Calculation and evaluation of cross-sections and kerma factors for neutrons up to 100 MeV on carbon

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We present an evaluation of the interaction of neutrons with energies between 20 and 100 MeV with carbon nuclei. Our aim is to accurately represent integrated cross sections, inclusive emission spectra, and kerma factors, in a data library for use in radiation transport simulations of fast neutron radiotherapy. We apply the FKK-GNASH nuclear model code, which includes Hauser-Feshbach, preequilibrium, and direct reaction mechanisms, and use experimental measurements to optimize the calculations. We determine total, elastic, and nonelastic cross sections, angle-energy correlated emission spectra for light ejectiles with A$\leq$4 and gamma-rays, and average energy depositions. Coupled-channel optical model calculations describe the total, elastic, and nonelastic cross sections well. Our results for charged-particle emission spectra agree fairly well with the UC-Davis, as well as the new Los Alamos and Louvain-la-Neuve measurements. We compare our results with the recent ENDF/B-VI evaluation, and argue that some of the exclusive channels between 20 and 32 MeV should be modified. We also compare kerma factors derived from our evaluated cross sections with measurements, providing an integral benchmark for our work. The evaluated data libraries are available as electronic files.

I. INTRODUCTION

A number of new applications, such as radiation transport simulations of cancer radiotherapy and the accelerator-driven transmutation of waste, require evaluated nuclear data libraries when modeling the interaction of neutrons above 20 MeV [1]. The major efforts in nuclear data evaluation work over the last few decades have concentrated on reactions below 20 MeV, for fission and fusion applications. Above this energy, transport calculations have been generally performed with codes which calculate nuclear cross sections on an event-by-event basis using intra-nuclear cascade (INC) methods. However, the underlying physical assumptions of the INC theory are not well satisfied below 100 MeV, and there is a need to extend evaluated nuclear data libraries up to higher energies. Furthermore, evaluated libraries can represent the physical interactions more accurately since they can be based upon experimental measurements in addition to model calculations. Our work aims to improve the evaluated nuclear data for carbon up to 100 MeV, by making use of recent experimental results and improvements in modeling capabilities, to produce data libraries which can be utilized in radiation transport calculations.

The motivation for this work comes primarily from the Lawrence Livermore National Laboratory PEREGRINE project, which is developing an all-particle Monte Carlo transport code for calculating and optimizing absorbed dose in cancer radiotherapy [2]. This code transports neutrons, photons and charged particles in a fully coupled manner, and can be used for simulating the effects of radiation beams on the dose delivered to a patient. The transport is performed through a three-dimensional mesh obtained from a CT-scan of the patient, and the calculated dose distributions can be used to optimize the dose delivered to a tumor. Most modern fast neutron therapy facilities use a ^{9}Be(p,n) source reaction, which produces a broad spectrum of neutrons with energies up to 70 MeV. In a recent review of the status of nuclear data for use in neutron therapy, White *et al.* [3] emphasized that with the exception of hydrogen, sufficiently accurate nuclear data does not yet exist in this energy range to allow neutron therapy to reach its full potential. Since "standard man" consists (by mass) of hydrogen (10%), carbon (18%), nitrogen (3%), and oxygen (65%), and various trace elements (4%), an accurate understanding of neutron nuclear reactions on carbon is essential. As natural carbon consists of only 1.1% ^{13}C, the present work for ^{12}C can be used for natural carbon. In subsequent papers we shall present our evaluations of neutron reactions on the other biologically-important elements.

Since only a limited number of experiments for neutron reactions on carbon have been performed for energies between 20 and 100 MeV, we have based our evaluations mainly on the results of nuclear model calculations, benchmarked to the measurements where they exist. To do this, we have developed and applied the FKK-GNASH modeling code [4,5], which uses Hauser-Feshbach theory for equilibrium decay, Feshbach-Kerman-Koonin (FKK) [6] theory for preequilibrium emission, and includes corrections for direct processes. Our theoretical efforts, described in Sec. III, have concentrated on improvements to the modeling of reaction processes that become important at higher energies, particularly in preequilibrium emission, optical models, and level densities. The light mass of carbon, and consequently the relatively wide-spacing of its nuclear levels, presents a particular challenge to model calculations which rely on statistical assumptions in their derivations. As we shall show, however, our calculations in most cases provide a good description of the data. In part this is because our implementation of Hauser-Feshbach theory uses experimental nuclear level schemes for low excitation energies where a statistical level-density model is not applicable. It is also due to the fact that even in carbon the density of nuclear states above about 10 MeV excitation energy becomes large enough for non-statistical effects to become small.

This evaluation is available as an electronic database in the Lawrence Livermore National Laboratory (LLNL) Evaluated Nuclear Data Library (ENDL) format, and we plan to translate the library into the ENDF format. It can be used together with existing evaluations for neutrons below 20 MeV, such as the ENDL evaluation by Howerton [7] or the ENFD/B-VI evaluation by Fu *et al.* [8]. A detailed description of the evaluation is available in an LLNL report [9]. Table I contains a summary of quantities evaluated.

