Re-evaluation of neutron-^{4}He elastic scattering data near 20 MeV

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Measured differential elastic-scattering cross sections of 17.72-, 20.97-, and 23.72-MeV neutrons from liquid helium-4 were re-evaluated and were corrected for sample-size and multiple-scattering effects by means of a Monte Carlo technique implemented in a more recent code (MCNPX). Results indicate that earlier corrections via the code MAGGIE-2 overestimated the size of multiple-scattering effects by an order of magnitude. The corrected differential cross sections and Legendre coefficients obtained by least-squares fits are given.

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I. INTRODUCTION

Interaction of neutrons with ^{4}He is of interest in primordial and stellar nucleosynthesis, in nuclear fusion reactions, and in *ab initio* theory of light ion reactions [1]. Recently, it has been shown [2] that multiple-scattering corrections made earlier by means of the Aldermaston Monte Carlo technique MAGGIE-2 [3] to measurements of elastic scattering of neutrons from ^{3}He had been significantly overestimated. In the present paper, similar corrections made to the measurement of elastic scattering of neutrons from ^{4}He in the energy range near 20 MeV [4] are re-evaluated. Unlike other experimental n-^{4}He data in this energy range that measure the energy of the associated recoil α particle [5–7], the present re-evaluated differential cross-sectional data are based on direct measurement of the scattered neutron.

Re-evaluation of the data [4] was made possible by means of thorough documentation of the experiments at hand. In these experiments on a liquid-helium target, the geometric size of the sample, the mass of the target, and the structural background were reduced, compared to a high-pressure gas target. A disadvantage is that the target had to be maintained at a very low temperature.

The best approach to account for the experimental conditions (geometric effects and attenuation in the sample), in particular, when a tight scattering geometry is involved, is to simulate the experiment as closely as possible in a computer. Two side issues in which computers can help in re-evaluation of these measurements are as follows: (1) applying the same kind of simulation to the neutron-proton reference measurement, and (2) making a relativistic conversion from the laboratory to the center-of-mass (c.m.) system. In a few nucleon systems, relativistic correction is on the order of magnitude of 1% for neutron energies as low as 10 MeV. Furthermore, improved knowledge of the stopping power reduces the uncertainty in the neutron beam energy. Improved knowledge of the neutron-proton reference cross section also improves the scale of the neutron-^{4}He cross-sectional data.

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II. CURRENT DATA

Measurements of the absolute differential cross section of neutrons elastically scattered from helium were carried out over a period of approximately 1 yr (1969–1970) with three or four separate runs each, at energies of 17.6, 20.9, and 23.7 MeV [4]. Measurements were expressed relative to neutron elastic scattering from hydrogen [8]. Improved knowledge of the energy dependence of the detection efficiency of the neutron detector [9] resulted in improved data values with smaller uncertainties [10]. Monoenergetic neutrons were produced by bombardment of a gas cell (3-cm long filled with up to 5 atm of tritium) by deuterons accelerated in the single-ended Van de Graaff, or the tandem accelerator at Los Alamos National Laboratory (LANL). The target was 0.754 mol of liquid helium at a temperature of 3.9 K contained in a cryostat with stainless-steel walls with a combined (window) thickness of 0.18 mm.

Data-reduction procedures were the same as applied in the present paper. Net raw yields were corrected for the energy dependence of the neutron detection efficiency and then were normalized to the net cross-sectional reference yields obtained from scattering of neutrons by hydrogen. Both yields were corrected for neutron flux attenuation and multiple scattering in the respective samples. The latter was performed with the Monte Carlo code MAGGIE-2 adapted for a CDC 7600 computer from the Atomic Weapons Research Establishment version [3]. The cross-sectional library necessary as the input for this code, which originally contained all previous data on the n-^{4}He reaction, was changed after a first iteration that incorporated the new corrected results and deleted unreliable older cross sections. Multiple-scattering correction factors obtained in this way changed the shape of the distributions by as much as 20%. Neutron flux attenuation correction was on the order of 2% and took both the cryostat and the sample itself into account.

