or alternatively we can calculate the resonance width by

$$\Gamma = 4\pi\hbar^2 \Big/ \int_{-\infty}^{\infty} dE\, \mathcal{T}^2. \qquad (48)$$

We have chosen to use Eq. (47) with E_0 taken to be the real part of the energy of the resonance pole.

VII. NUMERICAL RESULTS

The results of using the three methods described above to evaluate the resonance half-width of our simple model are displayed in Table I. The calculations were done for a range of coupling strengths v_0/Δ and a range of elastic scattering strengths b/Δ. The numerical results show that the golden-rule result is only reliable when the coupling strength is very small, or equivalently, when the width of a resonance is very narrow. From our tabulated results we can guess that for Γ smaller than about $10^{-4}Q$ [or channel couplings $(\hbar^2 v_0^2)/(2m)$ less than about $10^{-2}Q$], the error in the golden-rule calculations will be less than a few percent. Nuclear Q values being a few MeV, we conclude that the golden rule can be used with confidence when the width is less than a kilovolt or the channel coupling is less than 0.1 MeV. This means that the golden rule can be used with confidence for calculating α-decay lifetimes and sharp structure widths but not for neutron-scattering resonances. There is also a question as to the validity of treating intermediate structure resonances in a first-order perturbative manner. The time-delay method is seen to give consistently more accurate results for varied coupling strengths. Of course, these conclusions must be regarded as only a crude guide, since they apply only to a very simple model.

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Determination of the Neutron Polarization from the $^{13}C(^3He,n)^{15}O_{g.s.}$ Reaction from 2.9 to 3.9 MeV*

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Angular distributions of the polarization of neutrons produced in the $^{13}C(^3He,n)^{15}O_{g.s.}$ reaction have been obtained at 2.95, 3.45, and 3.85 MeV. The polarization at 20° lab at six additional energies between 3.0 and 3.9 MeV was measured also. Scattering from ^4He contained at a high pressure in a scintillation cell served as the neutron polarization analyzer. The three angular distributions were somewhat similar in shape, in that they showed large negative minima around 40° and 120° lab and zero or positive polarization around 80° lab. Preliminary attempts to describe the polarization using an $l=0$ diproton-stripping-reaction approach were unsuccessful, but this is attributed to inadequate knowledge of the optical-model parameters.

1. INTRODUCTION

Recently, our laboratory reported the first measurements[1,2] of polarizations produced in $(^3He,n)$ reactions. Large neutron polarizations were found in the $^{12}C(^3He,n)$ reaction over the 2.2 to 3.7-MeV range investigated. An attempt to fit the cross section and polarization at 3.7 MeV using the distorted-wave Born-approximation (DWBA) code[3] JULIE was somewhat successful although the effects of resonances clouded the conclusions. The second reaction investigated was the $^9Be(^3He,n)$ reaction whose cross section exhibits little resonance structure[4] below 4 MeV and whose neutron polarization distributions likewise showed little change with energy.[2] So far the effort[5] to describe the $^9Be+{}^3He$ elastic and reaction cross sections *and* the neutron polarization have not succeeded and more searching throughout parameter space is being done. This analysis is complicated as the diproton can be transferred with an orbital angular momentum of $l=0$ or $l=2$. The third reaction studied was $^{13}C(^3He,n)^{15}O$ because the differential cross section[6] indicates that there is a large amplitude for $l=0$ diproton stripping at energies below 4 MeV, our maximum attainable energy with suitable beam currents. This paper is a report of polarization angular distributions $P(\theta)$ produced in the latter reaction at 2.95, 3.45, and 3.85 MeV. Also reported is a determination of $P(20°\text{ lab})$ for six additional ^3He energies from 3.0 to 3.9 MeV.

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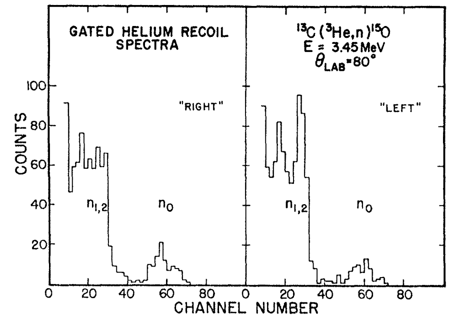

FIG. 1. Gated ^{4}He recoil spectra taken with a ^{3}He energy of 3.45 MeV at a reaction angle of 80° lab. The peaks labeled n_0 and $n_{1,2}$ correspond to neutrons, which left the residual nucleus ^{15}O in its ground state and 1st or 2nd excited state, respectively.