In Sec. II we describe our evaluation methods and compare them to those of previous analyses (Axton *et al.* [10], Brenner and Prael [11], Caswell *et al.* [12], Dimbylow *et al.* [13], Pearlstein [14], Young *et al.* (1990) [15], and others). Section. III describes the nuclear theory and models we use. In Sec. IV we give a detailed description of our results compared with experimental cross sections, and in Sec. V we compare kerma factors derived from our evaluated cross sections with measurements, and with other calculations. In Sec. VI we compare our work with the recent ENDF/B-VI evaluation, which extends up to 32 MeV. A summary and a description of directions and needs for future work are given in Sec. VII.

II. EVALUATION METHODS

A. Evaluation Methods Used in This Work

For incident energies above 20 MeV the number of possible exclusive reactions following the interaction of a neutron with a carbon nucleus becomes large. Rather than representing each possible reaction separately, we determine the corresponding inclusive emission spectra of the particles which need to be transported in the Monte Carlo calculations (gammas, and light particles with $A \leq 4$), as well as the total kinetic energy given to heavier charged particles which is assumed to be deposited locally. This representation of the data is adequate for Monte Carlo calculations of radiation transport and absorbed dose. In the future, if applications such as micro-dosimetry require a description of the energy deposited by all types of nonelastic recoils, we can extend the libraries to include this information.

The libraries are fully angle-energy correlated, and describe the emission spectra at various angles, all in the laboratory frame of reference, facilitating straightforward comparisons with measurements. Tabulating the inclusive production cross sections in evaluated files above 20 MeV was first introduced in the Los Alamos evaluations [15], and is recommended by the Nuclear Energy Agency of the OECD in its intermediate energy data activities [16]. We have omitted triton and helium-3 emission reactions since measurements show these cross sections to be small. This does not imply that our calculated total kerma factor will be underestimated, since kinetic energy to these channels gets redistributed. Trial calculations confirmed this, for including triton emission did not significantly change our total calculated kerma factors.

The evaluations are based mainly on model calculations using the FKK-GNASH code system [4], benchmarked to available experimental data. But other reaction model codes were also used in this work: optical model calculations were performed with the ECIS79 [17] and SCAT2 [18] codes; and when evaluating preequilibrium cross sections we also considered hybrid model results from the ALICE code [19] and exciton model results from the GNASH [4] code. There are a number of advantages to using nuclear theory and model calculations to produce evaluated cross section libraries: (1) The model input parameters can be adjusted (within the uncertainty ranges to which they are known) to optimize agreement with experimental data at incident energies where measurements have been made. The calculations then provide a useful way to interpolate and extrapolate to other energies; (2) Model calculations enable evaluated libraries to be generated for all reaction products in a fully consistent way, automatically conserving energy, unitarity, spin, and parity.

Table II summarizes the experimental data used in this evaluation, in some cases pointing to other places in this paper where the data are shown in more detail. Here we note that in addition to the UC-Davis emission spectra [20,21] we used recent emission spectra results from Louvain-la-Neuve [22] and Los Alamos [23]. We show these various experimental data sets compared with our evaluations in Sec. IV.

Some of the major steps involved in this evaluation are: (1) Optical model analyses for n, p, d, α particles to generate elastic and inelastic (coupled-channels) cross sections and transmission coefficients; (2) Build a database of low-lying nuclear levels for all product nuclides for use in Hauser-Feshbach and preequilibrium calculations. (3) Match a statistical level density on to the experimental low-lying levels; (4) Perform preequilibrium calculations using FKK, exciton, and hybrid models for comparison purposes. On the basis of these calculations, and measured cross sections, evaluate the primary preequilibrium spectra; (5) Use the FKK-GNASH code to generate inclusive cross sections based on primary and multiple preequilibrium emission, equilibrium decay, and direct reactions; (6) Use the Kalbach systematics [24] to give continuum angular distributions, and transform the double-differential cross sections to the laboratory frame assuming 2-body kinematics; and (7) Generate ENDL-format library files.

B. Comparison With Previous Evaluations

In addition to the present work, Refs. [1,13,15,25] used preequilibrium models with Hauser-Feshbach compound nucleus decay to study neutron reactions on carbon. Dimbylow [13] used an early version of the GNASH code, and the model calculations were compared against the UC-Davis cross section and kerma measurements. Even though details of the preequilibrium spectral shapes were not described very well, the resulting kerma factors were modeled fairly accurately. The calculations performed by Herling and Bassel [25] used similar techniques, though their results compared poorly with measurements. More recently, Young *et al.* [15] performed model calculations using the GNASH code for incident neutron and proton energies to 100 MeV. However, because of the large number of nuclei evaluated in this work, detailed comparisons against emission spectra and kerma were not shown.

