erties of the parts of the states that lead to an interaction with the external probe.

It is a pleasure to acknowledge the stimulation of R. M. Macfarlane to consider this problem and numerous helpful comments from S. R. Chinn.

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PHOTONEUTRON CROSS SECTION FOR He^4 †

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The photoneutron cross section for He^4 has been measured with monoenergetic photons from threshold to 31 MeV. The cross section reaches its maximum value of 1.0 mb from 24.3 to 27.3 MeV; the integrated cross section is 7.9 MeV mb. These are considerably lower than corresponding values for the $He^4(\gamma,p)$ reaction measured elsewhere.

Perhaps the most fundamental and sensitive test of charge symmetry in nuclear reactions consists in a comparison of the mirror reactions $He^4(\gamma,n)He^3$ and $He^4(\gamma,p)H^3$, since the initial-state electromagnetic interaction is well understood, the isospin selection rule requires that $E1$ transitions populate $T=1$ states only, and barrier and threshold effects are expected to be negligible in the giant-resonance region. Although there have been a number of measurements of the latter reaction[1-7] and its inverse[8-10] reported in the literature, there have been only a few of the former,[4,11,12] and all these have been made using continuous bremsstrahlung sources, with all the attendant difficulties. [Only a single measurement of the $He^3(n,\gamma)He^4$ cross section has been reported,[13] for neutrons of average energy 4 MeV.] The present measurement of the $He^4(\gamma,n)He^3$ cross section was made in an effort to remedy this situation, and for this experiment monoenergetic photons were used.

The source of radiation for the present experiment was the positron-annihilation photon-beam facility at the Livermore electron linear accelerator. The techniques for the use of annihilation photons for photonuclear cross-section measurements have been described elsewhere.[14] The liquid-helium sample, approximately 6 moles in size and 17 cm thick, intercepted the entire collimated photon beam and was located at the center of a 4π neutron detector consisting of 48 BF_3 neutron detectors in a polyethylene moderator. This detector has been described by Kelly et al.[15] Its efficiency was measured by a variety of techniques, using calibrated neutron sources, spontaneous-fission coincidence measurements, and photoneutrons of known energy from C^{12} and Y^{89} (whose cross sections were measured previously at this laboratory[14,16]), and was found to vary smoothly from 24% for neutrons having an energy of 1 MeV to 17% for energies of 5 MeV and above. The photon energy resolution was at most 400 keV.[17] The energy scale and resolution were checked by a measurement of the 17.28-MeV peak in the $O^{16}(\gamma,n)$ cross section, using a water sample in the (warm) cryostat. The absolute photon-beam intensity was calibrated with the use of a 20×20-cm NaI(Tl) crystal. Backgrounds were determined from sample-blank measurements, and from measurements with no annihilation target in the positron beam performed before and after each datum point. The effect of the helium sample on the detector efficiency was determined by successive measurements of the $C^{12}(\gamma,n)$ cross section with and without helium in the cryostat. This effect necessitated a small (~5%) correction to the cross-section data. A total of approximately 5×10^5 events were recorded.

A subsidiary experiment was performed with a bremsstrahlung radiation source, in which the end-point energy was stepped from 29.7 to 42.2 MeV. This measurement served to check the magnitude, at the higher energies, of the neutron yield resulting from the positron bremsstrahlung which must be subtracted from the

