Mass of lowest $T = 2$ state of ^{12}C

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A precise measurement of the excitation energy of the lowest $T = 2$ state in ^{12}C has been made via the $^{14}C(p,t)^{12}C$ reaction. The value obtained, 27.5950 ± 0.0024 MeV, is in agreement with earlier (less precise) measurements and therefore does not explain the failure to observe the $T = 2$ state in isospin-forbidden resonance reactions. Also reported in this work are an upper limit of 30 keV for the total width of the $T = 2$ state and an excitation energy of 3.3492 ± 0.0012 MeV for the first excited state of ^{10}C.

[NUCLEAR REACTIONS $^{14}C(p,t)$, $E_x = 27.6$ MeV, measured Q, Γ. $^{12}C(p,t)$, $E_x = 3.35$, measured Q. Magnetic spectrograph.]

I. INTRODUCTION

The T = 2 states in the mass-12 nuclei have a number of unusual properties which have singled them out for detailed experimental and theoretical investigation in recent years. Three members of the lowest isobaric quintet are now definitely known, in ^{12}Be, ^{12}B, and ^{12}C (see Ref. 1) and preliminary evidence for ^{12}O has been obtained by Kekelis *et al.* via the $^{16}O(^6He,^8He)$ reaction.[2] However, the T = 2 state in ^{12}N has not been detected despite a number of efforts.[1] The cross section for the $^{14}C(p,t)^{12}C$ (27.6) reaction is significantly lower than the typical magnitude, ~ 100 μb sr^{-1}, for analogous reactions to T = 2 states in other 4n nuclei. Although this may be due in part to the extremely negative Q-value, -32 MeV, Barker[3] has interpreted both the low cross section and discrepancies in the Coulomb energies in terms of configuration mixing. (A particularly interesting feature of Barker's calculations is the implication that there may be another low-lying 0^+, T = 2 state, possibly the first excited T = 2 state.)

Many experimental efforts to observe the lowest T = 2 state in ^{12}C as an isospin-forbidden resonance have been made. Black, Caelli, and Watson[4] investigated the $^9Be(^3He,\gamma\gamma)$, $^{10}B(d,p)$, $^{10}B(d,\alpha)$, and $^{10}B(d,\gamma\gamma)$ reactions, observing a small anomaly only in $(^3He,\gamma\gamma)$. Subsequent investigations,[5,6] however, did not find that resonance at a level of sensitivity substantially greater than the original experiment. Snover,[7] and more recently Nathan and Noé,[8] have sought to observe the resonance in radiative proton capture, also without success. These results appear to indicate that the particle widths in all the accessible (ground-state) channels are very small. Ashery *et al.*[9] investigated the particle decays of the T = 2 state and found a ground-state proton branch $\Gamma_{p_0}/\Gamma \lesssim 0.1$, which is presumably consistent with the estimate made by Nathan and Noé, $\Gamma_{p_0}/\Gamma < 0.006$. Very recently, the particle decays have been investigated at Princeton University,[10] and a preliminary analysis indicates that both the ground-state proton and ground-state deuteron decay branches are less than 5%. The ^3He decay could not be investigated. While it may well be that the ground-state particle widths are indeed all very small, one other possibility exists that would explain the non-observation of the state, and that is an error in the excitation energy. Four measurements of the energy have been made,[9,11-13] all in reasonable agreement, giving a weighted average of 27.591 (12) MeV. The motivation for the present work was to check that result and to improve its precision with a view to future resonance searches.

II. EXPERIMENTAL METHOD

The $^{14}C(p,t)^{12}C$ (27.6) reaction is far from ideal as a basis for a mass measurement. The low cross section becomes even smaller at the forward angles preferred for kinematic reasons. (At 45 MeV and a laboratory angle of 22°, the cross section is found to be approximately 5 μb sr^{-1}.) The Q value is so negative that there are no suitable (p,t) reactions that could serve as direct calibrations, and rather high beam energies are required. The thickness and uniformity of the targets (made by cracking ^{14}C-enriched acetylene onto a gold backing) are matters of concern when high precision is desired. There is also a continuous triton background, partly from $T_<$ states in ^{12}C and partly from the backing, which exacerbates the cross section problem.

