96% enriched ^{6}Li (200 g). Anticounters after the target and in front of the photon detector ensure the detection of a neutral particle in coincidence with a stopped pion. A 180° pair spectrometer identical to the one described in detail in Ref. 1, except for the wire spark chambers, was employed to detect high-energy photons. The photons are converted in 3% radiation lengths (0.22 g/cm^2) of gold. The coordinates of the electron-positron pair were measured with three wire spark chambers consisting of four planes each. The wire spacing was 0.1 cm, and the wire angles with the horizontal midplane of the magnet were +12, −12, −12, and 0°. The 12° stereo view had to be used to keep the magnetostrictive readout wires out of the high-field region. This reduces the spatial resolution for the critical horizontal coordinate to 0.5 cm

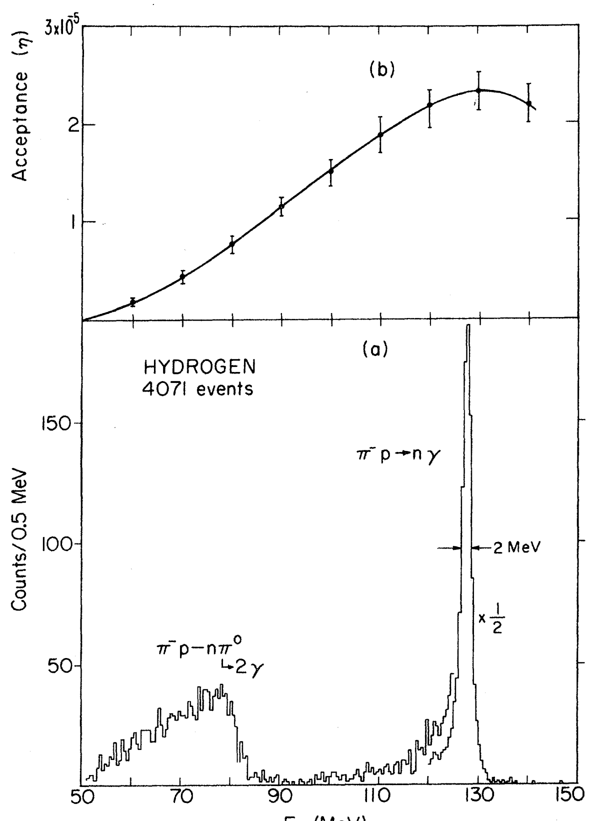

FIG. 2. (a) Photon spectrum for π^- capture in hydrogen. The distortion of the rectangular shape of the π^0 spectrum is due to the reduction in efficiency at the low-energy end. The Panofsky ratio deduced in this experiment is $P = 1.56 \pm 0.10$. (b) Efficiency of pair spectrometer as a function of photon energy.

for a given spark, and limits our energy resolution to 2 MeV full width at half maximum at 130 MeV. The signal of two nonadjacent scintillator pair counters out of the eight pair counters across the magnet completed our trigger requirements. A PDP 15 on-line computer performed the tasks of recording the data and consistently monitoring the performance of the chambers.

The over-all acceptance of the spectrometer and its resolution were checked repeatedly between ^{6}Li runs with a 15-cm-diam thin-window liquid-hydrogen target, mounted on rails. Figure 2(a) shows one of the calibration spectra and Fig. 2(b) shows the combined acceptance of the spectrometer, i.e., the product of solid angle, detection, and conversion efficiency divided by 4π. This curve was calculated with a Monte Carlo simulation of the spectrometer and it includes the efficiency of the off-line analysis program, which selects the 4–10% good triggers from the total sample. The different classes of background events are described in Ref. 1, and were easily distinguishable from the desired pairs. About 30 000 triggers have been examined by eye in a direct display of the chamber information to eliminate possible bias of the selection programs. Using the mesonic capture, $\pi^- p \to \pi^0 n$, we check the acceptance in the region $55 < E_\gamma < 83$ MeV; the radiative capture, $\pi^- p \to \gamma n$, yields a single line with $E_\gamma = 129.4$ MeV. With an accuracy of 10% (statistical and systematic errors combined in quadrature) we find that the hydrogen results agree with the expected values[20] as shown in Table I. The number of pions captured in the target was determined from the number of pions stopped as a function of degrader thickness with and without the target material present. In this way electronic and geometric inefficiencies, including decays, could be accounted for properly within an accuracy of ±4%. A small correction (2.4%) is applied to account for the photons that convert in the target and the anticounter in front of the spectrometer. This information is summarized in Table I for both H and ^{6}Li targets.