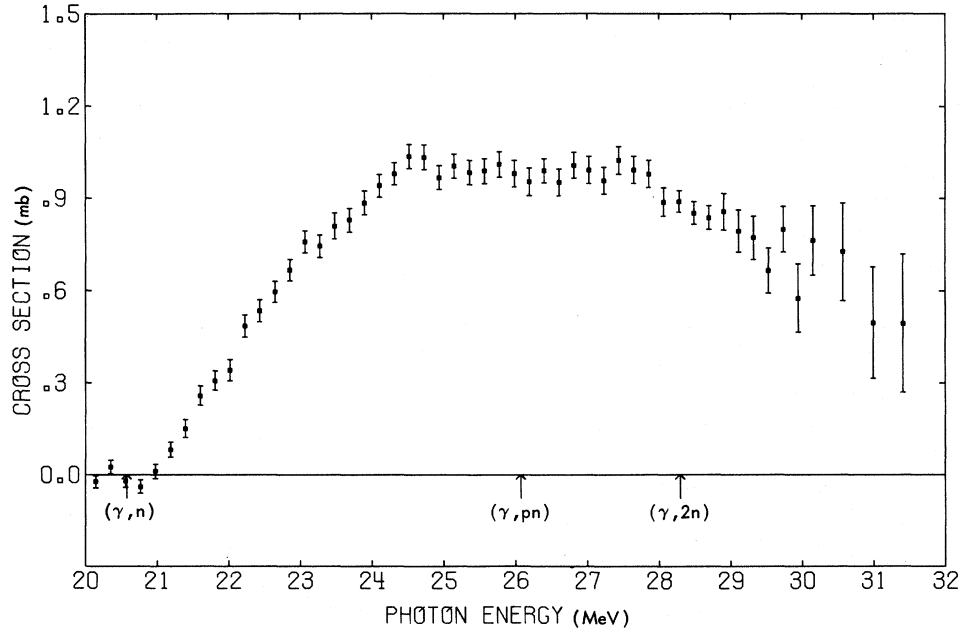

FIG. 1. Photoneutron cross section for He^4.

total neutron yield for the positron runs in order to determine the yield resulting from the annihilation photons alone, and it also served to indicate that the cross section, while falling, is still appreciable at 40 MeV.

The results are shown in Fig. 1. The error bars shown are statistical only. Systematic uncertainties are such that the absolute cross section might be in error by at most +15 or −10%. The cross section rises sharply from 21 MeV, reaches its maximum value of 1.03 mb at about 24.3 MeV, decreases slightly to a shallow minimum at about 26 MeV, rises again to a second maximum at about 27.3 MeV, then decreases rapidly to about 0.55 mb at 31 MeV. The integrated cross section from threshold to 31.41 MeV is 7.94 MeV mb, about 13% of the electric-dipole sum-rule value; its first moment, σ_{-1}, is 0.30 mb, and its second moment, σ_{-2}, is 0.012 mb MeV^{-1}.

The peak $He^4(\gamma,n)$ cross section measured in the present experiment (1.0 mb) is about 20% lower than (but still within the experimental uncertainties of) the measurements of Ferguson et al.[11] and Ferrero et al.,[12] and disagrees strongly (about 40% lower) with the measurement of Gorbunov.[4] However, the $He^3(n,\gamma)$ measurement of Zumühle, Stephens, and Staub[13] gives $\sigma(n,\gamma) = 42$ μb at $E_n = 4.0$ MeV, which corresponds to $\sigma(\gamma,n) = 0.94$ mb at $E_\gamma = 25.9$ MeV, essentially identical to the value of 0.95 mb at this energy from the present experiment. The peak $He^4(\gamma,p)$ cross section, as reported in Refs. 1-10, whose results are all in rough agreement with each other, is about 1.8 mb. The present integrated cross section up to 31 MeV is likewise about half that for the (γ,p) reaction. This striking discrepancy was completely unexpected in a nucleus as simple as the alpha particle, and can result from only two possibilities: (a) that there exists a large amount of isospin mixing, over a wide range of excitation energy, from strongly overlapping or nearly degenerate underlying $T=0$ levels, or (b) that the n-n interaction in the final state for the $He^4(\gamma,n)$ process differs appreciably from the p-p interaction in the final state for the $He^4(\gamma,p)$ mirror process—a breaking of charge symmetry in nuclear interactions. In the terminology of the early work of Barker and Mann,[18] this requires an isospin impurity $|a_0/a_1|$ of 13%, computed from the relation

