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Search for a purported resonance in ^{13}C at 20 MeV via analyzing power measurements of ^{12}C(n,n)

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Excitation functions of the analyzing power $A_y(\theta)$ for neutron elastic scattering from ^{12}C were measured at two angles in the neutron energy range from 15.6 to 16.5 MeV. The results do not support the existence of the narrow resonance in n-^{12}C scattering located at $E_n = 16.1$ MeV that was observed recently by Benetskii *et al.* through similar $A_y(\theta)$ experiments. Instead, the data are moderately well described by our previous n-^{12}C phase-shift analysis, which gave no evidence of a pronounced narrow resonance anywhere between neutron energies from 15.5 to 16.5 MeV.

Recently Benetskii *et al.*[1] reported the discovery of a resonance about 100 keV wide in neutron elastic scattering from ^{12}C at an incident energy of 16.1 MeV. This finding was based on their measurements of the analyzing power $A_y(\theta)$ for elastic scattering of neutrons from ^{12}C at a laboratory scattering angle of $\theta_{lab} = 41°$ in the energy range between 16.0 and 16.35 MeV, and on a single $A_y(\theta)$ datum obtained by Begum *et al.*[2] at Edinburgh at 16.1 MeV. These data are shown in the top half of Fig. 1 with triangles representing the data of Benetskii *et al.* (labeled Moscow) and the open square displaying the Edinburgh data point. The vertical error bars represent the measurement uncertainties as reported by these two groups. The horizontal bars indicate the neutron energy spread used in the experiments; $\Delta E_n = 140$ keV and $\Delta E_n = 220$ keV at Moscow and Edinburgh, respectively. The solid curve through these data is a guide to the eye. From the resonancelike behavior of $A_y(\theta)$ observed at $\theta_{lab} = 41°$ Benetskii *et al.* concluded the existence of an intermediate structure in n-^{12}C scattering. It was argued that doorway states may show up more pronounced in the excitation function of $A_y(\theta)$ than in differential cross-section data due to the higher sensitivity of polarization observables to the interference of scattering mechanisms, although, to our knowledge, doorway states have not yet been observed via such excitation functions.

From an optical model analysis which included a Breit-Wigner resonance, Benetskii *et al.* extracted the following resonance parameters: $E_n = 16.1$ MeV, corresponding to $E_x = 19.9$ MeV excitation energy in ^{13}C, total width $\Gamma = 0.1$ MeV, lifetime $\tau = 7 \times 10^{-21}$ s, and the most probable angular momentum $L = 1$. The total width is almost completely given by the neutron elastic width, that is $\Gamma_n/\Gamma \approx 1$.

On the other hand, contrary to the measurements at $\theta_{lab} = 41°$, Benetskii *et al.* found no indication of the resonance in additional measurements at $\theta_{lab} = 31°$ (lower half of Fig. 1). The likelihood of seeing an effect also at this angle was suggested by the other datum reported by the Edinburgh group, shown in the lower half of Fig. 1 as the open square.

The situation is made even more complicated by considering earlier data[3] measured at TUNL with a slightly broader energy spread than the Edinburgh experiment. These measurements, conducted at 30° and 50° from 15.75 to 16.35 MeV with $\Delta E_n = 250$ keV did not give any evidence of resonances in this energy range. The $A_y(\theta)$ distribution obtained by the Tübingen group[4] at 15.85 MeV provided no indication of a resonance, but presumably the energy would have been too low. The interpretation of Benetskii *et al.*, who interpolated the TUNL data to estimate a value at 41°, suggests that the result reported by TUNL at 16.15 MeV is inconsistent with their measurement as well as that of Ref. 2.

