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Study of Resonant States in ^{13}C by Scattering of Fast Neutrons on ^{12}C

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Total elastic and inelastic scattering cross sections for fast neutrons are measured on ^{12}C between 17 and 20.5 MeV in order to check the validity of standard optical-model parameters and to investigate the nature of resonant states in ^{13}C. The region around 18 MeV is found to be free of isolated resonances, and good fits are obtained with standard parameters. A resonant state is apparent at an energy corresponding to 23 MeV in ^{13}C, and indications of the spin and the structure of this state are obtained.

I. INTRODUCTION

In recent years, much attention has been given to the problem of intermediate structure in the mass-13 nuclei. The resonant structure observed[1,2] in elastic scattering of 19–30-MeV protons from ^{12}C has been confirmed in various other reactions: photoreactions on ^{13}C,[3] scattering of nucleons from ^{12}C,[4–6] and (α, n) reactions on ^{9}Be.[7] These experiments have led to the conclusion that broad resonances are present in the ^{13}C-^{13}N pair of mirror nuclei.

The elastic scattering of protons from ^{12}C between 19 and 30 MeV shows two broad resonances at 21- and 27-MeV proton energy (respectively, 21.3 and 27 MeV in the case of the compound nucleus ^{13}N); on the other hand, it is impossible to fit the angular distributions in the resonance region with an optical model involving constant parameters.[8] Coupled-channel calculations are also incompatible with the inelastically scattered proton measurements and the polarization measurements of Craig *et al.*[4] Tamura and Terasawa[9] succeeded in fitting these angular distributions with calculations based on an optical model using a coherent Breit-Wigner amplitude; their work has been successfully extended by Lowe and Watson,[10] who took polarization measurements into account. The same situation occurs on examining the excitation curve of protons which are inelastically scattered from ^{12}C (15.11 MeV, $T=1$)[11]: Broad resonances have been identified for incident energies between 18 and 27 MeV; a very intense peak at 20.5 MeV dominates two weaker peaks at 22.25 and 25.5 MeV. Angular distributions taken at these three energies[12] show a symmetry around 90°, which is characteristic for compound-nucleus formation; spin assignments as proposed by Scott *et al.*[12] are consistent with the values given by Lowe and Watson.[10] The same broad resonances appear in the (p, n) and (n, p) reactions[13] on ^{12}C; these reactions leave the residual nuclei in the isobaric analog states of the 15.11-MeV level in ^{12}C. Cross-section measurements on the $^{13}C(\gamma, n)$ and $^{13}N(\gamma, p)$ reactions [the latter being deduced from the $^{12}C(p, \gamma)$ data of Fisher *et al.*[3]] indicate the presence, in the compound nucleus, of two broad resonances at 13- and at 21-MeV excitation energies. Independent analyses performed by Vinh-Mau *et al.*, by Easlea, and by Measday *et al.*[14] agree on the attribution of $T=\frac{1}{2}$ to these resonant states.

The (α, n) reaction[7] in ^{9}Be also indicates an important variation in the structure of the angular distributions between 15.5 and 18 MeV; this has been attributed to resonant states in ^{13}C. Elastic scattering of neutrons from ^{12}C also indicates the presence of resonances in ^{13}C at a 23-MeV excitation energy.[6]

At present, the problem of the nature of these resonances is not yet solved. The first purpose of this

[1] B. B. Kinsey, Phys. Rev. **99**, 332 (1955).
[2] J. K. Dickens, D. A. Haner, and C. N. Waddell, Phys. Rev. **129**, 743 (1963); **132**, 2159 (1963).
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[9] T. Tamura, and T. Terasawa, Phys. Letters **8**, 41 (1964).
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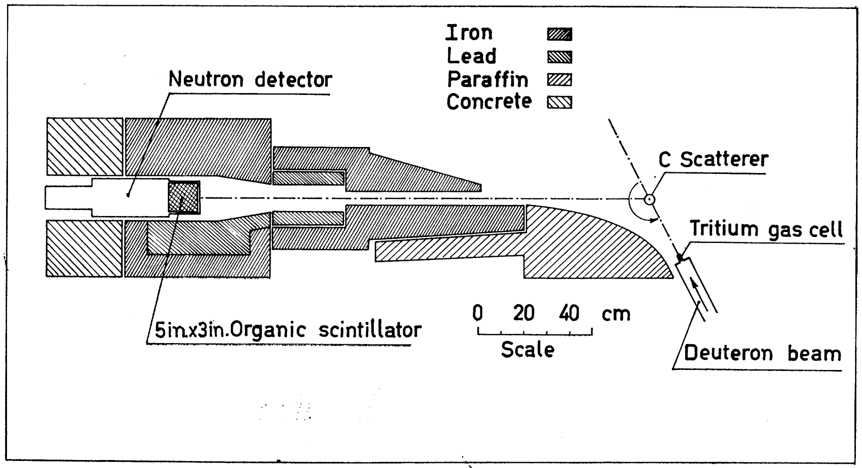

FIG. 1. Experimental arrangement used in the angular distribution measurements.