Nolen, Hamilton, Kashy, and Proctor[14] have described a technique for precision mass measurements which makes use of nuclear emulsions in a magnetic spectrograph. The reaction products from the reaction under investigation are recorded simultaneously with suitably chosen calibration lines. Then, by a linearized least squares fit, all the unknown parameters in the experiment, the beam energy, the reaction angle, the spectrograph focal plane calibration and the target thickness, can be determined

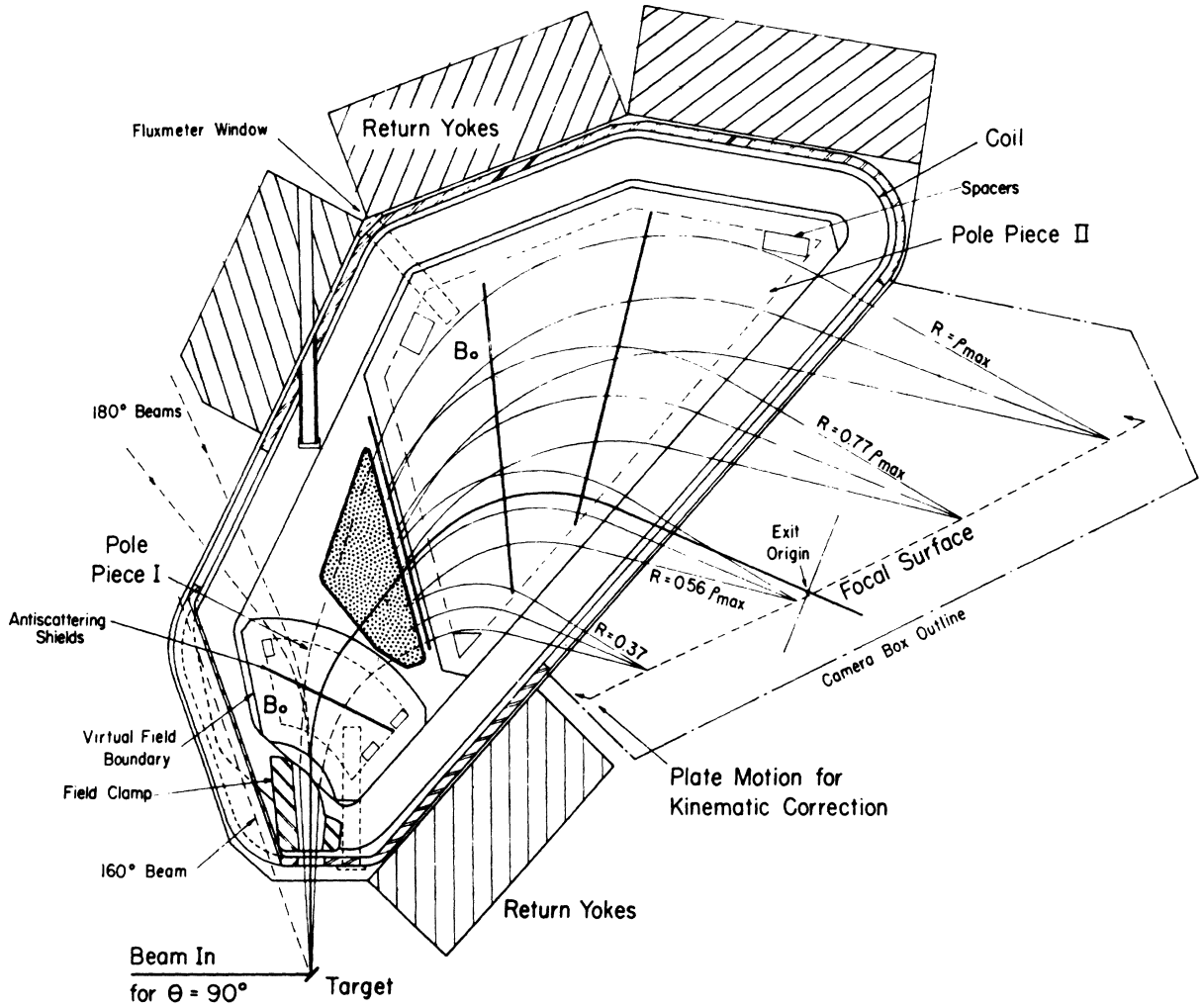

FIG. 1. Cross-sectional view of Enge split-pole magnet, showing electrostatic deflector (stippled area) used to separate particle types.

precisely. The chief advantages of the method are its immunity to variations in the parameters during the course of an experiment, which cause most of the uncertainties in sequential calibration techniques, and its independence of detailed knowledge of the spectrograph saturation and hysteresis behavior. For the highest precision, nuclear emulsions (rather than active detectors) are preferred in this method because of their linearity and the freedom from systematic shifts in peak centroid positions for different particle types. Ordinarily, the use of plates to record a reaction as weak as $^{14}C(p,t)^{12}C$ (27.6) would be out of the question because of the competition from intense fluxes of protons, deuterons, and alpha particles. To resolve this difficulty, an electrostatic deflector has been added to the Enge split pole magnet in order to separate (vertically) particles of different charge-to-mass ratio. Figure 1 shows the shape and location of the deflector, consisting of a pair of plates separated by 3.79 cm. The shape of the plates is intended to provide constant deflection along the length of the focal plane (except near the low-radius end), in the approximation that the focal plane is the vertical focus for the second magnet pole.[15] The deflector is biased by a voltage applied to the top plate – the lower plate is grounded.