The n-^{12}C total cross section[5] does not exhibit a narrow resonance at $E_n = 16.1$ MeV. In our recent phase shift analysis[6] of total cross section, differential cross section, and $A_y(\theta)$ data for n-^{12}C, we found that in the energy range of interest there exists a broad $\frac{5}{2}^-$ state in ^{13}C, located at $E_x = 19.5$ MeV excitation energy. This phase-shift analysis does not predict a narrow resonance at 16.1 MeV. However, the analysis is based on $A_y(\theta)$ data obtained with a broader neutron energy spread than that of the measurements of Benetskii *et al.*

In order to shed more light on the reported resonance at $E_n = 16.1$ MeV, we performed very careful and accurate $A_y(\theta)$ measurements at both 41° and 31° across the energy range of interest. Because our experimental setup is described elsewhere,[7] only a brief description is given here. Polarized neutrons were obtained via the ^{2}H(d,n)^{3}He polarization transfer reaction at a reaction angle of 0°. The pulsed and polarized deuteron beam at the TUNL FN tandem Van de Graaff laboratory was used. Typical deuteron beam intensities at the deuterium gas cell were 150 nA. The deuteron beam polarization, as measured by the quench-ratio method,[8] was typically 0.66. This deuteron beam polarization produces a neutron beam polarization[9] of 0.57 at 0°. The deuterium gas pressure in the 3-cm long cell was adjusted to yield neutrons with an energy spread of 100 keV. This was intentionally less than the 140 keV and 220 keV used by the Moscow and Edinburgh groups, respectively. The deuteron energy was stepped in

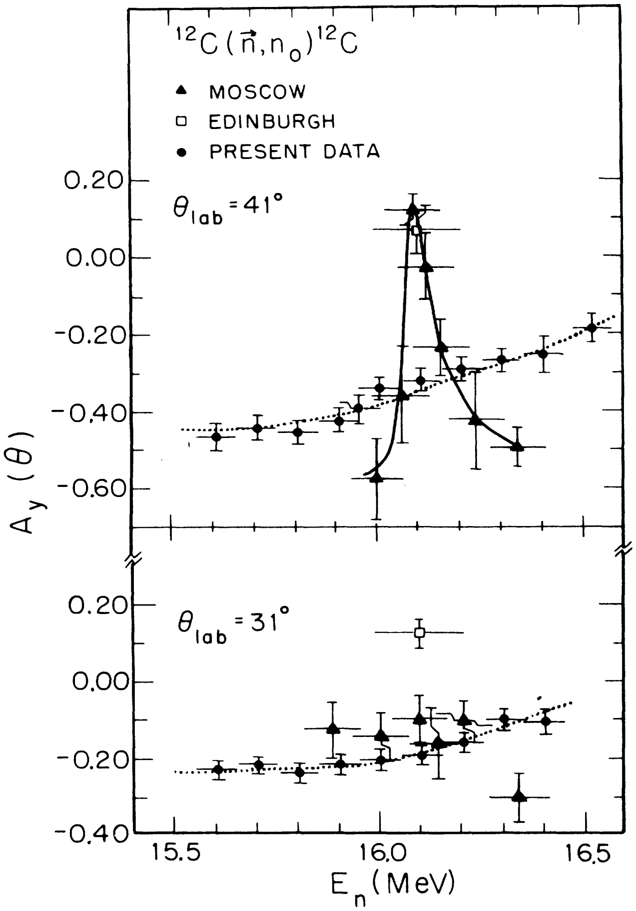

FIG. 1. Excitation function of the analyzing power for elastic n-^{12}C scattering at $\theta_{lab}=41°$ (top) and $\theta_{lab}=31°$ (bottom). The solid curve is a guide to the eye taken from Ref. 1. The dotted curves are calculated from a revised phase shift analysis which incorporated the present data.

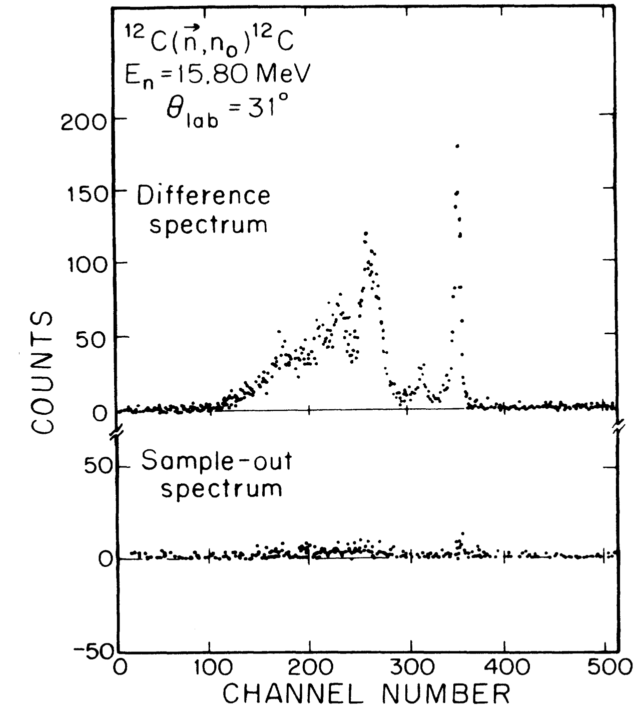

FIG. 2. Time-of-flight spectra for n-^{12}C scattering at $E_n=15.8$ MeV and $\theta_{lab}=31°$.