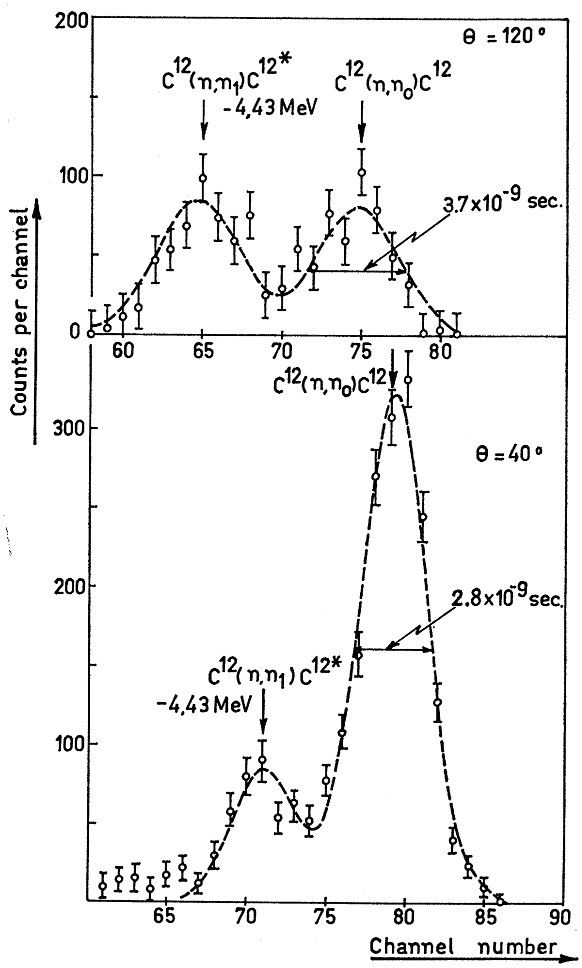

FIG. 2. Time-of-flight spectra of neutrons elastically and inelastically scattered on ^{12}C, after subtraction of the background. O, experimental points; ---, calculated double-Gaussian curve after automatic search of the parameters.

work is to present new information on the subject by neutron scattering experiments on ^{12}C. As regards the fitting of the angular distributions of fast neutrons in light nuclei, a satisfactory solution based on the optical model has been obtained for every light nucleus, except ^{12}C.[15] This exception may be due to the fact that the only measurements available are relevant for 14–15-MeV neutrons, where a resonance exists in the ^{13}C compound nucleus.[15] In this work, an energy region free of isolated compound-nucleus resonances was evidenced. At this energy the angular distribution measurements on the neutrons agree with the predictions of an optical model with standard parameters.

II. EXPERIMENTAL ARRANGEMENT

In order to study the complicated situation described above, different kinds of measurements are necessary: total cross sections, small-angle elastic scattering excitation curves, and elastic and inelastic scattering angular distributions. The experimental arrangement used for all differential cross-section measurements will be described in more detail.

The 4-MeV Van de Graaff accelerator at the University of Louvain provides a pulsed beam of deuterons, with a pulse length of 2 nsec. Neutrons of variable energy are generated by the T(d, n)^{4}He reaction. The tritium target consists of a gas cell filled with 18 Ci/cm^2; the energy spread of the produced neutrons depends on the deuteron energy and varies from 200 to 500 keV. The average total resolution of the time-of-flight spectrometer is 3.5 nsec and the flight path is fixed at 2 m. The cylindrical sample (5 cm in diameter and 7 cm long) of high-density graphite was located at a distance of 30 cm from the center of the gas target (Fig. 1).

[15] H. F. Lutz, J. B. Mason, and M. D. Karvelis, Nucl. Phys. **47**, 521 (1963).