The following corrections to the number of photons in the spectrum or the number of pions captured in the target are neglected, so that our quoted rates could be subject to an additional small systematic normalization error: (a) photons produced by pions interacting in flight (−~4%); (b) nonradiative pion absorption in flight (+1%); (c) pions stopping in the ^{7}Li content of the target (4.4%); (d) photons produced in the reaction $^7\mathrm{Li}(\pi^-, \gamma)$ (−2.7%); the ratio of radiative pion capture of ^{7}Li to ^{6}Li is measured to be 0.58 ± 0.07.[21]

III. RESULTS

The photon spectrum is shown in Fig. 3 together with calculations based on the pole model[22, 23] and three-body phase space ($^5\mathrm{He}\,\gamma\, n$). The experimental spectrum exhibits three components:
(a) a discrete line at 132 MeV corresponding to the ^{6}He(g.s.) transition;
(b) a continuum component associated with quasi-free capture, i.e., the $^5\mathrm{He} + n$ ($^4\mathrm{He} + n + n$) channels;
(c) possible resonances at higher excitations around 105, 111, and 119 MeV.

Expressed in photon energies, we have the ^{6}He(g.s.) ($J^\pi = 0^+$, $T = 1$) transition at $E_\gamma = 133.95$ MeV, the transition to the 1.8-MeV state[12] ($J^\pi = 2^+$, $T = 1$) at $E_\gamma = 132.19$ MeV, the $^4\mathrm{He} + n + n$ threshold at 133.00 MeV, and the $^5\mathrm{He} + n$ threshold at 132.06 MeV. With a resolution of 2 MeV the spectrum does not clearly show the separation of

TABLE I. Total capture rates in hydrogen and lithium.

Target nucleus	Target mass (g/cm^2)	Number of photons $10^{-3}N_{\gamma 1}$ [a]	$10^{-3}N_{\gamma 2}$ [b]	$10^{-8}N_{\gamma 3}$ [c]	Number of pions $10^{-10}N_{\pi 1}$ [d]	$10^{-10}N_{\pi 2}$ [e]	Branching ratio R_γ [f] (%)	R_γ [g] (%)
H_2 ($n\gamma$)	0.99	2.55 ± 0.05	2.55 ± 0.05	1.12 ± 0.08	0.0405	0.0264 ± 0.019	42.4 ± 4.4	39.5 ± 0.3 [h]
H_2 ($n\pi 0$)	0.99	1.52 ± 0.04	7.96 ± 0.51	3.49 ± 0.26	0.0405	0.0264 ± 0.0019	66.0 ± 6.4	60.5 ± 0.3 [h]
Panofsky ratio			1.56 ± 0.10					1.53 ± 02 [h]
^{6}Li	2.76	9.77 ± 10	12.74 ± 1.26	5.50 ± 0.68	1.66	1.25 ± 0.06	4.4 ± 0.6	3.3 ± 0.2 [i]

[a] Raw number of events.
[b] Number of events corrected for energy-dependent efficiency $\eta_\gamma(130) = 1$.
[c] Number of photons into full solid angle.
[d] Raw number of stopping pions.
[e] Pions captured in the target.
[f] This experiment $N_{\gamma 3}/N_{\pi 2}$.
[g] Previous experiments.
[h] Reference 20.
[i] Reference 21.

the ground state from the first excited state and the onset of the two breakup channels.

A. ^{6}He Ground State and 1.80-MeV State

Three different methods were employed to extract the ground-state transition rate:

(1) The hydrogen line at 129.41 MeV was shifted by 4.54 MeV and then normalized to the upper end of the lithium spectrum ($E_\gamma > 132$ MeV). Here we assume only that contributions from other channels are small. Comparison with the other two methods described below indicates that this assumption is indeed correct.