The deflection obtained is approximately 10.0 (Vq/E) mm, where V is the applied voltage in kV, q the ionization state of the particle, and E the particle energy in MeV at the high-momentum end of the focal plane. For particles of the same magnetic rigidity, the deflection is proportional to m/q, where m is the mass. Provided the beam separate the ions of interest in most cases. Of course, the vertical deflection may also be accompanied by horizontal deflection, which must be corrected for if the separated spectra are to be used in a common calibration. If the plates are accurately flat and parallel to the median plane, the principal remaining effect which leads to shifts is the electrostatic field between the biased plate and the magnet pole pieces. Since particles cross these gaps non-normally, they experience a net horizontal deflection. The shift was measured by recording the $^{27}Al(p,p')$ reaction on nuclear emulsions at high resolution and, during the exposure, cycling the deflector on and off many times to average out the time dependence of other experimental conditions. A horizontal shift 2.4% of the vertical deflection was observed. (This small effect could in principle be virtually eliminated by driving the plates symmetrically about ground potential, with a slight

increase in the complexity of the device.)

The $^{14}C(p,t)^{12}C$ experiments were carried out with a target made by cracking ^{14}C-enriched acetylene onto a 1 mg-cm^{-2} gold backing. The target thickness as determined from energy losses was equivalent to 0.25 mg-cm^{-2} of ^{12}C. The target contained approximately 10% ^{12}C, and a small amount of H. With a 45 MeV proton beam extracted from the Michigan State University (MSU) cyclotron, calibration lines close to the $^{14}C(p,t)^{12}C$ (27.6) peak on the focal plane came from $^{14}C(p,\alpha)^{11}B$, $^{12}C(p,d)^{11}C$, $^{14}C(p,p')$, $^{12}C(p,p')$ and $^{1}H(p,p)$. The $^{12}C(p,t)^{10}C$ (3.35) line, also present, was used not as a calibration but as a check on the accuracy of the method. To record the spectra, three 25 cm Kodak NTB-25 nuclear track plates were used end-to-end in each run.