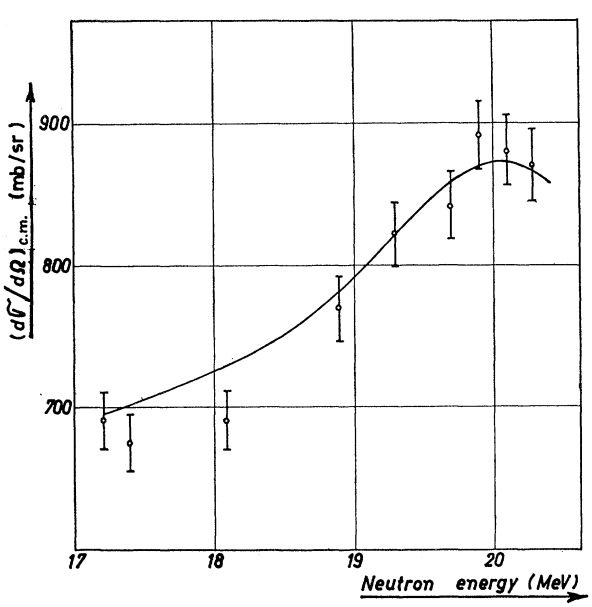

FIG. 3. Excitation curve of elastic scattering ($\theta_{\text{lab}}=10°$) cross sections. O, experimental cross section; ——, optical-model calculation with interference of $d_{5/2}$ resonance centered at $E_{\text{lab}}=19.6$ MeV ($\Gamma_{\text{c.m.}}=1.6$ MeV).

A NE213 scintillator detector, 5 in. in diameter and 3 in. long, was coupled to a 58AVP photomultiplier. A pulse-shape discriminator system was used in conjunction with the time-of-flight detection. The background level was reduced by the use of a large collimator supported on a rotatable frame. This apparatus allows angular distribution measurements between 0° and 145°, and the resolution is sufficiently high to separate the various neutron groups resulting from elastic and inelastic scattering (Fig. 2). A second time-of-flight spectrometer monitored the experiments; the detector, consisting of a plastic scintillator, was mounted at 90° to the deuteron beam. With this equipment the results have proved to be very reliable. The efficiency of the spectrometer has been determined in two different ways:

(1) elastic scattering of 19.6-MeV neutrons on a polyethylene scatterer;

(2) comparison with the known angular distribution of neutrons from the $T(d,n)^4He$ reaction at 3 MeV.[16]

The threshold of the neutron detector was fixed at 8 MeV in order to reduce background effects.

III. EXPERIMENTAL PROCEDURE

The total cross section was measured by a transmission method between 16.5 and 20.5 MeV at 40-keV intervals. The results were corrected for inscattering, taking into account the measured angular distribution of elastically scattered neutrons and using the formula given in Ref. 17.

In order to specify with greater accuracy the position of the resonance in the elastic channel, an excitation curve of the small-angle elastic scattering cross section appeared necessary. An angle of 10° was chosen and a conventional annular geometry was used to measure this excitation curve. The carbon ring was centered on the axis of the beam at a distance of 50 cm from the neutron source, while a small plastic scintillator was located at 100 cm. The ring had a thickness of 3.5 cm, an inner diameter of 5 cm, and an outer diameter of 12 cm.

The results were corrected for multiple scattering in the sample by means of the Monte Carlo method[18]; the various uncertainties introduced by the finite dimension of the source and of the detector, as well as the correction for the anisotropy of the neutrons, were also taken into account. Nine measurements were performed between 17.2 and 20.3 MeV.

Angular distribution of elastic and inelastic measurements were recorded at 3 different energies: 17.27±0.56, 18.25±0.34, and 19.88±0.21 MeV. In each case,

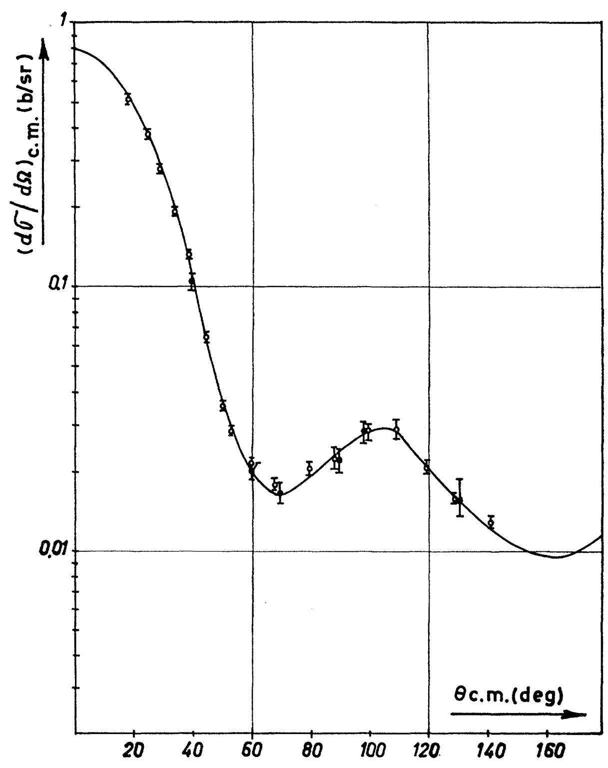

FIG. 4. Angular distribution of elastic scattering at $E_n=14.6$ MeV. O, data of Nakada *et al.* (Ref. 20); ●, data from Louvain.

