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Measurement of the ^{3}He and ^{4}He total neutron cross sections up to 40 MeV

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The total neutron cross sections of the helium isotopes were measured in the energy range from 1.5 to 40 MeV. A continuous energy neutron source was used in connection with a 190 m long flight path and high resolution time-of-flight techniques. The energy resolution achieved enabled us to improve considerably the parameters of the narrow $\frac{3}{2}^+$ resonance in the n+^{4}He system. The position of the resonance was found to be 22 133±10 keV, with a total width of 76±12 keV and a neutron width of 37±5 keV. This agrees well with previous analyses, which yield $\Gamma_n \sim \frac{1}{2}\Gamma$. Absolute values for the cross sections were determined with an overall error smaller than 3%. Comparison with older data shows agreement within the total errors. Our data are 4% to 5% higher than the most recent data set; however, in the case of ^{3}He, the data are still below the predictions from an R-matrix analysis. It was pointed out recently that a slight disagreement exists between the total neutron cross section of ^{3}He and the sum of the partial n-^{3}He cross sections. This discrepancy is removed by our new data.

[NUCLEAR REACTIONS Measured $\sigma(E_n)$ for ^{3}He, ^{4}He, 1.5–40 MeV, high resolution TOF techniques, high pressure gas samples, four-nucleon system, ^{5}He level parameters.]

I. INTRODUCTION

The development of theoretical approaches to the microscopic description of few nucleon systems has increased the interest in the properties of the very light nuclei. Especially the ^{4}He nucleus has gained more and more importance as a "testing ground for nuclear forces"[1] due to its well defined quantum numbers, its strong binding, and the complex structure of its excited states which can be investigated experimentally in various reaction channels. The work carried out until 1972 was compiled by Fiarman and Meyerhof[2]; the more recent experiments were reviewed by Sundquist[3] and Grüebler.[4] It became evident that there is still a lack of precise experimental information, especially in the scattering and reaction channels where neutrons are involved. Based on the data available in 1976, Lisowski *et al.*[5] performed a phase shift analysis for the n-^{3}He system in the energy range up to 23 MeV. Phase shifts smoothly varying with energy were able to reproduce the data at all energies but 22 MeV, where the analyzing power data of Busse *et al.*[6] showed a significant difference. The question remained open, whether this was due to an unsolved problem of the data or to hitherto unknown narrow structures in the ^{4}He nucleus at an excitation energy of about 37 MeV.

In a paper which followed by Bevelacqua,[7] an R matrix approach was presented which was able to produce narrow resonances in ^{4}He in the vicinity of this tentative experimental level. In both analyses the need for more experimental information in this energy range was pointed out. The measurement of the total neutron cross section is the simplest way to search for resonant structure. The most recent data set of Goulding *et al.*[8] covers the energy range up to 30 MeV, whereas previous measurements[9] were carried out at discrete energies only. No narrow structure was found in the ^{3}He cross sections. On the other hand, the resolution in the experiment of Goulding *et al.* was not sufficient to resolve the well known $\frac{3}{2}^+$ resonance[10] at 22.1 MeV in the n-^{4}He cross section, which was measured also. The width of this resonance was determined, using monoenergetic neutron beams,[11] to be 100±50 keV.

As the first experiment in a series of investigations on the n-^{3}He system, it was the aim of the present work to measure the total neutron cross sections of the helium isotopes with ultrahigh resolution. The efficiency of the experimental method could be demonstrated by improving the parameters of the $\frac{3}{2}^+$ resonance in the n-^{4}He system.

II. EXPERIMENT

A. Arrangement

The neutron transmission measurements were carried out at the 190 m flight path of the Karlsruhe cyclotron.[12] Figure 1 shows a schematic drawing of the experimental setup. The neutrons were produced inside the cyclotron by bombarding a thick uranium target with deuterons of about 46 MeV. A special internal deflection system was used to reduce the repetition rate of the cyclotron pulses. At a frequency of 30 kHz an average beam current of 8 μA was achieved. The pulse width of the deuteron bunches was 1.2 ns. The energy distribution of the neutrons produced in the uranium target is dominated by two processes. The direct reactions yield neutrons with energies up to 50 MeV and a maximum in flux around 16 MeV. The neutron evaporation processes of the highly ex-