$$\frac{\sigma(\gamma,n)}{\sigma(\gamma,p)} = \frac{P_n(E_n)}{P_p(E_p)}\left|\frac{a_1-a_0}{a_1+a_0}\right|^2,$$

where a_0 and a_1 are the amplitudes for the $T=0$ and $T=1$ components in the wave function(s) for the excited He^4 (giant-resonance) state(s), and the penetrabilities are $P_n(E_n) \cong P_p(E_p) \cong 1$. The energy dependence of this ratio would throw a good deal of light on the amount and shape of underlying $T=0$ strength, but the present state of disagreement on the details of the shape (not the magnitude) of the $He^4(\gamma,p)$ cross section precludes further analysis of this kind here. It suffices to note that in the absence of very appreciable and relatively constant Coulomb mixing across the entire giant-resonance region (or, probably less likely, an appreciable $T=1$ admixture in the He^4 ground state) there would have to be a charge-symmetry–breaking nuclear force leading to an intensity of the order of $|a_0/a_1|^2 = 1.7\%$ of that resulting from the charge-symmetry-nonbreaking component. This should be compared with the value of $\approx(0.25 \pm 0.80)\%$ given by Henley[19] from a summary of the low-energy scattering data. Finally, it should be noted that the fact that such a small charge-symmetry-breaking force causes such a large difference in the mirror photoreactions illustrates the great sensitivity of this type of measurement.[20]

The fore-aft asymmetry of the photoneutrons also has been determined. Since the neutron detector was divided into four sections, two forward of the laboratory angle 90° and two backward of it,[15] this asymmetry was measured simultaneously with the cross section. Although scattering of the photoneutrons in the sample or detector material during moderation could reduce the observed asymmetry, so that these data represent a lower limit to the true asymmetry, such an effect is expected to be small. The results are shown in Fig. 2. The photoneutron asymmetry rises from zero near threshold to a forward peaking at about 23.5 MeV and then passes through zero again at about 27 MeV to a backward peaking at 30 MeV. Thus, between 23.5 and 30 MeV, there is a sign reversal in the interference between the dominant $E1$ amplitude and an underlying positive-parity contribution.

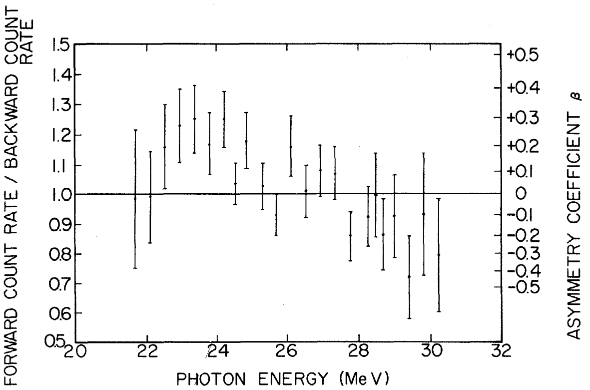

FIG. 2. Fore-aft asymmetry of the photoneutrons. The asymmetry coefficient β is computed on the assumption that the angular distribution is given by $\sin^2\theta(1+\beta\cos\theta)$.

The backward peaking of the photoneutrons at 30 MeV is confirmed by the angular-distribution data of Ref. 4.