[16] J.-P. Meulders and G. Deconninck, Rev. Phys. Appl. 4, 243 (1969).

[17] G. Deconninck, Bull. Acad. Roy. Belgique **XLIV**, 10 (1958).

[18] J.-P. Meulders, Ph. Monseu, and G. Deconninck, Ann. Soc. Sci. Bruxelles **81**, 149 (1967).

TABLE I. Optical-model parameters used for the analysis of the elastic scattering of neutrons on ^{12}C.

Parameters	Set I $E_n=18.25$ MeV	Set II $E_n=18.25$ MeV	Set III $E_n=17.27$ MeV
U (MeV)	43.7	42.7	44.5
W (MeV)	9.4	10.6	7.9
U_s (MeV)	8.4	5.9	7.2
W_s (MeV)	0	0	0
a_U (F)	0.46	0.57	0.49
a_W (F)	0.63	0.63	0.71
a_s (F)	1.74	0.60	0.40
$r_U=r_W$ (F)	1.25	1.25	1.25
r_s (F)	1.30	1.30	1.25
Theor σ_{tot} (b)	1.34	1.32	1.28
σ_{el} (mb)	880	857	809
σ_r (mb)	460	458	473
Expt σ_{tot} (b)	1.40	1.40	1.39
σ_{el} (mb)	899	899	884
σ_r (mb)	(~500)	(~500)	(~500)
χ^2	24	33	45

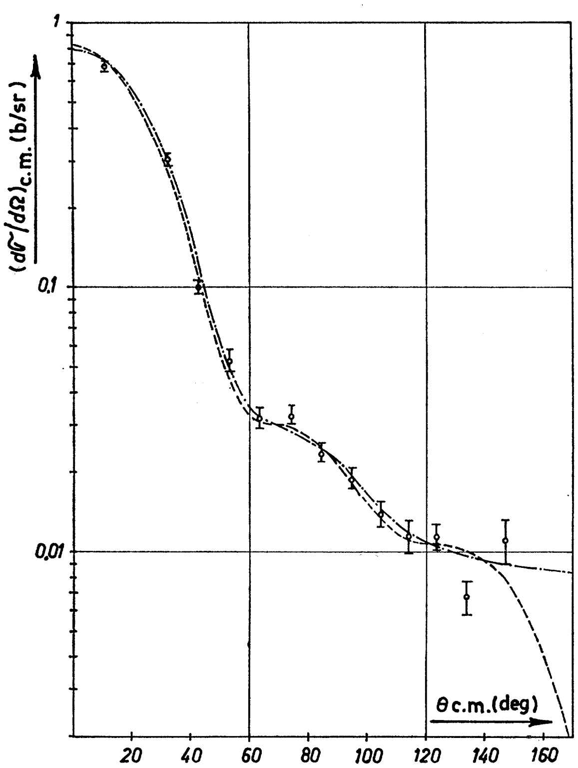

FIG. 5. Angular distribution of elastic scattering at 18.25 MeV. O, experimental cross sections; —•—•—, optical-model calculation with parameters from set I (Table I); – – –, optical-model calculation with parameters from set II (Table I).

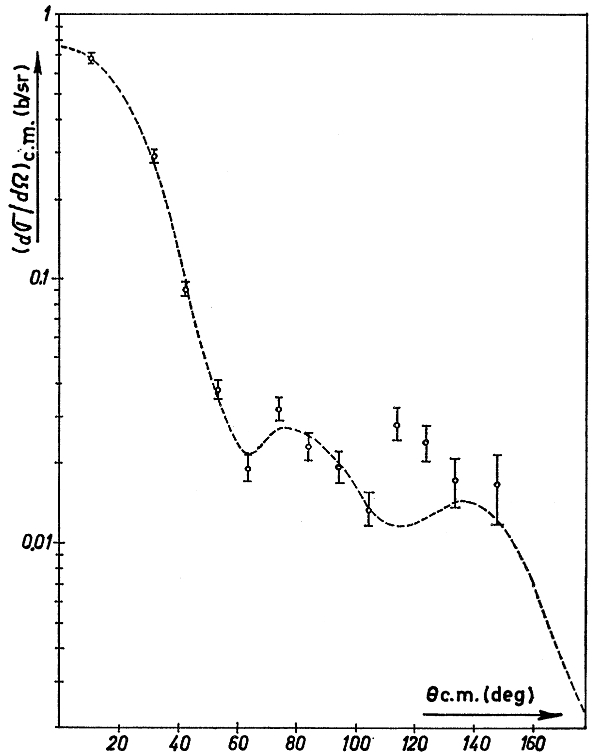

FIG. 6. Angular distribution of elastic scattering at 17.27 MeV. O, experimental cross sections; – – –, optical-model calculation with parameters from set III (Table I).