2. EXPERIMENTAL PROCEDURE

A beam of 4μA singly charged ^{3}He from the Duke 4-MeV Van de Graaff was incident on a 53% enriched ^{13}C target. The ^{13}C targets were prepared by irradiation of a gas target filled with the ^{13}C enriched CH_4 at a pressure of about 0.3 atm. The cracked CH_4 forms a target of 1×10^{19} C atoms/cm^2 after 3 h of bombardment with about 1μA of 3 MeV He$^+$. The target thickness in C atoms/cm^2 was determined by comparing the yields of the cracked target and the initial gas target. The energy loss in the cracked material was then calculated by assuming a compound between CH_3 and CH_4, which gives an uncertainty of $\pm15\%$. Because of low counting rates, the targets employed in the measurement were necessarily thick. The targets had 200-keV energy loss for the $P(\theta)$ measurement of 3.85 MeV, 400 keV at 3.45 MeV, 700 keV at 2.95 MeV, and 120 keV for the $P(E)$ measurement at 20° lab.

The polarimeter for measuring the neutron polarization has been described earlier.[7,8] It consists of a gaseous ^{4}He scintillator[9,10] with a pressure of 130 atm and two neutron detectors located above and below the He scintillator to measure the asymmetry of neutrons scattered by He through an angle of 120° lab. These latter detectors are $5\times7.5\times15$-cm^3 NE-213 scintillators with their centers 20 cm away from the He cell. A solenoid for 90° spin precession is used to avoid experimental asymmetries due to all drifts of electronics and beam parameters and due to different counting efficiencies in the two neutron detectors.

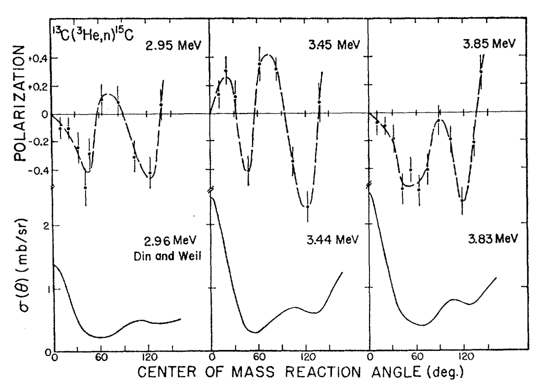

FIG. 2. Polarization distribution for the ^{13}C(^{3}He,n)^{15}O$_{g.s.}$ reaction measured at 2.95-, 3.45-, and 3.85-MeV mean energy. The dashed curves are smooth lines drawn through the data points. The cross sections in the lower part of the figure are taken from the publication by Din and Weil (Ref. 6).

TABLE I. Neutron polarization from the ^{13}C(^{3}He,n)^{15}O$_{g.s.}$ reaction.

E (MeV)	θ(lab) (deg)	θ(c.m.) (deg)	E_n (MeV)	P_1	ΔP_1
2.95	10	10.6	10.05	−0.10	0.08
	20	21.2	9.99	−0.10	0.08
	30	31.8	9.90	−0.23	0.11
	40	42.3	9.78	−0.51	0.13
	45	47.5	9.71	−0.27	0.11
	60	63.1	9.46	0.10	0.11
	80	83.5	9.08	0.09	0.11
	100	103.5	8.69	−0.29	0.11
	120	123.1	8.34	−0.41	0.11
	135	137.5	8.13	0.06	0.11
3.45	10	10.7	10.55	0.13	0.11
	20	21.3	10.49	0.30	0.11
	30	31.9	10.38	0.12	0.11
	45	47.7	10.17	−0.40	0.11
	60	63.3	9.89	0.34	0.12
	80	83.7	9.47	0.31	0.08
	100	103.7	9.04	−0.33	0.10
	120	123.3	8.66	−0.64	0.10
	135	137.7	8.43	0.08	0.13
3.85	10	10.7	10.95	−0.07	0.09
	20	21.3	10.88	−0.09	0.07
	30	32.0	10.78	−0.18	0.11
	40	42.5	10.62	−0.54	0.11
	50	53.0	10.44	−0.40	0.09
	60	63.4	10.24	−0.55	0.11
	70	73.7	10.02	−0.41	0.11
	85	88.9	9.67	−0.06	0.11
	100	103.9	9.33	−0.19	0.10
	115	118.6	9.01	−0.62	0.10
	130	133.0	8.74	−0.21	0.10
	140	142.5	8.45	0.27	0.12
3.25	20	21.3	10.29	−0.08	0.12
3.40	20	21.3	10.44	0.13	0.12
3.50	20	21.3	10.54	0.29	0.11
3.60	20	21.3	10.64	0.23	0.11
3.70	20	21.3	10.74	−0.14	0.11
3.75	20	21.3	10.79	−0.02	0.10