The unknown parameters determined by a linearized least-squares fit[16] to the calibration lines were: a) the three coefficients in a quadratic expression for magnetic rigidity as a function of position [established mainly by the (p,d) and (pα) spectra]; b) the reaction angle [fixed almost exclusively by $^{1}H(p,p)$]; c) the beam energy [determined from the relative positions of (p,d) and (p,α) spectra]; d) the target thickness [from the relative positions of (p,p') and (p,α) lines]; and e) the gap between adjacent plates [from the $^{12}C(p,d)$ spectrum, which crossed the gap]. The (p,p') lines were not in fact used in the final calibration. Since they behave magnetically the same as (p,α) lines but have less accurately determinable centroids, their only role was to uncorrelate target thickness and beam energy. The energy losses for deuterons, tritons, and alphas of the same rigidity are such that a change in target thickness is indistinguishable from a change in beam energy, permitting those two parameters to be combined into one if the inelastic proton lines are not used.

III. RESULTS

Data were taken in three separate runs, I, II, and III, with the beam energies, angles, and charges listed in Table I. Three 25-cm plates were exposed on each run, two of which recorded the spectra used in determining the mass of the lowest T = 2 state. The third covered the region expected to contain the first excited T = 2 state in ^{12}C,[9] but there was no indication whatsoever of this state. Figure 2 shows the spectra from the central plate of Run II. The plates were scanned on the MSU automated scanner[16] and peak centroids extracted by a variety of different, but standard, techniques. Special treatment of certain peaks and a number of corrections were necessary, as enumerated below.

Since several different reactions are used as calibrations, not all of them can be in focus at once at the surface of the plates. If angular distribution effects across the entrance aperture (1° wide and 2° tall in this case) can be neglected, it can readily be shown that the centroid of the peak is displaced toward the high-momentum end of the focal plane from the point of intersection of the median ray by a fraction

$$(\theta_2-\theta_1)^{-1}\ell n\{\frac{\cos\theta_1}{\cos\theta_2}\}-1$$

of the perpendicular distance from the plate to the focus (taken as positive when the focus is in front of the plate). In this expression θ_1 and θ_2 are the smallest and largest angles of incidence, respectively, of rays on the focal plane. In the present instance this difference is of order 4 μm, a negligible amount. The $^{1}H(p,p)$ line is so broad that is is preferable not to use its centroid but rather to use the better-defined edges of the peak. In that case, the median ray intersects the plate a fraction

$$(1-\tan\theta_1)\ (\tan\theta_2-\tan\theta_1)^{-1}$$

of the peak width from the high-radius (low-radius) edge of the peak when the actual focus is behind (in front of) the plate. This fraction is 0.487 for a 1° wide aperture. The technique of using the peak edges was also employed with some peaks that were so intense that their central regions could not be accurately scanned.

TABLE I. Experimental parameters of $^{14}C(p,t)^{12}C$ runs.

Run	Proton Energy (MeV)	Lab angle (degrees)	Charge (mC)
I	45.150	21.89	2.0
II	45.211	21.33	3.0
III	45.196	21.39	3.7

Because both ^{12}C and ^{14}C provided calibration lines, the accumulation of a layer of natural C on the target during the experiments could cause relative shifts. Some build-up on the Au backing was apparent, and fortunately was easily gauged by means of the $^{12}C(p,t)^{10}C$ (3.35) peak, which showed a weak satellite with an energy difference corresponding to the loss in the backing. This information was used to make small corrections to the $^{12}C(p,d)$ peak centroids, where the satellite was not resolved. Build-up on the ^{14}C side of the target could not be effectively monitored, but if it occurred at a similar rate, the corrections would be negligible.