12 angles between 30° and 145° were chosen. An additional angular distribution in the region of 14 MeV and in identical geometrical conditions provided a check on the accuracy of the data obtained. In these measurements, the sample was positioned at 90° with respect to the deuteron beam. The time-of-flight spectra contain two important components, corresponding to elastically and inelastically ($Q=-4.43$ MeV) scattered neutrons. A search program which fits the spectra with two Gaussian curves was used for processing[19] (Fig. 2). Each result was corrected for double scattering by Monte Carlo calculations.[16] Moreover, the angular spread introduced by the finite size of the sample was evaluated by the same method. The values obtained vary between 3.5° and 4.5°. Corrections for variations with distance of the solid angle subtended by the detector and for anisotropy were also applied.

IV. RESULTS AND ANALYSIS

A. Total Cross Sections

The total-cross-section data agree with the results given in Ref. 5. When plotted, the curve consists of a plateau between 17.5 and 18.5 MeV and a broad

[19] J.-P. Meulders, Ann. Soc. Sci. Bruxelles **82**, 319 (1968).

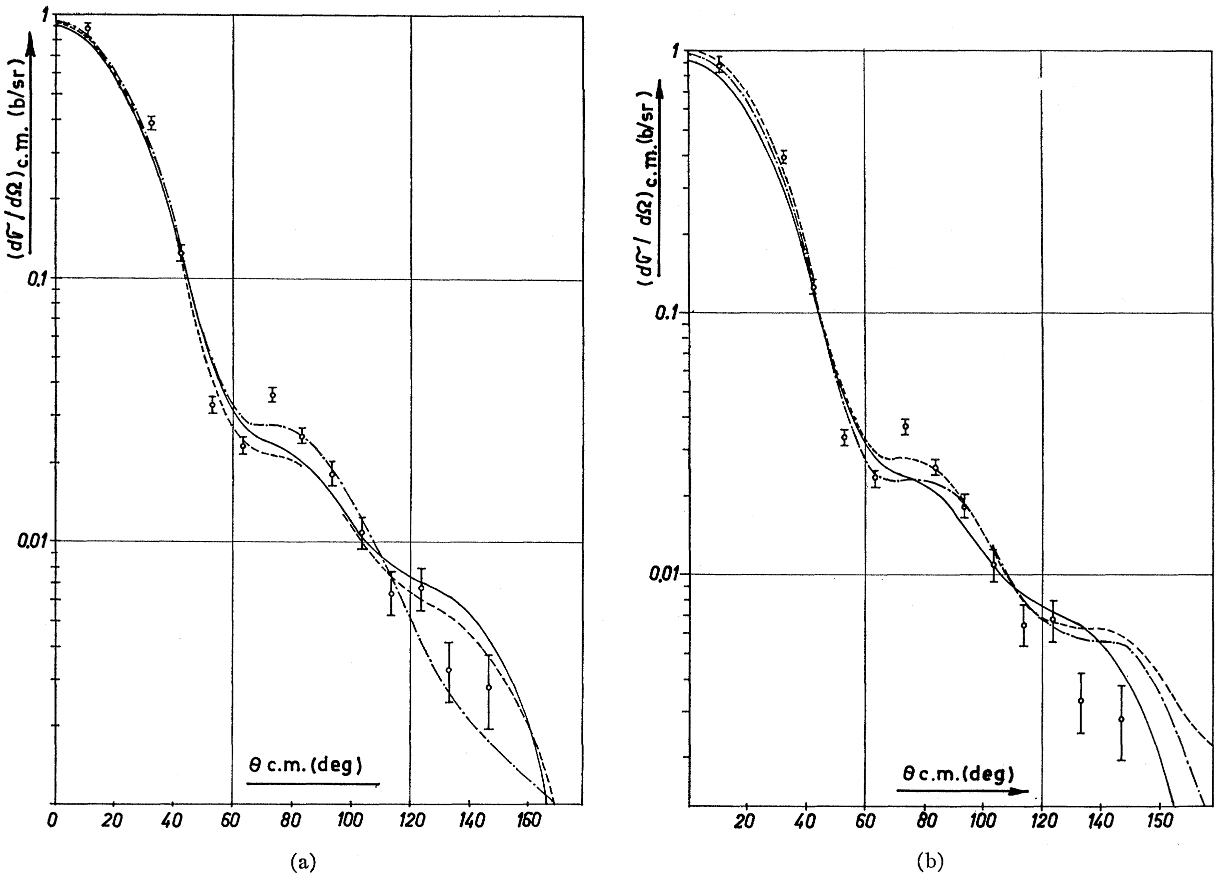

FIG. 7. Angular distribution of elastic scattering at 19.88 MeV. (a) O, experimental cross sections; ——, optical-model calculation without resonance, $\chi^2=184$; —•—•—, optical-model calculation with $p_{1/2}$ resonance, $\chi^2=122$; – – –, optical-model calculation with $p_{3/2}$ resonance, $\chi^2=163$. (b) O, experimental cross sections; ——, optical-model calculation without resonance, $\chi^2=184$; —•—•—, optical-model calculation with $d_{3/2}$ resonance, $\chi^2=139$; – – –, optical-model calculation with $d_{5/2}$ resonance, $\chi^2=126$.