(2) We assumed that the quasifree capture can be described by the single-proton exchange model.[22] We selected Δ values at the nucleus vertex suited for (^{4}He$+n$)$+n$ ($\Delta = 6.56$) and the ^{5}He $+ n$ ($\Delta = 7.43$ MeV) channel. The ground-state transition rate was found not to depend too critically on the choice of this parameter (see Table II) and is in agreement with the value obtained with the first method.

(3) Single as well as a two-neutron emission,

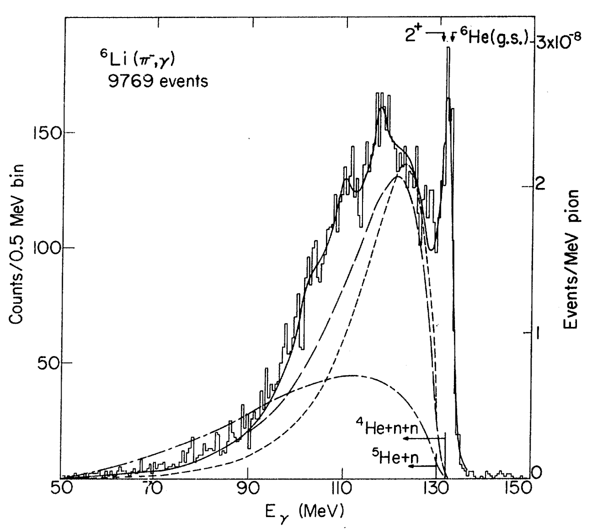

FIG. 3. The ^{6}Li (π^-,γ) photon spectrum in the 50–150-MeV regions. The instrumental lineshape, shown in Fig. 2(a), causes the peak in the spectrum to appear 2 MeV lower than the photon energy. We therefore indicate breakup thresholds and the position of the 2+ and 0+ states shifted down by 2 MeV. Solid line: fit to spectrum between 98 and 135 MeV assuming 2 lines at $E_x = 0$ and 1.80 MeV, three Breit-Wigner resonances at $E_x = 15.6$, 23.2, and 29.7 MeV, and the pole model (Ref. 22) with $\Delta = 6.56$ MeV using relative strengths given in Table III; long dashed line: pole model of Ref. 22 with $\Delta = 6.56$; short dashed line: pole model with complete kinematics (Ref. 23); dash-dot line: ^{5}He $+ n + \gamma$ phase space, normalized to the same number of photons as the pole model (Ref. 23).

when calculated with phase space or the pole model, exhibits a dependence on the photon energy near the maximum value E_0 given closely by the form

$$k(E_0 - E_\gamma)^{1/2}.$$

We fit the spectrum above 120 MeV with this function plus two lines at the correct energies for the 0^+ and 2^+ states.

There are two observations which force us to consider the population of the 1.8-MeV state. One is the fact that a single level fit with one Breit-Wigner shaped resonance folded with the resolution as obtained from the hydrogen spectrum yields values for the level position of $E_0 = 133.4$ MeV and a width of $\Gamma = 0.5$–0.7 MeV, where we expect $\Gamma = 0$ and $E_0 = 134.0$. Since the energy scale was frequently checked with hydrogen runs, and we find the correct energy for the ^{3}He(π^-, γ)^{3}H reaction to be reported elsewhere,[24] we can exclude the possibility of an instrumental energy shift. To exclude further possible shifts, the fits were repeated for different subsets of data, each one with a resolution taken from a hydrogen run during the same running period. Second, we can improve considerably the fit to the upper end of the spectrum (a factor of 3 in χ^2) obtained with method 3 above if we introduce a second line at 132.19 MeV. The results of these fits are summarized in Table II.

In addition to the two line fits given in the table, we attempted to verify the position of the second level by leaving the position and width of the level as a free parameter. When doing this, the fit resulted in values $E_x = 1.6 \pm 0.1$ MeV and $0 < \Gamma < 0.25$ MeV for the position and width, respectively. These numbers are in agreement with the known values[12] for the 2^+ state of $E_x = 1.80 \pm 0.03$ and $\Gamma = 0.112 \pm 0.002$ MeV. The ground-state branching ratio obtained this way is lower by 7%, the 1.8-MeV branching ratio higher by 13.5%, and the χ^2/degree of freedom decreases by 15%.