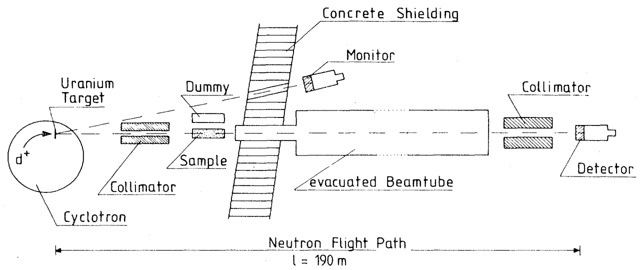

FIG. 1. Schematic drawing of the experimental setup at the Karlsruhe cyclotron. The monitor detector was placed 12 m from the source at an angle of 5°.

cited compound nuclei give high flux at a few MeV. The neutrons emitted to 0° were collimated by heavy shielding. The beam diameter was 12 mm at the position of the sample, which was located at a distance of 8 m from the source. Behind the sample the neutrons traveled through an evacuated beam tube with a length of 180 m. At the end of the tube a metal collimator defined a solid angle of 2×10^{-7} sr. A liquid scintillation detector (NE 213, 10.2 cm diam, 5.1 cm long) was placed at a distance of 190 m from the source for the measurement of the transmitted neutrons.

The neutron flux from the cyclotron was monitored during the experiment with a small scintillation detector (Stilbene, 2.5 cm diam, 2.5 cm long) positioned at a distance of 12 m from the source. The monitor viewed the target at an angle of 5° with respect to the collimated neutron beam.

B. Samples

Stainless steel cylinders, 526 mm long, with an inner diameter of 16 mm and 0.5 mm thick semispherical end caps were used as sample cells. They were filled with high purity helium gas using cryogenic pumping. Inside a cryostat vessel two identical cells were mounted parallel to each other. The evacuated "dummy" cell was used in the "sample out" cycles of the experiment. The alignment of the sample cells with the neutron beam axis was done using a theodolite. To investigate possible errors connected to the sample thickness, the ^{4}He experiment was carried out once with a pressure of 398 bars and repeated with 204 bars. The pressure used in the ^{3}He measurements was 376 bars. The gas pressure was measured with a high precision piezoresistive gauge. The areal density of the samples was calculated taking into account the sample length, the temperature, the pressure, and the specific compressibility of the gas. The accuracy of this procedure was tested by filling a similar cell with argon gas. The calculated argon sample density agreed within 1% with the argon content measured by weight. The specifications of the samples are listed in Table I.

C. Data acquisition

The energy of the transmitted neutrons was determined using high resolution time-of-flight techniques. The time measurement was started by a signal derived from the cyclotron rf and was stopped by the fast timing signal from the neutron detector. Time spectra were taken using a 16 bit resolution UC/KB time digitizer (Laben) with a channel width of 0.25 ns. The data were stored in 63 488 channels of the external memory of an on-line computer NOVA 2 (Data General).

The overall time resolution achieved during the experiment was 1.4 ns. Including the uncertainty in the flight path length, mainly the detector thickness, the resulting energy resolution varied from 0.3×10^{-3} at 1.5 MeV to 1.3×10^{-3} at 40 MeV.

The energy scale was calibrated by the prompt γ peak in the time spectra. To reduce the background from uncorrelated events, very efficient pulse shape discrimination techniques were used in the neutron detector and only a negligible amount of γ-ray events were leaking through. Therefore, to measure the exact position of the prompt γ peak, 1% of the γ-ray events were admitted in the time range of this peak.

In the experiment sample in/out cycles were repeated every ten minutes. After each sample change the time spectrum of the neutrons transmitted through the sample or the dummy was written on magnetic tape. For the monitor detector at the 12 m station also time spectra were measured using pulse shape discrimination techniques. These spectra with a length of 2048 channels were also dumped on tape after each sample change. In each measurement data were taken for more than 600 cycles,

TABLE I. Properties of the helium samples.

Sample	^{3}He	^{4}He (I)	^{4}He (II)
Tube length (mm)	526±1	526±1	526±1
Tube diameter (mm)	16±0.01	16±0.01	16±0.01
Pressure (bars)	376±1.6	398±1.8	204±0.9
Temperature (°C)	21.6±0.1	23.8±0.1	23.8±0.1
Compressibility factor	0.849±0.023	0.840±0.016	0.910±0.011
Areal density (atoms/b)	0.412±0.007	0.428±0.006	0.238±0.004

TABLE II. Contribution to the total errors for the neutron cross sections and for the energy scale.