resonance at 19.6 MeV. The amplitude of the resonance is 130±50 mb, and the width is of the order of 1 MeV.

B. Excitation Curve by Elastic Scattering at 10°

The 10° elastic scattering data (Fig. 3) confirm the presence of the resonance and allow an estimation of the width: $\Gamma_{lab}=1.8$ MeV. The curve is flat between 17 and 18 MeV; this region will be utilized for optical-model optimizations. This shape of the cross-section curve is also revealed by Harlow's measurements[5] taken at other angles.

C. Angular Distributions of Elastic and Inelastic Scattering

First of all, the elastic scattering is measured at 14.7 MeV in order to test the experimental procedure. Figure 4 shows the good agreement between our results and those of Nakada *et al.*[20]; in these measurements, our results are normalized to the 40° data of Ref. 20. Elastic scattering data are represented in Figs. 5–6. As discussed above, the 18.25-MeV distribution is considered representative for the optical-model region. A computer program with an automatic search of the parameters has been developed for this purpose. The complex potential has the form

$$V(r)=-Uf(r)-iWg(r)-(U_s+iW_s)h(r)\boldsymbol{\sigma}\cdot\mathbf{l},$$

where

$$f(r)=\{1+\exp[(r-R_U)/a_U]\}^{-1},$$

$$g(r)=\exp\{-[(r-R_W)/a_W]^2\},$$

$$h(r)=(\hbar/m_\pi c)^2(1/a_s r)\times\exp[(r-R_s)/a_s]/\{1+\exp[(r-R_s)/a_s]^2\}.$$

m_π stands for the pion mass and $R_i=r_iA^{1/3}$, where A is the mass number of the target nucleus.

Good fits were obtained (Fig. 5) with the parameter sets I and II of Table I. The first set gives the smallest χ^2, but the value of a_s is unrealistic; for this reason, the

[20] M. P. Nakada, J. D. Anderson, C. C. Gardner, and C. Wong, Phys. Rev. **110**, 1439 (1958).