The parameters of the different fitting procedures are summarized in Table II and the fitted curves are shown in Fig. 4. In Fig. 4(b) the ^{6}He(g.s.) contribution has been subtracted from the data. One can see clearly that one must assume the population of the 2^+ state if one does not introduce an unusual behavior of the continuum at its endpoint.

B. Continuum and Possible Resonances

From Fig. 3 it can be seen that neither phase space nor the one-proton-exchange pole model[22,23] give a good description of the spectrum below 128 MeV. There are indications of some resonance-

TABLE II. Experimental branching ratios for ^{6}Li (to ground state + 1.8-MeV state of ^{6}He).

Energy (MeV)	Ground-state width (MeV)	$R(0+)$ (%)	1.8-MeV state Energy	Width	$R(2+)$	χ^2/DF degrees of freedom	Number of data points	Energy region used in the fit	Method of fit
133.44 ± 0.07	0.58 ± 0.16	0.464 ± 0.048				1.39	29	121–135	1 Breit-Wigner + pole model ($\Delta = 6.56$)
133.31 ± 0.08	0.74 ± 0.18	0.521 ± 0.053				1.81			1 Breit-Wigner + pole model ($\Delta = 7.43$)
133.95	0.0	0.369 ± 0.043				4.05	29	121–135	line + pole model ($\Delta = 6.56$)
133.95	0.0	0.390 ± 0.049				6.57			line + pole model ($\Delta = 7.43$)
133.95	0.0	0.370 ± 0.045				4.69	29	121–135	line + k $(133.00 - E_\gamma)^{1/2}$
		0.296 ± 0.035							hydrogen line, shift and normalized at $E_\gamma > 132$ MeV
133.95	0.0	0.307 ± 0.035	132.19	0.1	0.140 ± 0.025	1.50	29	121–135	two lines + pole model ($\Delta = 6.56$)
133.95	0.0	0.306 ± 0.035	132.19	0.1	0.189 ± 0.027	1.72			two lines + pole model ($\Delta = 7.43$)
133.95	0.0	0.306 ± 0.035	132.19	0.1	0.151 ± 0.026	1.74	29	121–135	two lines + k $(133.00 - E_\gamma)^{1/2}$
(133.95	0.0)	0.306 ± 0.035	(132.19	0.1)	0.151 ± 0.026				Extracted values

like structures in the spectrum at approximately 120 and 110 MeV and possibly near 105 MeV. To describe these, we fit three Breit-Wigner resonances plus the pole model[22] ($\Delta = 6.56$ MeV) to the data and obtain the fit shown in Fig. 3. The corresponding resonance width, positions, and partial branching ratios are given in Table III. Evidence from other experiments regarding higher resonances in the mass-6 system[25] is discussed in the next section.

IV. DISCUSSION

In Table IV we compare the ground-state transition rate with the different theoretical predictions and with the only previous measurement. As in the case of ^{12}C (Ref. 1), a large discrepancy exists between the pair-spectrometer value and that obtained from the activation method. The latter is higher by a factor of 3.3. This disagreement is unexplained, but there are indications[26] that neutron-induced activity in the target may account for the higher rate. Since the 1.8-MeV state is observed to decay entirely via particle emission ($\Gamma_\gamma/\Gamma < 4\times10^{-4}$[27]), it cannot contribute the ^{6}He β