Sample thickness	1.4—1.7 %
Monitor normalization	$\leq 0.5\%$
Background subtraction	0.1%
In-scattering	$<0.01\%$
Dead time corrections	$<0.1\%$
Statistical uncertainty	see text
γ-peak position	≤ 100 ps
Flight path length	10^{-4}
TDC nonlinearity	$<0.1\%$

corresponding to a total of 380 h beam time.

III. DATA ANALYSIS AND ERROR DISCUSSION

In the first step about 4000 time spectra were corrected for time shifts during the experiment using the position of the prompt γ peak. All "good" spectra of the measurement with one specific sample were added up in two sum spectra: "sample in" and "sample out." In the same way the corresponding spectra of the monitor detector were treated. The integrated neutron flux from these monitor spectra was used for the normalization of the sample in/out ratio. The stability of the system was checked by the comparison of the flux ratio for identical conditions but independent measuring cycles. In addition, the variation in flux during sample out runs at various times during the three week experiment was used to check the monitor. The stability of the monitor system was found to be better than 0.5%. The deviations were mainly correlated to small changes of the beam position on the uranium target.

In the sum spectra the time-independent background was subtracted using the channel contents of the time range before the prompt γ peak and the range of very long times corresponding to neutron energies below the detector threshold. Due to the pulse shape discrimination in the neutron detector this background was very low. The background was measured independently using three different methods: (1) the internal deflection system was switched off to prevent the interaction of the deuterons with the uranium target; (2) with the neutron production working normally the neutron beam was blocked by a 1 m long copper shadow bar; and (3) the neutron detector was placed outside the neutron beam defined by the last collimator (see Fig. 1). All results are in agreement with the assumption that the background was generated mainly by cosmic ray events and was not correlated to the cyclotron rf. The background produced by the fast neutrons on the 190 m flight path was negligible.

The count rate in the neutron detector was of the order of 300 s^{-1}. The time digitizer was started at a rate of 30 kHz with a measuring time of 16 μs and a conversion time of ~ 8 μs. The time-to-digital converter (TDC) is able to accept two detector pulses per beam burst. The probability to have more than two events in 16 μs is smaller than 10^{-4}. Therefore, dead time corrections were not necessary in the transmission experiment. Also in-scattering was negligible due to the good geometry of the experiment.

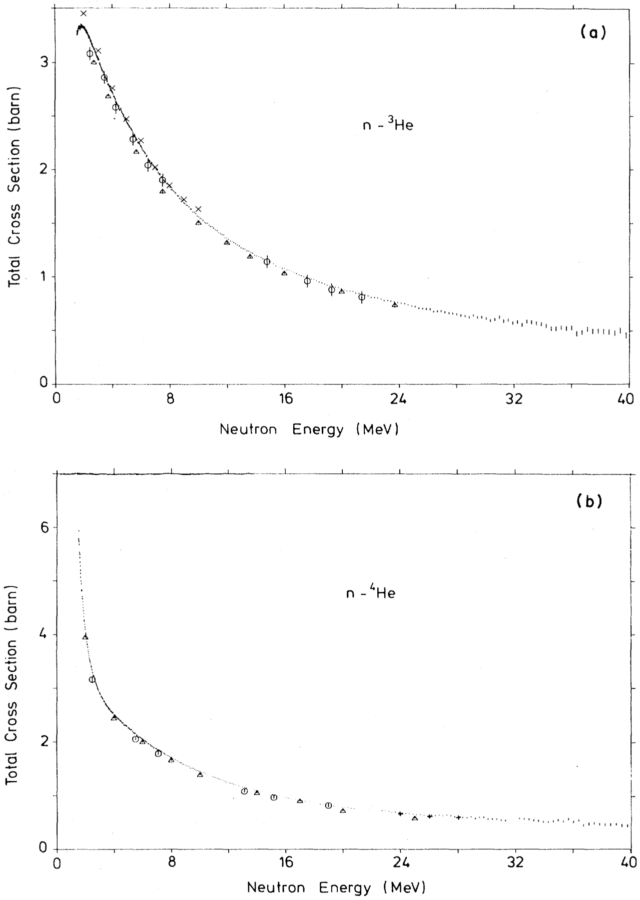

FIG. 2. Total neutron cross sections of the helium isotopes: (a) the ^{3}He data of this work (|) compared to data of Refs. 8 (△) and 9 (○) as well as to R matrix predictions of Ref. 14 (×); (b) our ^{4}He results (|) together with data from Refs. 8 (△), 9 (○), and 11 (+). The energy resolution of our data is 10^{-2}.