Uncertainty in the dead-time correction (less than 0.5%) was negligible. Changes in pulse-height discrimination bias (primarily caused by gain changes in the photomultiplier) affect the results only slightly, as the neutron energy is high compared to the equivalent recoil proton energy of the bias of 3.2 MeV. Neutron detector stability was checked frequently by measuring the spectrum produced by the 0.667-MeV γ

line of ^{137}Cs. Uncertainties caused by unobserved shifts were estimated to be less than 1% and were not included. The uncertainty for the multiple-scattering correction was taken to be less than 1% for the point with the largest correction and was negligible when added quadratically. In addition, correlated uncertainties in the background subtraction were not accounted for. The uncertainty in the relative efficiency was assumed to be ±2.5% per 10 MeV [9]. This uncertainty does not enter in the scale of the cross section as it only affects the shape. Obviously, that point of the distribution that coincides in energy with the energy of the cross-sectional standard comparison has no efficiency uncertainty of this kind. With increasing difference in energy, the uncertainty increases. Consequently, an individual efficiency uncertainty was assigned to each data value.

Other differential cross sections in the energy range 2–30 MeV have been measured by Austin *et al.* [7], Shamu and Jenkin [6], and Hoop and Barschall [5]. The latter two publications include detailed measurements through the lowest $3/2^+$ state in ^{5}He at 22.13-MeV neutron energy, just above the ^{4}He$(n,d)^3$H threshold at 22.064 MeV. These measurements employ a recoil particle technique. Namely, detection and energy measurements of the recoiling-associated α particle is proportional to the angular distribution of the scattered neutrons in the zero-momentum system if the angular distribution is expressed in terms of the cosine of the c.m. scattering angle [11]. It should be pointed out that this proportionality also holds relativistically [12]. Other measurements of neutron-α scattering in this energy range include asymmetry measurements of 15-MeV neutrons doubly scattered from ^{4}He [13], asymmetry measurements and phase-shift analysis at 25 and 28 MeV [14,15], and ^{4}He$(n,n)^4$He analyzing power in the energy range of 15–50 MeV [16]. Again, it should be emphasized that the differential cross sections re-evaluated in the present paper are the only data in this energy range based on direct measurements of the scattered neutrons.

III. RE-EVALUATION OF DATA

A. Computer simulations

The present simulation was carried out using the LANL neutron transport code MCNPX [17]. In 1971, simulation was accomplished using 100 000 seeds for a Monte Carlo calculation on a CDC7600 mainframe computer. Nearly 40 yr later, the corresponding calculation was carried out in an hour on a personal computer using ⩾200 000 000 seeds. The kinematics and geometric situation of the neutron source was simulated by a pencil source of 3.0-cm length and the (energy-dependent) intensity distribution of the ^{3}H$(d,n)^4$He source into the forward direction. Actual geometric measures were used in the simulation. The simulation included:

(i) Helium-4 target medium (liquid-helium density 0.1294 g/cm^3), its inner and outer containers (stainless-steel wall with a combined thickness of 0.018 cm), and ambient atmospheric pressure (0.96 mg/cm^3).
(ii) Reference cross-sectional target medium (polyethylene, slab 13.617 g) and ambient atmospheric pressure (0.96 mg/cm^3). In both cases, background contributions (empty cryostat and graphite sample, respectively) were also simulated.
(iii) Energy-dependent geometry correction factors for the shape difference between the helium cylinder and the polyethylene slab were determined at each of the three neutron energies by comparing the yields from a polyethylene slab with that from a cylinder of the same mass but in the shape of the helium cylinder.

As the database of MCNPX for ^{4}He$(n,n)^4$He covers only energies up to 20 MeV, it had to be extended to 24 MeV using the LANL 1971 data (version 1978) [10]. A revision of the original database, based on an *R*-matrix analysis from 1973 [18], which used the present corrected data instead of the original ones, resulted in minute changes of the sample-size corrections (typically 0.2%). The sample-size correction factors were obtained by comparing the simulated yield (foreground-background) with a simulated reference spectrum of a low-density bare helium sample of the same dimensions.

B. Scale adjustments

Table I summarizes the ratios of the re-evaluated scale adjustment factors over that of the original data. The three tabulated values at 23.72 MeV are for measurements of the reference sample at 40.0°, 45.0°, and 50.0°, respectively. The procedure of comparing the yield from a very thin sample with that from the actual sample does not allow a separation of the attenuation in the sample from the multiple-scattering effect. Therefore, this combined sample-size effect was dealt with separately.

Table I illustrates that the ^{1}H$(n,n)^1$H reference cross sections used in 1970 [8] scarcely differ from the present Evaluated Nuclear Data File version B-VII values [19]. Also,

TABLE I. Correction factors applied to differential cross-sectional scales [10].