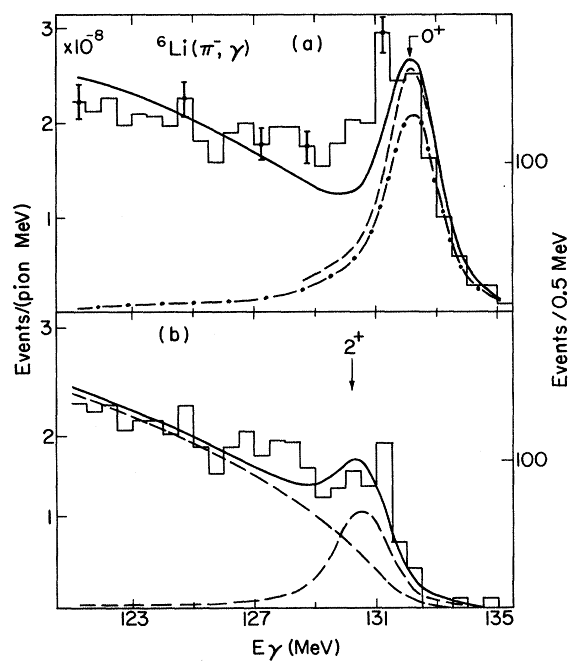

FIG. 4. (a) Upper end of ^{6}Li spectrum. Solid line: single line fit ($E_\gamma = 133.96$) + k $(133.02 - E_\gamma)^{\frac{1}{2}}$; dashed line: contribution from the ^{6}He(g.s.) in the single line fit; dashed-dotted line: contribution from ^{6}He(g.s.) in two-line fit ($E_x = 0$ and 1.80 MeV). (b) Upper end of ^{6}Li spectrum with the ^{6}He(g.s.) contribution subtracted; dashed line: Background as in (a) and single line at $E_x = 1.80$ MeV; solid line: sum of background and 1.8-MeV state.

activity. The excellent agreement of our hydrogen calibration data with the accurately measured values gives us confidence in our absolute normalization. Furthermore, we note that our total capture rate, 4.4 ± 0.6%, is even higher than the older NaI value.[21]

The quantity we measure is the branching ratio R_γ of radiative to total capture from all atomic orbitals. This ratio is related to the theoretical matrix elements for each pion initial state by the incoherent sum over all Bohr orbitals

$$R_\gamma = \sum_{nl} \frac{\lambda_\gamma(nl)}{\lambda_a(nl)}\,\omega(nl),$$

where the quantities $\lambda_\gamma(nl)[\lambda_a(nl)]$ are the radiative [total] capture rates from orbital nl. The $\omega(nl)$ are probability/π atom formed for capture from orbital nl. It is generally assumed that the ratio radiative/total capture is independent of the principal quantum number n and depends only on l. Therefore the quantity

$$R_\gamma = \frac{\lambda_\gamma(1s)}{\lambda_a(1s)} \sum_n \omega(ns) + \frac{\lambda_\gamma(2p)}{\lambda_a(2p)} \sum_n \omega(np)$$

is compared with experiment.

There have been seven evaluations (Table IV) of the ground-state transition rate; however, only three attempts have been made to calculate the $2p$ contribution also. Griffiths and Kim,[18] Fulcher and Eisenberg,[16] and Pascual and Fujii[17] use the "elementary particle" (EP) method to compute $\lambda_\gamma(1s)$ and their results could in principle check the more model-dependent calculations of Vergados and Baer,[9] Roig and Pascual,[19] and Maguire and Werntz[10] with the impulse-approximation (IA) and shell-model wave functions. The accuracy of the elementary particle approach, however, is limited through the quality of the input data from the other reactions; e.g., the transition rate for the process $^6Li(\mu^-, \nu_\mu)^6He$ is known to only 20%[13]: $(1.60^{+0.33}_{-0.133})\times 10^3\ sec^{-1}$. The difference between the result of Fulcher and Eisenberg[16] and Griffiths and Kim[18] is traced[16] to the use of the axial form factor as determined from β decay and μ capture, respectively. However, the calculations differ also in other aspects, such as the treatment of the distortion of the pionic orbit due to the strong interaction[28] or the choice of the correction factor[29] that is introduced into the soft-pion result. The most detailed treatment with the elementary particle method is the one of Delorme,[15] where all corrections have been included,[30] and also an attempt has been made to evaluate the $2p$ capture rate. For the $2p$ contribution one has to rely on the model-dependent calculations. The three impulse-approximation calculations[9,10,19] differ in the following respect: In the calculations of Refs. 9 and 10 the distortion of the pionic orbit is taken into account by a multiplicative factor; in Ref. 19 the distorted pion wave function is kept in the matrix element. The coefficients in the effective Hamiltonian differ but not very much. Roig and Pascual[19] and Maguire and Werntz[10] use a set obtained from pion-photoproduction multipole tables of Berends, Donnachie, and Weaver.[31] Vergados and Baer[9] use two sets, one due to Ref. 2 which has been shown to be in error by Maguire and Werntz,[10] the other one due to Ref. 32 which is close to the ones used by the other groups. The coefficients in the shell-model wave functions (e.g., the size parameter of the p-shell harmonic oscillator) are chosen in such a way that other transition rates involving the same levels are well reproduced. Roig and Pascual vary the parameters to fit the rms radius of ^6Li, the ft value for the $^6He \to {}^6Li + e^+ + \nu$ decay, the width of the $^6Li(3.56\ MeV) \to {}^6Li(g.s.) + \gamma$ magnetic-dipole transition, and the $^6Li(\mu^-, \nu_\mu)^6H(g.s.)$

TABLE III. Experimental branching ratios for ^6Li (total spectrum).