Two broad $J^\pi = 1^-$, $T=1$ states are expected to dominate the photoabsorption cross section for He^4 below 30 MeV.[21] It is clear from the shape of the cross section of Fig. 1 that this is likely to be the case. Indeed, a single-level Breit-Wigner fit to these data (including threshold and penetrability effects) yields a χ^2 value of 2.8, while a fit using two noninterfering levels yields a χ^2 value of 1.1. This fit gives resonance energies of 25.0 and 27.7 MeV, in excellent agreement with one of the two possible sets of values given in Ref. 21, namely, 25.1 and 27.8 MeV, corresponding to the level scheme wherein the lower state is mainly $^1P_1$ and the upper state is mainly $^3P_1$ (see also Ref. 6). The evidence that two distinct states are populated is bolstered by the fact that the fore-aft asymmetry of the photoneutrons (Fig. 2) changes sign between these two energies. Since the photoprotons from the $He^4(\gamma,p)$ reaction are peaked at forward angles throughout this energy region,[4,10] it appears that for the lower 1^- state, the photoneutrons and photoprotons in the final state interfere with the underlying positive-parity amplitude with the same phase, while for the upper 1^- state they interfere with opposite phase. It should be noted, finally, that the main effect of $E2$ photoabsorption, which can populate $T=0$ states that can interfere with the $T=1$ states populated by $E1$ absorption, is only in the angular distributions (because the interference term vanishes upon integration over all angles), and hence will not change the preceding argument concerning the breaking of charge symmetry.

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EVIDENCE FOR PARITY-FORBIDDEN α-PARTICLE DECAY FROM THE 8.87-MeV 2^- STATE IN ^{16}O

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The energy spectrum of 1.3×10^8 α particles from the sequential decay $^{16}\mathrm{N}(\beta^-)^{16}\mathrm{O}(\alpha)^{12}\mathrm{C}$ has been obtained. A group of 7100 ± 1800 α particles with an energy of 1278 ± 10 keV has been identified. They are attributed to the parity-forbidden decay from the ^{16}O 8.87-MeV 2^- state into $^{12}\mathrm{C}+\alpha$. A width $\Gamma_\alpha = (1.8\pm0.8)\times10^{-10}$ eV has been obtained for this transition.

A search for α-particle decay from unnatural-parity states in even-even nuclei provides a direct test of parity mixing in nuclear energy levels.[1] The 8.87-MeV 2^- state in ^{16}O offers the most favorable conditions for such a test. The excitation energy of this level exceeds the binding energy of an α particle in ^{16}O by 1.71 MeV. It can be populated from the β^- decay of ^{16}N ($T_{1/2}$ = 7.1 sec). A fraction (1.1%) of the betas from ^{16}N goes into the 8.87-MeV state, which in turn is de-excited by γ-ray cascades to the ^{16}O ground state. The beta branching ratio to the neighboring 9.61-MeV 1^- level is only 1.2×10^{-3}%. Beta transitions to this state give rise to a broad α-particle distribution from the parity-allowed decay into $^{12}\mathrm{C}+\alpha$. Superimposed on this distribution, a group of α particles with an energy[2] of 1280 ± 2 keV should appear in the case of the parity-forbidden decay from the 8.87-MeV state. The first attempts to observe this unusual decay were undertaken independently by several groups[3-6] nearly ten years ago. Low intensity and insufficient energy resolution restricted their results to an upper limit, $\Gamma_\alpha \leq (3\text{-}6)\times10^{-9}$ eV, for the width of the parity-forbidden α-particle decay of the 8.87-MeV state. Recently,[7] this upper limit has been reduced to $\Gamma_\alpha \leq 1.6\times10^{-9}$ eV.

^{16}N was produced by the reaction $^{15}\mathrm{N}(d,p)$, bombarding 96%-enriched ^{15}N gas at atmospheric pressure with 3-MeV deuterons. The irradiated gas was allowed to flow from the target vessel through a thin capillary into a small detection chamber (2 cm^3 volume). The gas pressure within this chamber was kept at 7 ± 1 Torr. α-particles leaving the chamber through four circular windows (8 mm diam), consisting of 30-μg/cm^2-thick collodion foils, were detected by four Ortec A-018-025-100 surface-barrier detectors. The pulses from the detectors, after appropriate amplification, entered a 4×128-channel Laben pulse-height analyzer. From repeated calibrations, the energy of the α particles was determined with a precision of ±10 keV. A detailed description of the experimental arrangement has been given elsewhere.[8]

Figure 1 shows the pulse-height distribution of