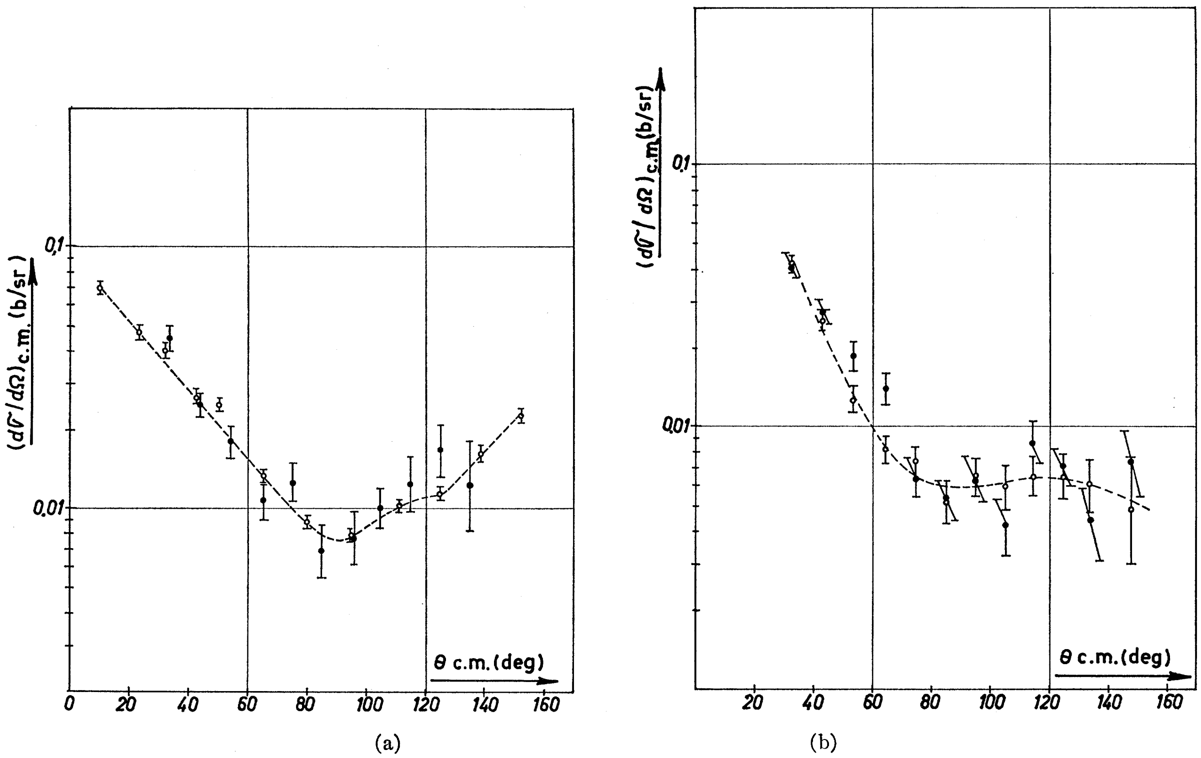

FIG. 8. Inelastic scattering of neutrons from $^{12}C^*$ ($Q=-4.43$ MeV). (a) --○--, experimental cross sections at 14.1 MeV (Ref. 23); ●, experimental cross sections at 17.27 MeV (Louvain). (b) Comparison of the angular distribution taken off resonance (●, $E_n=18.25$ MeV, $\sigma_{2^+}=176$ mb) and on resonance (○, $E_n=19.88$ MeV, $\sigma_{2^+}=172$ mb).

second set is preferred, as it shows better agreement with 14-MeV calculations on light nuclei (Refs. 15 and 21). A fit at 17.27 MeV was also tried, but, as is known from the recent work of Borelli *et al.*,[6] this region is not completely free from resonances, and the fit is not very good (Fig. 6). The same technique applied to the 19.88-MeV distribution leads to a set of parameters which are totally unphysical ($a_U=0.13$ F, $\sigma_r=339$ mb). Based on a coherent interference between an optical model and a Breit-Wigner amplitude, a trial fit for the 19.88-MeV angular distribution was calculated. The differential cross section is then obtained from

$$d\sigma/d\Omega=|A(\theta)|^2+|B(\theta)|^2$$

with the amplitudes

$$A(\theta)=A_{\text{opt}}(\theta)-\frac{1}{2k}\frac{R_\lambda+iI_\lambda}{E-E_\lambda+i\Gamma_\lambda/2}\times[(l+1)\delta_{j,l+1/2}\exp(2i\delta_{l+})+l\delta_{j,l-1/2}\exp(2i\delta_{l-})]P_l(\cos\theta),$$

$$B(\theta)=B_{\text{opt}}(\theta)+\frac{i}{2k}\frac{R_\lambda+iI_\lambda}{E-E_\lambda+i\Gamma_\lambda/2}\times[\delta_{j,l+1/2}\exp(2i\delta_{l+})-\delta_{j,l-1/2}\exp(2i\delta_{l-})]P_l^1(\cos\theta),$$

where E_λ and Γ_λ represent the energy and the width of the resonance λ.

The parameters of the optical model are available from the 18.25-MeV analysis, except for the few which had to be extrapolated from the values of U (39.5 MeV) and W (10.1 MeV); the latter parameters are known to vary slowly as a function of the neutron energy. Resonances centered at $E_{\text{c.m.}}=18.52$ MeV ($\Gamma_{\text{c.m.}}=1.6$ MeV) were tentatively computed for spins ranging

TABLE II. Reduced widths of reactions induced by 20-MeV neutrons on ^{12}C and leading to $T=0$ and $T=1$ states of the residual nucleus.