about 100 keV intervals between E_d of 12.8 and 13.8 MeV to produce neutron beams having an average energy between 15.6 and 16.5 MeV. In the present experiment the incident neutron energy was known absolutely to about ±25 keV.

The carbon (graphite) scatterer, 1.9 cm in diameter and 2.5 cm high, was placed at a distance of 12 cm from the deuterium gas cell. Neutrons scattered from carbon to the left and to the right were detected by a pair of well-shielded liquid organic scintillators located at flight paths of 4 m and 3 m from the scatterer, respectively, and at symmetric scattering angles with respect to the incident deuteron beam axis. In order to minimize instrumental asymmetries, successive runs were taken with the deuteron spin vector oriented to produce neutron beams with the spin axis alternately up and down relative to the horizontal reaction plane.

The time-of-flight (TOF) technique allows for a clean measurement of the elastically scattered neutrons. A typical TOF spectrum obtained at $\theta_{lab}=31°$ is displayed in Fig. 2. Time of flight increases from right to left. The dominant peak on the right is due to elastic neutron scattering from ^{12}C. The small adjacent peak around channel number 320 is due to inelastic neutron scattering to the first excited state in ^{12}C, a 2^+ state at 4.44 MeV. The structure seen for longer flight times is caused in part by n-^{12}C scattering of neutrons produced in deuteron breakup reactions in the deuterium gas, i.e., ^{2}H(d,np)^{2}H and ^{2}H(d,np)np, and in the tantalum beam stop of the gas cell. In addition to a "sample-in" spectrum, which was obtained with the ^{12}C sample in place, a corresponding spectrum was recorded with the sample removed ("sample-out" spectrum, lower part of Fig. 2). In the spectrum resulting from the difference of these two spectra, only a very small residual background remains in the region of the peak of interest (see top half of Fig. 2). This typically flat background was subtracted using a fitting program.

From the yields in the elastic scattering peak and the known neutron polarization, analyzing power values were extracted. These data were corrected for finite geometry and multiple scattering effects using Monte Carlo techniques.[7] The necessary n-^{12}C cross-section and analyzing power libraries used in the Monte Carlo simulation of the present experimental setup were calculated from our recently published phase shifts.[6] The calculated corrections were typically smaller than 0.015, and moved the measurements in the direction of increasing magnitudes.

The present results are shown in Fig. 1 as full dots. The uncertainties of our data, shown in Fig. 1 by the vertical error bars, are typically ±0.03 at $\theta_{lab}=31°$ and ±0.04

at $\theta_{lab}=41°$. This uncertainty includes all known errors, except for an estimated $\pm 3\%$ scale error due to the uncertainty in the neutron beam polarization. Except for the data point at 16.34 MeV, the present data are consistent with the data of Benetskii *et al.* at $\theta_{lab}=31°$. However, our data at $\theta_{lab}=41°$ clearly *do not support* the measurements of Benetskii *et al.* nor of Edinburgh. That is, the $A_y(\theta)$ data of the present measurement exhibit a monotonic behavior with energy—*there is no indication for any 100 keV wide resonance located near 16.1 MeV.* The slowly varying magnitude of $A_y(\theta)$ is probably due mainly to the 500-keV wide $\frac{5}{2}^-$ resonance at $E_x=19.5$ MeV, which corresponds to $E_n=15.8$ MeV. The present data are very consistent with the previous TUNL data of Ref. 3 and with the Tübingen result of Ref. 4.