Neutron energy (MeV)	Reference cross section	Attenuation in reference sample	Geometry correction	Total scale correction
17.72	1.000	0.997	0.987	0.984
20.97	1.001	1.006	0.975	0.981
23.72[a]	1.008	1.041	0.960	1.007
23.72[a]	1.012	1.040	0.960	1.010
23.72[a]	1.002	1.039	0.960	0.999

[a]The three values are for measurements of the reference sample at 40.0°, 45.0°, and 50.0°, respectively.

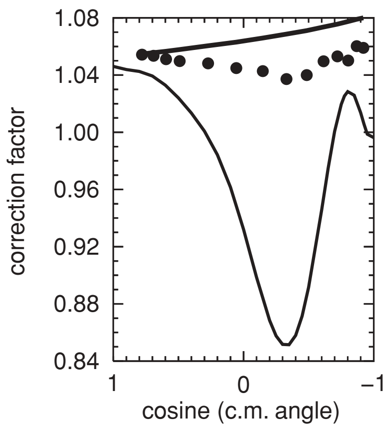

FIG. 1. Comparison of the angular dependence of the original multiple-scattering correction [4] (lower curve) with the present paper (solid circles) for 17.72-MeV neutron elastic scattering from ^{4}He. The simulation uncertainty is smaller than the size of circles. The upper curve shows the correction factor for self-attenuation alone.

the attenuation correction factors, except for the highest energy, have scarcely changed, although the original factors were calculated analytically. However, the geometry factor was disregarded in 1970 because the strong anisotropy of the neutron source intensity [20] was not considered. Because of compensating factors, the total corrections of the scale remained below 2% in all cases.

C. Sample-size corrections

The largest change in the data was due to the sample-size correction. For reasons unknown, the previous multiple-scattering corrections based on the Aldermaston code MAGGIE-2 [3] were 1 order of magnitude too large (see Fig. 1, which compares the original correction at 17.6 MeV with the present one). This difference is far outside the uncertainties given in Niiler *et al.* [4]. Figure 1 provides a solid justification for the present paper. Namely, it would have been better either not to correct for multiple scattering or to use one of the analytical recipes [21–23], had they been available at the time of the experiment.

By investigating the original raw data analysis of the time-of-flight spectra, it was found that the background under the line of the scattered neutrons was minimized by subtraction not only of the structural background (measured in a separate background run), but also of a flat background contribution. This procedure would, to some unknown extent, remove background stemming from multiply scattered neutrons. Consequently, it was decided not to consider multiple scattering at all, by risking that the actual minimum may be deeper by perhaps as much as 1.5%.

The complete documentation (log book of the experiment; data sheets with raw data analysis) allowed further improvements to the data. From the accelerating voltage, the thickness of the molybdenum entrance foil, and the tritium gas pressure, the beam energies at the center of the gas target could be recalculated by using more reliable stopping powers [24] than those available at the time of the original experiment. Moreover, there has also been improvement in the knowledge of the d-^{3}H neutron source properties [20]. By using the best data available, the incoming neutron energies E_n (at 0°) of the three angular distributions have been determined to be (17.72 ± 0.05) MeV (previously 17.6 MeV), (20.97 ± 0.04) MeV (previously 20.9 MeV), and (23.72 ± 0.03) MeV (previously 23.7 MeV). The actual energy uncertainty is somewhat higher because of the calibration uncertainty of the accelerator. In Table II, this fact was approximated by increasing each uncertainty by 0.01 MeV.

TABLE II. Differential cross sections (mb/sr) for elastic neutron scattering from ^{4}He (angles in degrees).