Outgoing channel	Γ (relative)	Γ (absolute) (MeV)
Γ_n	145	1.30
$\Gamma_{n'}$ (4.43 MeV)	0	0
$\Gamma_{n'}$ (15.11 MeV)	13.5	0.12
Γ_p	20	0.18
Γ_{tot}	178.5	1.60

[21] F. G. Perey and B. Buck, in *Proceedings of Antwerp Conference—Nuclear Study with Neutrons, 1965*, edited by M. Nève de Mévergnies, P. Van Assche, and J. Vervier (North-Holland Publishing Co., Amsterdam, 1965), p. 385.

from $s_{1/2}$ to $h_{11/2}$, involving an automatic search for the amplitudes R_λ and I_λ. Typical fits are shown in Fig. 7 for the p and d resonances. The best results were obtained with $p_{1/2}$, which gave a good fit at backward angles; and with $d_{5/2}$, which gave a good fit at forward angles and a more realistic value for σ_{el}. The hypotheses of $d_{3/2}$ and $f_{7/2}$, which give moderately good agreement between calculations and data, may also be considered. To check the importance of optical-model parameters in the spin assignment, use is also made of the first set of parameters. The results thus obtained are then rather similar, so that one should conclude that the spin determination is not highly sensitive to small variations in the parameter values. The smooth curve of Fig. 3 reproduces the results of a calculation based on the parameters which fit the 19.88-MeV angular distribution.

Inelastic scattering data are given in Fig. 8. In the first part of the figure, 14.1- and 17.27-MeV data are compared; in the second part, 18.25- and 19.88-MeV data. The similarity between the latter distributions is evident; this means that this inelastic channel in unaffected by the resonance.

V. CONCLUSIONS

From the preceding results, the following facts are derived:

(1) The resonant state discovered in other reactions is confirmed; the energy is 23 ± 0.2 MeV and the width is 1.6 MeV.

(2) The conclusions of the angular distribution analysis are compatible with a spin of $\frac{5}{2}^+$, in agreement with Lowe and Watson; this analysis, however, is unable to eliminate other possibilities: $\frac{1}{2}^-$ (Ref. 6), $\frac{3}{2}^+$, or $\frac{7}{2}^-$.

(3) The distribution of the neutrons inelastically scattered from ^{12}C and leading to the 4.43-MeV state shows that the cross sections are insensitive to the resonance.

(4) The resonant contribution to σ_{el}, estimated by integration of $(d\sigma/d\Omega)_\theta$, amounts to 145 mb, which is equal to the total-cross-section variation.

The nature of the resonances discovered in photoreactions and in reactions induced by nucleons in the neighborhood of 22 MeV in the mirror nuclei ^{13}N-^{13}C has been discussed in detail by Scott *et al.*[12] They attribute these resonances to states of ^{13}N which are of a different nature; the selection rules for photoreactions constitute their primary criterion. Owing to the fact that in this work the spin ambiguity cannot be resolved, the abovementioned conclusions lack confirmation.

Fortunately, as isobaric analog states are dealt with, the application of some simple rules for the comparison of the resonant cross sections in different channels is permissible. Moreover, the penetrabilities of the $l=0$, 1, and 2 waves are closely similar[22] for neutrons (T_n) and for protons (T_p) of 20 MeV in the entrance channel; the ratio of the cross sections can thus be obtained from the ratio of the reduced widths. Considering the decay of the mass-13 nuclei $(T=\frac{1}{2})$ to the first triplet state of the mass-12 nuclei $(T=1)$, the ratio of the neutron reduced width to the proton reduced width is obtained from the ratio of the vector addition coefficients. In the case of (n, p) and (p, p') reactions on ^{12}C one has $\gamma_p^2/\gamma_{p'}^2=2$. This is confirmed by the experimental cross-section values:

$$\sigma_{np}=20 \text{ mb},$$

$$\sigma_{pp'}=10 \text{ mb},$$

since the pentrabilities of the protons are nearly the same in the outgoing channel.[22]

In the same way it is possible to evaluate the unknown cross section of the reaction ^{12}C$(n, n')^{12}$C(15.11 MeV, $T=1$). Taking into account the penetrabilities in the outgoing channels, one obtains

$$\sigma_{nn'}/\sigma_{np}=(T_{n'}/T_p)(\gamma_n^2/\gamma_p^2)=0.8/0.6\times\tfrac{1}{2},$$

$$\sigma_{nn'}=13.5 \text{ mb}.$$

In Table II, the reduced widths are compared.

As a conclusion, the state at 23 MeV in ^{13}C comprises mainly a mixture of two configurations, the first being ^{12}C($T=0$ state)+ an extra neutron, the second a mass-12 nucleus ($T=1$ state)+ an extra nucleon.

ACKNOWLEDGMENTS

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[22] G. S. Mani, M. A. Melkanoff, and I. Iori, Rapport CEA No. 2379, Saclay, 1963 (unpublished).