Energy (MeV)	Width (MeV)	R_γ [a] (%)	Energy (MeV)	Width (MeV)	R_γ [b] (%)	^6He excitation energy
133.96	0	0.307 ± 0.035	133.96	0.	0.308 ± 0.033	0.
132.16	0.1	0.140 ± 0.205	132.16	0.1	0.189 ± 0.027	1.8
118.80 ± 0.46 [c]	2.67 ± 1.90	0.238 ± 0.113	118.75 ± 0.49	1.67 ± 1.97	0.143 ± 0.082	15.6 ± 0.5
111.51 ± 0.73 [c]	4.33 ± 3.37	0.346 ± 0.265	111.30 ± 0.74	4.08 ± 3.12	0.282 ± 0.185	23.2 ± 0.7
104.92 ± 1.29 [c]	7.39 ± 4.24	0.502 ± 0.302	104.86 ± 1.06	5.65 ± 3.65	0.339 ± 0.202	29.7 ± 1.3
pole		2.864 ± 0.292			3.181 ± 0.312	pole
		4.392 ± 0.584			4.462 ± 0.512	total
		1.21			1.22	χ^2/degree of freedom
		75			75	data points
		$98 < E_\gamma < 135$			$98 < E_\gamma < 135$	energy region

[a] Pole model with $\Delta = 6.56$ ($^4He + n + n$ upper cutoff).
[b] Pole model with $\Delta = 7.43$ ($^5He + n$ upper cutoff).
[c] The indicated uncertainties for the parameters of the Breit-Wigner resonances do not reflect the uncertainties of the pole model.

TABLE IV. Comparison of experimental and theoretical capture rates to the ^{6}He (0^+) ground state and ^{6}He (2^+) first excited state. For the total pion-absorption rate and the capture schedule we use the experimental values from pionic x-ray data.

$\lambda_\gamma(1s)$ (10^{15} sec^{-1})	$\frac{\lambda\gamma(1s)}{\lambda_a(1s)}$ [a] (%)	$\lambda\gamma(2p)$ (10^{10} sec^{-1})	$\frac{\lambda\gamma(2p)}{\lambda_a(2p)}$ [b] (%)	$\frac{\lambda\gamma(1s)}{\lambda_a(1s)}\times\sum_n \omega(ns)+\frac{\lambda\gamma(2p)}{\lambda_a(2p)}\times\sum_n \omega(np)$ [c] (%)	Reference
1.46 ± 0.22	0.50 ± 0.08	4.12 ± 0.62	0.18 ± 0.06	0.31 ± 0.07	Ref. 19 Ground state (IA)
1.51 ± 0.15	0.51 ± 0.06	5.26 ± 0.06	0.23 ± 0.06	0.34 ± 0.07	Ref. 10 (Theoretical) (IA)
2.08	0.70 ± 0.05	4.32	0.19 ± 0.05	0.39 ± 0.08	Ref. 9
1.40	0.47 ± 0.03	4.44	0.19 ± 0.05	0.30 ± 0.05	Ref. 9
2.3 ± 0.5	0.78 ± 0.18		0.52 ± 0.14	0.62 ± 0.11	Ref. 15 (EP)
1.86 ± 0.18	0.63 ± 0.08			(0.25 ± 0.07) [d]	Ref. 17 (EP)
$1.9^{+0.4}_{-0.2}$	$0.64^{+0.14}_{-0.08}$			$(0.26^{+0.08}_{-0.07})$ [d]	Ref. 16 (EP)
1.65	0.56 ± 0.04			$\underline{(0.23\pm0.06)}$ [d]	Ref. 18 (EP)
				0.306 ± 0.035	This experiment [e] (Experimental)
				1.0 ± 0.1	Ref. 13
0.227	0.076 ± 0.051	1.57	0.069 ± 0.018	0.07 ± 0.02	Ref. 33 1.8-MeV state (Theoretical)
				0.151 ± 0.026	This experiment (Experimental)
0.11		0.36		0.18 ± 0.03	Ref. 33 $R_\gamma(1.8)/R_\gamma(0)$
				0.49 ± 0.10	This experiment $R_\gamma(1.8)/R_\gamma(0)$