Peak centroids were corrected for the horizontal shift introduced by the electrostatic deflection. The corrected peak centroids and their corresponding excitation energies were used in an unweighted least squares fit. The calibration peaks used (after a preliminary iteration with inelastic proton lines to fix the approximate target thickness) were: $^{12}C(p,d)^{11}C$ (2.000, 4.319, 4.804, 6.478, 6.905), $^{14}C(p,\alpha)^{11}B$ (0.0, 4.445, 5.021, 6.743) and $^{1}H(p,p)$. The $^{14}C(p,\alpha)^{11}B$ (6.743) line is unresolved in the plate spectra from the 6.793-MeV line, but higher-resolution data showed the population of the latter state to be

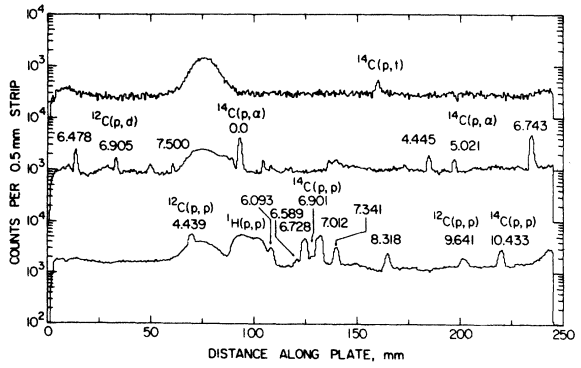

FIG. 2. Scans of three bands having (from top) m/q = 3, 2, and 1. The broad feature near 75 mm in all three spectra is a diffuse proton group arising from scattering at the entrance to the target chamber.

TABLE II. Summary of measurements of excitation energy of T = 2 state of ^{12}C.

Run	E_x (keV)	Uncertainties (keV) Statistical	Calibration	Total
I	27595.7	4.5		
II	27596.9	1.9		
III	27591.8	2.4		
Average	27595.0	2.1[a]	1.2	2.4

[a]Adjusted to give $\chi^2_\nu = 0.693$

negligibly small. The excitation energies used were those given by Ajzenberg-Selove,[18] and the ground state masses those given by Wapstra and Bos.[19] The results for the excitation energy of the T = 2 state in ^{12}C are summarized in Table II. With the estimated statistical uncertainties in peak centroids, (normalized) χ^2_ν for the three measurements is 1.5, corresponding to 23% probability that such a distribution would be obtained by chance. While this is not an unreasonably small probability, the adopted statistical uncertainty has been adjusted upward to correspond to 50% probability. The revision seems prudent in view of the difficulty in estimating those contributions to the statistical uncertainty, such as background subtraction, which have a subjective component. The calibration uncertainty arises chiefly from the excitation energies of states in ^{11}C, which are known[18,20] typically to ± 1.3 keV. If these uncertainties are completely uncorrelated, the resulting uncertainty in the T = 2 state energy is 1.2 keV as given in Table II. However, the ^{11}C energies were measured in magnetic spectrograph experiments[20] and there is a distinct possibility of correlation of systematic errors. Although the quoted uncertainties[20] are statistical, had they been 100% correlated (but still uncorrelated with the ^{11}B excitation energies), the effect on the final uncertainty would be to increase it from 2.4 to 2.9 keV, a relatively small change.

As a check on the procedure, the Q value for the $^{12}C(p,t)^{10}C$ reaction to the first excited state of ^{10}C has been extracted from the data. Table III summarizes the results. In this case the three measurements lead to a normalized χ^2_ν of 0.67, without adjustment, suggesting that the statistical uncertainties have been reasonably well estimated. (Nevertheless, the adjusted uncertainty for the ^{14}C result is retained because a substantial part of the uncertainty comes from the $^{14}C(p,t)^{12}C$ (27.6) peak itself, which is possibly influenced by errors in background subtraction.) The Q-value derived for the $^{12}C(p,t)^{10}C$ (3.35) reaction, −26.7130 (10) MeV, is in good agreement with a recent result of Benenson and Kashy.[21] They obtained an excitation energy of 3.3500 (10) MeV, which corresponds to a Q-value of −26.7138 (12) MeV. The weighted average of these two results is −26.7133 (8) MeV.