For the monitor detector dead time corrections of the order of 5% were applied.

The contributions to the total errors for the cross section values and for the energy scale are listed in Table II. The statistical errors depend on the number of time channels put together in the calculation of the cross sections. For a resolution of 10^{-2} (Fig. 2, Table III) these errors vary from 0.3×10^{-2} at 2 MeV to 6×10^{-2} at 40 MeV.

IV. RESULTS

The total cross sections were determined using the relation

$$\sigma_t = \frac{1}{\rho^*}\ln\left[f\frac{N_0}{N_i}\right],$$

with ρ^* the areal density of the sample, f the monitor flux normalization factor, and N_i and N_0 the transmission detector count rates for sample in and sample out after subtraction of background.

The evaluation can be performed in any chosen energy bin by integration of the corresponding channel contents

TABLE III. Total neutron cross sections for the helium isotopes, calculated using an energy resolution of 10^{-2}. The quoted errors are statistical uncertainties only.

E_n (MeV)	$\sigma(^3\mathrm{He})$ (mb)	$\sigma(^4\mathrm{He})$ (mb)
2	3324± 9	4095± 9
4	2732± 8	2505± 7
6	2215± 7	2047± 7
8	1837± 6	1714± 6
10	1561± 5	1450± 5
12	1360± 4	1253± 4
14	1197± 4	1090± 4
16	1078± 3	966± 4
18	976± 4	864± 4
20	888± 4	779± 4
22	815± 5	731± 6
24	756± 6	669± 7
26	697± 8	626± 8
28	652±11	605±11
30	609±13	560±13
32	571±15	550±16
34	555±18	515±18
36	521±20	506±21
38	490±23	463±23
40	451±27	436±27

in the time spectra. The results are converted into the energy scale using a relativistic calculation. The scale calibration was checked by an independent transmission experiment using a carbon sample. The sharp n-^{12}C resonances[13] were reproduced with an accuracy of better than 2 keV.

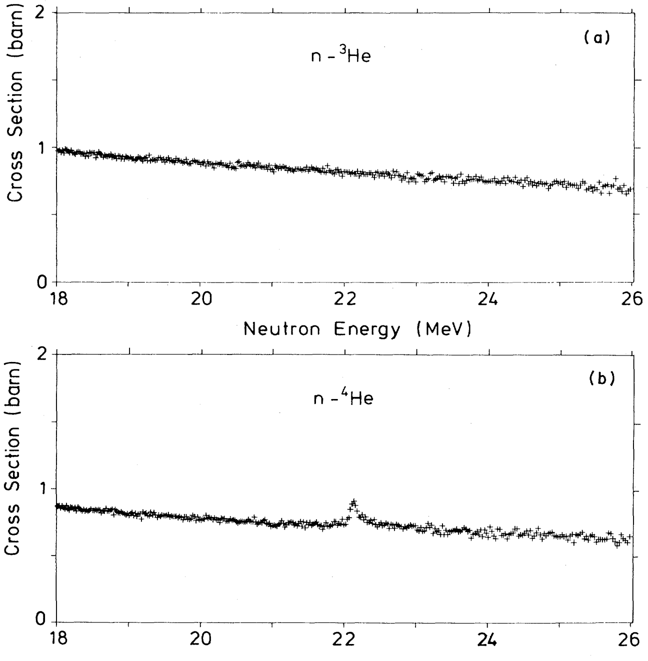

FIG. 3. The total neutron cross sections for the helium isotopes in the energy range from 18 to 26 MeV, presented with an energy resolution of 10^{-3}.

Figure 2 shows the results for the total neutron cross sections of the helium isotopes in the energy range from 1.5 to 4.0 MeV. Above 40 MeV the neutron flux was too low to obtain results with reasonable statistical accuracy. In this case a relative energy resolution of 10^{-2} was used. Some data points of Goulding *et al.*[8] and of the Los Alamos Group[9] are shown for comparison. In the region below 10 MeV the R matrix prediction of Hale[14] for the n-^{3}He cross section is indicated. Our results are 4% to 5% higher than the Goulding data, but the agreement is reasonable when all possible scale errors are included. It should be noted here that our slightly higher data for the n-^{3}He total cross section are in perfect agreement with a recent evaluation of Drosg[15] using elastic n-^{3}He scattering data and detailed balance calculations for the ^{3}H(p,n)^{3}He reaction channel. The ^{4}He data of Shamu and Jenkin[11] in the range from 20 to 29 MeV agree well with our results.