[a] $\lambda_a(1s)=(1/\hbar)\Gamma_{2p\to1s}$: $(2.95\pm0.20)\times10^{17}$ sec^{-1}, G. Backenstoss and Koch, private communication; 2.28 ± 0.76, R. J. Harris, W. B. Shuler, M. Eckhouse, R. T. Siegel, and R. E. Welsh, Phys. Rev. Lett. 20, 505 (1968) (exp); 2.13, M. Krell and T. E. O. Ericson, Nucl. Phys. B11, 521 (1969) (theor.).

[b] $\lambda_a(2p)$: $(2.28\pm0.61)\times10^{13}$ sec^{-1} Sapp *et al.* (Ref. 7); 3.4, M. Ericson and T. E. O. Ericson, Ann. Phys. (N. Y.) 36, 323 (1966); M. Ericson, Compt. Rend. 258, 1471 (1963); 1.06, G. Backenstoss, Ann. Rev. Nucl. Sci. 20, 467 (1970).

[c] $\sum_n\omega(ns)=0.40\pm0.09$; $\sum_n\omega(np)=1-\sum_n\omega(ns)$, Sapp *et al.*, Ref. 7.

[d] 1s capture only.

[e] Our results given in a preliminary analysis of the ^{6}Li spectrum for the ground-state transition rate should then be taken as the sum of the contributions for the first two states. [H. W. Baer, J. A. Bistirlich, K. M. Crowe, J. A. Helland, and P. Truöl, in *Proceedings of the International Conference on Few Particle Problems in the Nuclear Interaction, Los Angeles, California, 1972,* edited by I. Slaus, S. A. Moszkowski, R. P. Haddock, and W. T. H. van Oers (North-Holland, Amsterdam, 1972), p. 877.]

μ capture rate. Similarly, Maguire and Werntz use inelastic electron scattering to the ^{6}Li(3.56-MeV) state, in addition. Vergados and Baer give two values: one for a size parameter to fit the energy calculations, the other one fitting the rms radius.

From the results shown in Table IV one can draw the following conclusions:

(1) The elementary particle and impulse-approximation values of $\lambda_\gamma(1s)$ are in general agreement; however, the average EP value (excluding the Ref. 18 estimate, which did not include some corrections) $\lambda_\gamma(1s) = 2.03\times10^{15}$ sec^{-1} is higher than the average IA value 1.46×10^{15} sec^{-1}. The EP value of Delorme[15] $(2.3\pm0.5)\times10^{15}$ sec^{-1} is the highest.

(2) Since the soft-pion limit does not apply to $2p$ capture, only IA values are available for $\lambda_\gamma(2p)$. All estimates in Table IV of $\lambda_\gamma(2p)/\lambda_a(2p)$ are close except Delorme's.

(3) The average IA value of the branching ratio R_γ to the ground state of ^{6}He $0.319\pm0.070\%$ agrees perfectly with our experimental value $0.306\pm0.35\%$ but disagrees with the $1.0\pm0.1\%$ of Deutsch *et al.*[13]

(4) By relying on the IA estimate for $\lambda_\gamma(2p)$, one can extract $\lambda_\gamma(1s)$, i.e., $\lambda_\gamma(1s) = [R_\gamma(\text{expt}) - R_p(\text{IA})] \times[\lambda_a(1s)/\omega_s] = (1.37\pm0.50)\times10^{15}$ sec^{-1}, where R_p(IA) is taken from the average calculated value $\lambda_\gamma(2p) = 4.61\times10^{10}$ sec^{-1}. This agrees with IA estimates but is somewhat lower than the EP values.

We can say that at the present level of comparison between theory and experiment, no major discrepancies with either the EP or IA calculations are seen.