The analyzing power for the scattering from ^{4}He has been calculated using the optical-model phase shifts of Satchler *et al.*[11] Corrections for the angular acceptance (full width at half-maximum) $\Delta\theta=14°$ and $\Delta\varphi=20°$ of the neutron detectors and also for the energy dependence of their efficiencies have been applied.

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The data were analyzed on-line by a DDP 224 computer,[12] which stored the pulses from the He recoils, gated by a fast coincidence (10 nsec) between He scintillator and neutron detectors, in four separate memory blocks according to whether the neutron was counted in the "up" or "down" detector and whether the spin precession was clockwise or counterclockwise. The sum of the 1st and the 4th of these He recoil spectra, as well as the sum of the 2nd and 3rd spectra, are both shown in Fig. 1 where they are labeled "left" and "right," respectively. The peaks marked with n_0 are the ones of interest; i.e., the He recoils corresponding to neutrons which left the residual nucleus ^{15}O in its ground state. The on-line data storage and analysis system will be described in a later paper. Room-scattered neutrons and accidental coincidences gave negligible contributions. The 47% ^{12}C in the target did not interfere with the measurement, as the neutrons from this isotope were much lower in energy than those of interest.

3. RESULTS AND DISCUSSION

The results of the present work are shown in Table I, and Figs. 2 and 3. Listed are the mean energy E of the incoming ^3He particles, reaction angles in the laboratory and center-of-mass reference frames θ_{lab} and $\theta_{c.m.}$, the neutron energy E_n, the derived polarization P_1 and its uncertainty ΔP_1. This uncertainty is given by counting statistics, other errors being negligible. Figure 2 shows the angular distributions $P_1(\theta)$ for mean energies of 2.95, 3.45, and 3.85 MeV together with differential cross sections published by Din and Weil.[6] Figure 3 shows the polarization as a function of energy at a reaction angle of 20° lab along with yield curves of Ref. 6.

Our results show that there is a sizable change in the polarization at 20° between 3.4 and 3.7 MeV although the diproton-stripping amplitude dominates the cross section at forward angles. Some structure is evident around 3.5 MeV in the 0° neutron yield (see Fig. 3) but this peak is somewhat narrower than the polarization structure at 20°. In addition to compound-nuclear effects, peaking can be produced in direct reactions at low energies through the energy sensitivity of the distorted waves.[13] We have not carried out sufficient calculations to test if 3 MeV is low enough to observe these latter effects in the $^{13}C(^3He,n)$ case.

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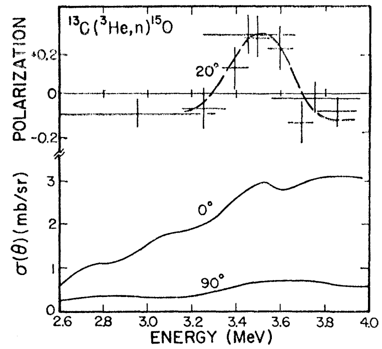

FIG. 3. Measured polarization as a function of incident energy at a reaction angle of 20° lab. The yield curves in the lower part of the figure are taken from the publication by Din and Weil (Ref. 6).

The gross features of the polarization distributions are quite similar at 2.95 and 3.85 MeV and, to a lesser extent, at 3.45 MeV. A brief attempt was made by the authors and R. M. Drisko to fit the 3.85-MeV polarization data using DWBA code JULIE[3] with the diproton-transfer option, but for several reasons we decided against pursuing this analysis at this time. The main reason was that little information exists concerning the optical-model parameters for ^3He-^{13}C elastic scattering. More experimental data is necessary. Secondly, a few preliminary measurements at Ohio State University by DeMartini and Donoghue[14] have shown that polarization experiments are feasible for this reaction up to at least 6 MeV. Similar to our results, their data indicate that the magnitude of the polarization is large and that there is considerable structure in the angular distribution. When these higher-energy measurements are completed, it will be more obvious whether one can expect the DWBA method to describe the polarization below 4 MeV or whether one has to be concerned with interference effects caused by broad or overlapping resonances.

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