Laboratory energy	17.72 ± 0.06 MeV			20.97 ± 0.05 MeV			23.72 ± 0.04 MeV		
Θ_{lab}	$\Theta_{c.m.}$	$\sigma_{c.m.}$	$\Delta\sigma_{c.m.}$	$\Theta_{c.m.}$	$\sigma_{c.m.}$	$\Delta\sigma_{c.m.}$	$\Theta_{c.m.}$	$\sigma_{c.m.}$	$\Delta\sigma_{c.m.}$
20.0				25.03	213.3	5.5	25.05	203.2	4.7
25.0	31.20	214.7	5.8	31.22	177.3	6.9			
30.0	37.35	188.3	5.8	37.66	158.1	4.0	37.38	149.9	3.2
35.0	43.43	163.3	4.3	43.45	139.2	3.1			
40.0	49.46	145.3	3.2	49.48	119.9	2.8	49.50	106.6	2.1
45.0				55.44	104.9	2.4	55.46	83.3	1.7
50.0	61.29	102.5	3.0	61.31	81.5	1.4	61.34	69.0	1.7
55.0				67.11	71.2	1.4	67.13	49.1	2.5
60.0	72.77	71.7	2.22	72.80	55.7	1.2	72.83	43.3	1.2
65.0				78.41	44.37	0.93			
70.0	83.87	40.5	1.4	83.91	33.72	0.57	83.93	23.92	0.86
80.0	94.55	21.66	0.80	94.58	17.16	0.41	94.60	13.28	0.90
90.0	104.77	11.88	0.58	104.80	8.50	0.25	104.82	9.11	0.53
100.0	114.53	8.94	0.77	114.56	5.75	0.26	114.58	7.69	0.55
110.0	123.85	10.77	0.44	123.87	8.43	0.28	123.89	9.76	0.61
120.0	132.74	17.23	0.65	132.76	12.69	0.32	132.78	12.62	0.64
130.0	141.24	26.1	2.0	141.26	19.05	0.40			
140.0	149.41	30.59	0.80	149.43	26.08	0.44			

TABLE III. Uncertainty components of the re-evaluated data.

Scale uncertainties			
(A) Correlated components (affecting all scales identically)			
(a) Connected with the standard:			
Accuracy of standard cross section	0.35%		
Mass of sample (abundance, weight)	0.3%		
Normalization (neutron dose)	0.1%		
Background subtraction	Disregarded		
Finite-sample correction	Disregarded		
Dead-time correction	Disregarded		
Difference in subtended solid angle	0.5%		
(b) Connected with the sample:			
Mass (volume, purity, density)	1.45%		
Normalization (neutron dose)	0.1%		
Background subtraction	Disregarded		
Finite-sample correction	Disregarded		
Dead-time correction	Disregarded		
Sum of correlated scale uncertainties	1.6%		
(B) Uncorrelated components (affecting each scale individually)			
At primary energies (MeV):	17.72	20.97	23.72
(a) Connected with the standard:			
Accuracy of standard cross section	0.35%	0.35%	0.50%
Normalization (neutron dose)	0.1%	0.1%	0.1%
Yield uncertainty (statistics, background)	1.3%	1.5%	1.7%
Dead-time correction	Disregarded		
Finite-sample correction	0.2%	0.3%	0.4%
Difference in subtended solid angle	0.7%	0.7%	0.7%
(b) Connected with the sample:			
Mass (density)	0.2%	0.2%	0.2%
Sum of scale uncertainty (energy independent)	1.55%	1.73%	1.96%
Total scale uncertainty (quadratic sum)	2.2%	2.4%	2.5%
Shape uncertainties			
Mass (density)	0.2%		
Normalization (neutron dose)	0.1%		
Statistical uncertainties	⩾0.5%, included in data table		
Background subtraction uncer uncertainty	Included in data table		
Energy dependence of efficiency	2.5%/10 MeV, included in data table		
Multiple-scattering correction	0.2%		
Dead-time correction	<0.3%, disregarded		
Detector bias stability	<1%, disregarded		
Parameter uncertainties			
Incoming energy	0.04 to 0.06 MeV		
Scattering angle	0.1°		

As the data were measured over a period of 9 months, the final distributions were combinations of three to four portions measured separately, at each of the three neutron energies. Each of these portions was measured absolutely (i.e., relative to the *n*-*p* cross section). However, their normalizations have uncorrelated uncertainties so that scale differences are unavoidable. By adjusting the scale of the portions by means of least-squares fits improves the shape of the angular distributions. Several such adjustments were performed to improve data consistency. The re-evaluated data are given in Table II.

D. Uncertainties

Most of the uncertainties of the original data remained the same [4]. The present uncertainties are displayed in Table III, which summarizes all sources of correlated and uncorrelated uncertainties. Energy-independent (correlated) contributions to the scale uncertainties include uncertainties in the number of scattering nuclei (±0.3% for the hydrogen standard and ±1.45% for the mass of the helium sample).