From the standpoint of testing nuclear wave functions, the ratio $R_\gamma(2^+)/R_\gamma(0^+)$ is of interest. In this ratio, though experimentally not too well determined because of the lack in resolution, the errors introduced from the pionic x-ray data cancel to a large degree. The theoretical result of Vergados[33] is 0.18 ± 0.03, in disagreement with our experimental result of 0.49 ± 0.10. Although this value depends on the way the background is treated, there does not seem to be disagreement with theory. We can think of the following sources for this.

(1) An enhancement of the rate for the reaction ^{6}Li$(\pi^-,\gamma)^4$He nn near the threshold. This is possible when the absorption proceeds via the absorption of the pion on a quasifree deuteron in the ^{6}Li (deuteron exchange) and the $d(\pi^-,\gamma)2n$ spectrum has the usual shape influenced by the n-n final-state interaction.[34]

(2) The shell-model wave functions do not describe the 1.8-MeV state too well. Since harmonic-oscillator wave functions were used, the fact that the 1.8-MeV state is unbound may not be properly taken into account. One expects for the unbound state that the nucleon wave function extends beyond the nuclear surface, more than is assumed in the calculation. Since this will place the nucleons closer on the average to the π^-, it is not unreasonable to expect an enhancement in the transition rate relative to the ground state above that given by the shell-model calculation.

Of the three resonances for which our data gives some evidence, there is supporting evidence for the one at $E_x\approx23$ MeV in the mirror nucleus ^{6}Be. Here a $T=1$, $T_z=-1$ $(I_z=+1)$ resonance is observed at approximately the same energy. Measurements of ^{3}He-^{3}He elastic scattering[35,36] and the radiative ^{3}He capture reaction[37] ^{3}He(^{3}He, γ)^{6}Be determined $L=3$, $S=1$, $T=1$ for this resonance, and it has been identified with the ^{33}F state predicted at ~27 MeV by Thompson and Tang.[38] Observation of the $T_z=0$ member of this isobaric triad in ^{6}Li was reported by Ventura, Chang, and Meyerhof.[39] To our knowledge this is the first evidence found for the $T_z=+1$ member in ^{6}He.

The possible peak at $E_\gamma=118.8$ MeV would correspond to an excitation energy in the ^{6}He of 15.6, or 3.3 MeV about the threshold for the breakup of the ^{6}He into two tritons. Considerable discussions have centered recently around the existence of a $T=1$ level in the $A=6$ system above the ^{3}H-^{3}H, ^{3}He-^{3}H, and ^{3}He-^{3}He threshold for ^{6}He, ^{6}Li, and ^{6}Be, respectively. The existence of such a level was originally put forward by Fowler[40] as a possible explanation of the low solar neutrino flux observed by Davis, Rogers, and Radeka.[41] The properties of this 0^+ level and evidence for and against its existence were later discussed by Fetisov and Kopysov[42] and by Barker.[43] The only other evidence for a level in this energy region in ^{6}He comes from the reaction ^{7}Li$(p,2p)^6$He, but the proposed spin-parity values are $J=1^-$ or 2^-.[12] In ^{6}Li, however inelastic scattering indicated a level at 15.8 MeV with $J^\pi=0^+$, 1^+, or 2^+.[12] A recent repetition of this experiment[44] with 37-, 50-, and 60- MeV electrons scattered at 180° did not observe any narrow transitions in the excitation region from 9 to 18 MeV, and an upper limit of 3 eV is placed on the $M1$ ground-state transition width for a narrow 0^+ state near 15.2 MeV in ^{6}Li. Unfortunately we can only estimate the width very crudely, and the transition rate given in Tables II and III for this level depends, of course, strongly on the model used to subtract quasifree capture. It seems desirable, however, to estimate theoretically the possible width and position of the proposed level in ^{6}He and its possible rate for our reaction.

A possible third level, at $E_x\approx30$ MeV, cannot be identified with any known states. However, the weak statistical evidence for it as well as the problem of knowing the quasifree background—e.g., reactions like $\pi^- + {}^6\mathrm{Li} \rightarrow {}^4\mathrm{He}^* + n + n + \gamma$ might yield spurious resonances in ^{6}He—preclude further comment.

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