Table III contains the cross section results for a selection of energies. The errors are the statistical uncertainties for an energy resolution of 10^{-2}. In the ^{4}He case the cross section results for the two samples used agree within the statistical errors, so the results could be combined.

Figure 3 shows our data in the energy range from 18 to 26 MeV with a resolution of 10^{-3}. In this representation the $\frac{3}{2}^+$ resonance in the n-^{4}He system is clearly resolved.

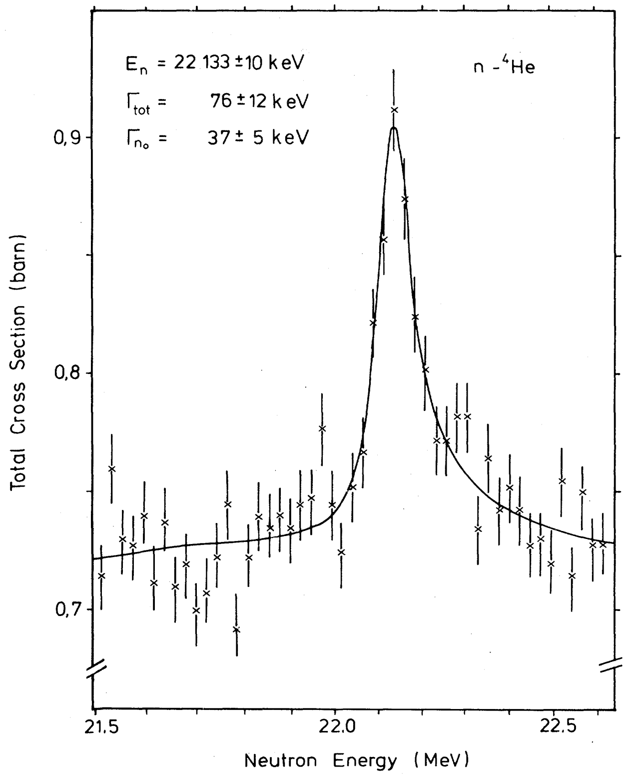

FIG. 4. The region of the $\frac{3}{2}^+$ resonance in the n-^{4}He system. The data are calculated in 1 ns time bins, whereas the overall time resolution was 1.4 ns. The solid line shows a single level Breit-Wigner fit to the data. The quoted errors of the resonance parameters include the uncertainties of the energy scale listed in Table II.

No narrow structure is found in the ^{3}He cross section in this energy range. The resonant behavior around 22 MeV, which was suggested by the analyses of Lisowski *et al.*[5] and Bevelacqua,[7] could not be confirmed in this experiment.

So we conclude that the levels in ^{4}He at this excitation energy ($\sim$37 MeV) are broad and overlapping, in agreement with the analyses summarized in Ref. 2. The measurement of the total cross section is not the appropriate method to investigate this structure. The differential cross section and the analyzing power of the elastic n-^{3}He scattering yield more detailed information on the ^{4}He structure if they are measured with high accuracy. Both experiments are on the way in our group.

The sharp resonance in the n-^{4}He system at 22.1 MeV was measured with much higher resolution than before. A single-level Breit-Wigner fit to the data assuming a smooth background, varying slowly with energy, gave the results shown in Fig. 4. The total width was found to be 76 ± 12 keV compared to 100 ± 50 keV in previous analyses,[10] the ground state neutron width being 37 ± 5 keV, whereas the old values were 50 ± 35 keV. The position of the resonance is determined to be $22\,133\pm10$ keV compared to $22\,150\pm120$ keV before. Our fit gives sharper constraints on the resonance parameters, in agreement with the previous values and with the old assumption[16] that the neutron width should be roughly half of the total width.

The cross section results for both helium isotopes indicate some broad structures at higher neutron energies. The statistical accuracy of our data is not sufficient to analyze this behavior in terms of overlapping levels in the compound nuclei.

The full numerical information on the total neutron cross sections for the helium isotopes is available on request.

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