The total width of the lowest T = 2 state of ^{12}C is a matter of some interest both for experimental searches for the isospin-forbidden resonance, and for calculations

TABLE III. Summary of measurements of excitation energy of first excited state of ^{10}C.

Run	E_x(keV)	Uncertainties (keV) Statistical	Calibration	Total
I	3.3475	2.3		
II	3.3489	1.0		
III	3.3502	1.2		
Average	3.3492	0.71	0.95[a]	1.2[a]

[a]Includes 0.7 keV uncertainty in the ^{10}C mass, which does not affect the Q-value for $^{12}C(p,t)^{10}C$ (3.35).

TABLE IV. Measured resonance and decay properties of lowest T = 2 state in ^{12}C for two different assumptions about the total width of the state. Quantities given without uncertainties are upper limits. Only the most sensitive experiment of a given type is listed – see Refs. 4–10.

Quantity	Narrow Resonance	Γ = 30 keV
$\Gamma_{d_o}\Gamma_{p_o}/\Gamma$	225 eV	1.9 keV[a]
$\Gamma_{d_o}\Gamma_{p_1}/\Gamma$	100 eV	0.8 keV[a]
$\Gamma_{d_o}\Gamma_{p_2}/\Gamma$	120 eV	1.0 keV[a]
$\Gamma_{d_o}\Gamma_{p_3}/\Gamma$	125 eV	1.0 keV[a]
$\Gamma_{d_o}\Gamma_{\alpha_o}/\Gamma$	100 eV	0.8 keV[a]
$\Gamma_{d_o}\Gamma_{\alpha_1}/\Gamma$	300 eV	2.4 keV[a]
$\Gamma_{d_o}\Gamma_{\gamma}/\Gamma$	0.2 eV	5.7 eV[a]
$\Gamma_{p_o}\Gamma_{\gamma}/\Gamma$	0.13 eV	1.1 keV[c]
$\Gamma_{\tau}\Gamma_{\gamma}/\Gamma$	1.5 meV	58 meV[d]
Γ_{d_o}/Γ	0.005	0.14 [a,b]
Γ_{p_o}/Γ	0.003	0.03 [b,c]
Γ_{τ}/Γ	4×10^{-5}	1.5×10^{-3} [b,d]
Γ_{p_o}/Γ	0.04(3)[e]	
Γ_{α_o}/Γ	0.10(3)[e]	
Γ_{d_o}/Γ	0.03(2)[e]	

[a]Ref. 4
[b]Assuming Γ_γ = 40 eV (1 W.u.)
[c]Ref. 8
[d]Ref. 5
[e]Ref. 10

of the isospin admixtures in the state. In the present data, the observed full width at half maximum of the peak was consistently about 30 keV, appreciably larger than the target thickness contribution of 15 keV. However, the $^{12}C(p,t)^{10}C$ (3.35) peak was also quite wide (~ 26 keV), and it is not possible to make any statement other than $\Gamma < 30$ keV for the T = 2 state. Several attempts were made with a thin (50 $\mu g\ cm^{-2}$) ^{14}C target and a carefully optimized beam to reduce the upper limit on the width, but the state was not seen at all.

IV. DISCUSSION

The excitation energy measured for the lowest T = 2 state in ^{12}C, 27.5950 (24) MeV, is in agreement with all the previous measurements,[9,11-13] and substantially more precise [a preliminary number reported,[22] 27.626 (7) MeV, is incorrect because of a computing error and should be disregarded.] This value places the state within the search range of all known resonance experiments. The results of the most sensitive of the experiments are summarized in Table IV, along with preliminary data on the decays of the T = 2 state from Ref. 10. It may be seen that if the state is narrow, then indeed the partial widths for decay into the p_o, d_o, or τ_o channels are remarkably small. However, for a state as broad as 30 keV, the limits are neither particularly stringent nor in conflict with measured branching ratios.[9,10] The present result for the excitation energy of the T = 2 state will, it is hoped, simplify future resonance searches.

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