Correlated uncertainty components were determined for the accuracy of the standard (±0.35%) and for the difference in the sample shape (the subtended solid angle ±0.5%). All other

TABLE IV. Results of least-squares fitting to Legendre polynomial expansion.

E_n	σ_0	A_0	A_1	A_2	A_3	A_4	A_5	σ_{el}	σ_{el} [4]
17.72	272	0.258	0.383	0.310	0.027	0.012	0.011	880	858
20.97	254	0.234	0.360	0.305	0.048	0.033	0.020	746	732
23.72	252	0.206	0.340	0.297	0.105	0.033	0.019	652	654

uncertainties were taken into account individually for each data set. To establish better corrections clearly does not reduce individual (uncorrelated) uncertainties of the data values.

IV. SUMMARY

Energy-independent fitting to a Legendre polynomial expansion was performed by implying that the integrated, the forward (0°), and the backward (180°) cross sections exhibit consistent energy dependence. In addition, it was ensured that Wick's limits, as derived from the optical theorem [25], were below the 0° cross sections.

Table IV presents the first six Legendre coefficients and the 0° cross section σ_0 (in mb/sr) for the three neutron energies E_n in MeV, where integrated elastic cross σ_{el} (in mb) in the present paper is compared with that reported in Ref. [4]. The differential cross sections are given in the c.m. system in the form

$$\frac{d\sigma(E,\Theta)}{d\Omega} = \frac{d\sigma(E,0^\circ)}{d\Omega}\cdot\sum_i A_i P_i(\cos\Theta) = \sigma_0\cdot\sum_i A_i P_i(\cos\Theta).$$

At 17.72 and 20.97 MeV, corrected elastic cross sections σ_{el} are higher than the original data [4], as one would expect from effects of multiple-scattering correction at the minima in the angular distributions. The change would be more pronounced if the total scale correction factor was not <1.000 (Table I). The smaller value, at 23.72 MeV, is caused by the increased neutron detection efficiency at higher energies [10]. The present data agree within uncertainty limits with total cross-sectional data [26] (by taking 32.9 mb [20] for the nonelastic cross section at 23.72 MeV).

V. DISCUSSION AND CONCLUSIONS

Changes in incoming neutron energies and in c.m. angles are small. However, absolute differential cross sections at the minima were increased by as much as 25% at 17.72 and 23.72 MeV and 22% at 20.97 MeV. This increase is three to six times the standard uncertainty reported in the original paper [4]. This significant correction merits attention to several critical points in the present paper:

(i) Neutron detection efficiency: As in most experiments where neutrons are detected, knowledge of efficiency of the detector is essential. In the present case, the (relative) efficiency curve has been used in numerous highly accurate neutron production measurements. There has not been a need for improvement after the first revision [10].

(ii) Reference cross section: The ^{1}H$(n,n)^1$H cross section standard is very well established, in particular, below 20 MeV. This is supported by the fact that the cross-sectional reference values used for the present data changed by less than 1% from 1971 [8] to 2005 [19].

(iii) Sample-size correction: Although the database for the Monte Carlo code was improved in the present paper by the inclusion of the present data, the changes in the sample-size correction factors were small (<0.2%), despite the fact that the resident database in MCNPX on ^{4}He is from 1973. If the assumption that the yield from multiply scattered neutrons was effectively removed by background subtraction is wrong, the present data might be systematically high by up to 1.5% (in the cross-sectional minimum).

(iv) Sample mass: It could not be established how much, if any, helium in the filling tube contributed to the measured yield. Density fluctuations caused by atmospheric pressure fluctuations were estimated to be <0.2%.

(v) Geometry: The distance of the neutron source to the center of the target was rather small, namely, 11.5 cm. By modeling the experiment in the Monte Carlo code, geometric effects (opening angles, angle dependence of the intensity of the incoming neutrons, and shape difference between the sample and the reference sample) were accounted for. Moreover, only the uncertainty in the relative difference in the position of the reference sample and the helium cell matters. It is believed that the assigned uncertainty of ±0.5% accounts for both the uncertainty in the shape correction and the uncertainty in the difference of the source-to-sample distance.

It is not clear why the original data were overcorrected. Since the scattering sample was small (<1 mol), the originally reported large corrections were unlikely. In addition, since other data corrected with MAGGIE-2 show a similar behavior [2], it is not unlikely that the problem lies in the code itself. Because the code MAGGIE-2 is no longer available, this issue could not be specifically addressed.

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