In our earlier work reported in Ref. 3, where $\Delta E_n \cong 250$ keV, we noted that the $A_y(\theta)$ values reported by the Edinburgh group at 31° and 41° seem to be in error. The present measurement supports this observation (see Fig. 1). We believe that the observed discrepancies between our data and the Moscow data at 41°, and between our data and the Edinburgh data at both 31° and 41° are due to problems associated with their measurement techniques. Both groups used the ^{3}H(d,n)^{4}He neutron source reaction and low voltage accelerators. For their measurements, the neutron polarization was only 0.15. It seems to be difficult to perform high accuracy $A_y(\theta)$ measurements using this neutron source reaction. With such a low beam polarization great care must be taken to minimize any instrumental asymmetries, especially when the beam polarization cannot easily be reversed, as it can when using polarization transfer reactions as employed in the present work.

In summary, the present accurate $A_y(\theta)$ data are in serious disagreement with earlier measurements and with the resonance interpretation of Benetskii *et al.* Our data do not support the existence of a narrow resonance in elastic n-^{12}C scattering at $E_n=16.1$ MeV, but do give credence to our recent n-^{12}C phase shift analysis[6] in the neutron energy range of interest. In fact, we have now incorporated these new $A_y(\theta)$ data presented here into the n-^{12}C data base, which now spans the region from 7.0 to 17.4 MeV, and slightly revised our earlier phase shifts for the region above 15.5 MeV. The dotted curves in Fig. 1 are calculated from this new phase shift solution. The present data are clearly compatible with this phase shift solution which does not illustrate resonance behavior in this region.

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[1]B. A. Benetskii, A. V. Klyachko, M. N. Lifanov, M. V. Plotnikova, and R. Radev, in *Proceedings of the 6th International Symposium Polarization Phenomena in Nuclear Physics, 1985, Osaka, Japan,* edited by M. Kondo, S. Kobayashi, M. Tanifuji, T. Yamazaki, K.-I. Kubo, and N. Onishi, J. Phys. Soc. Jpn. Suppl. **55**, 566 (1986).

[2]Amena Begum, R. B. Galloway, and F. K. McNeil-Watson, Nucl. Phys. **A332**, 349 (1979).

[3]W. Tornow, E. Woye, and R. L. Walter, in *Polarization Phenomena in Nuclear Physics—1980 (Fifth International Symposium, Santa Fe),* Proceedings of the 5th International Symposium on Polarization Phenomena in Nuclear Physics, AIP Conf. Proc. No. 69, edited by G. G. Ohlsen, R. E. Brown, N. Jarmie, W. W. McNaughton, and G. M. Hale (AIP, New York, 1981), Part 2, p. 1320.

[4]G. Mack, Z. Phys. **212**, 365 (1968); G. Mack, G. Hentschel, C. Klein, H. Lesiecki, G. Mertens, W. Tornow, and H. Speigelhauer, in *Proceedings of the 3rd International Symposium Polarization Phenomena in Nuclear Reactions, 1970, Madison, Wisconsin,* edited by H. H. Barschall and W. Haeberli (University of Wisconsin Press, Madison, 1971), p. 615.

[5]Evaluated Nuclear Data File ENDF/B Summary Documentation, edited by R. Kinsey, Brookhaven National Laboratory Report BNL-NCS-17541 (ENDF-201), 3rd ed. (ENDF/B-V), 1979; P. W. Lisowski, M. S. Moore, G. L. Morgan, and R. E. Shamu, in *Proceedings of the International Conference on Neutron Cross Sections for Technology, 1980,* Natl. Bur. Stand. (U.S.) edited by J. L. Fowler, C. H. Johnson, and C. D. Bowman (U. S. GPO, Washington, D. C., 1980).

[6]W. Tornow, E. Woye, and R. L. Walter, J. Phys. G **13**, 177 (1987).

[7]E. Woye, W. Tornow, G. Mack, C. E. Floyd, P. P. Guss, K. Murphy, R. C. Byrd, S. A. Wender, R. L. Walter, T. B. Clegg, and W. Wylie, Nucl. Phys. **A394**, 139 (1983).

[8]G. G. Ohlsen, J. L. McKibben, G. P. Lawrence, P. W. Keaton, and D. D. Armstrong, Phys. Rev. Lett. **27**, 599 (1971).

[9]P. W. Lisowski, R. L. Walter, C. E. Busch, and T. B. Clegg, Nucl. Phys. **A242**, 298 (1975).