Intranuclear cascade (INC) calculations with either evaporation or a Fermi break-up compound nucleus decay have been described in Refs. [11,26–29]. While the physical assumptions made in these models do not hold well below 100 MeV, some analyses [11] have shown that they can provide a reasonable description of experimental measurements at these energies. However, of these calculations many were performed prior to the UC-Davis measurements, and it is only the comprehensive work by Brenner and Prael [11] which makes comparisons with experimental charged-particle spectra. Brenner and Prael did not include elastic or inelastic coupled-channels scattering in their analyses, and did not present results for gamma-ray production.

Caswell *et al.* [12] and Axton [10] extended the evaluated ENDF libraries from 20 MeV to about 30 MeV, using optical model results to obtain the total, elastic, and nonelastic cross sections. But as the authors themselves attest, many of the partial cross section extrapolations are not based on either model calculations or experimental data and must be considered speculative. The total kerma factor resulting from these calculations overestimates measurements in the 26-32 MeV range. In Sec. VI we compare our evaluation against Axton's work, which has been incorporated into the ENDF/B-VI evaluation. More recently, Pearlstein has presented an evaluation of neutron and proton reactions on carbon up to 10 GeV using INC methods along with systematics [14], and adopting Axton's evaluation below 32 MeV. Some of Pearlstein's calculated production cross sections are in qualitative agreement with the present work, such as neutron and alpha emission, though there are differences for proton, deuteron, and gamma emission. Also, the diffraction model used for elastic scattering is less sophisticated than the optical model used in this work. Watanabe [30] has described his progress in evaluating neutron reactions on carbon up to 50 MeV [30] using the SCINFUL Monte Carlo simulation code. This code has branching ratios for different nuclear reaction pathways inputted, based on optimizations to measured data. But since model calculations are not used, it is difficult to extend this method to energy regions where experimental data do not exist.

Of the above published works, only those of Brenner and Prael, and Dimbylow, show detailed comparisons with measured emission spectra and kerma factors. Also, only the works of Brenner and Prael, Young, Caswell, Axton, and Pearlstein exist in an electronic format suitable for applications. Our evaluation is unique in that experimental measurements (of integrated cross sections and emission spectra) have been used wherever possible to optimize the calculated data, and the resulting kerma factors agree well with measurements.

III. NUCLEAR THEORY AND MODEL DEVELOPMENTS

A. General

In this section we describe the nuclear reaction models used to describe the interaction of a fast neutron with carbon. As a means of introducing the various nuclear reaction models we use, we show in Fig. 1 our calculated angle-integrated neutron spectrum at 80 MeV in the channel-energy frame. This illustrative example shows the contributions from primary and multiple preequilibrium processes, as well as the total inclusive spectrum. For clarity we do not show the elastically scattered neutrons. The impact on the total inclusive spectrum of compound nucleus emission at lower energies, and direct inelastic scattering at high energies, is also clear.

We note some features of the various contributing reaction mechanisms seen in Fig 1. At the highest emission energies, the importance of neutron inelastic scattering to the 2+ (4.4 MeV) and 3- (9.6 MeV) states in carbon is evident, and we describe in Sec. III B how we calculate these cross sections using a coupled-channel optical model. The long hard tail in the neutron spectrum is due to primary and multiple preequilibrium emission, described in Sec. III C. At low energies, the large increase in the spectrum comes from compound nucleus decay (see Sec. III D). The structure seen at the lowest and highest energies is a direct consequence of our use of experimental nuclear level information (see Sec. III E). The peak seen in the emission energy bin at 1 MeV comes mainly from the decay of nuclei in low-lying states by equilibrium neutron emission, with much of the contribution coming from the $^9Be^* \rightarrow 2\alpha + n$ reaction.

B. Optical Models

We determine total, elastic, and nonelastic scattering cross sections using optical model analyses, which are also needed for generating transmission coefficients and wavefunctions in the equilibrium and preequilibrium calculations. We have implemented a modified version of the coupled-channel optical potential developed by Meigooni *et al.* for neutrons with energies above 20 MeV [31]. This deformed potential couples the 0^+, 2^+ (4.4 MeV), 4^+ (14.1 MeV), and 3^- (9.6 MeV) states in ^{12}C, using an external form-factor input in the ECIS79 code [17]. A rotation-vibration model is assumed for the coupling interaction [31], and we use relativistic kinematics. Below 20 MeV we use a spherical optical model which has been optimized to fit reaction cross section data, which is important for obtaining accurate transmission coefficients for our Hauser-Feshbach calculations. From 0-10 MeV we use the Los Alamos spherical potential for ^{12}C [32], and from 10-20 MeV the spherical potential of Dimbylow [33]. The transition energies between these different potentials were chosen to result in a reaction cross section that changes continuously.

In addition to neutrons, optical potentials are also needed for the other ejectiles for calculating transmission coefficients for their decay. Proton potentials were obtained from the neutron potentials using the Lane model isospin transformation [34], namely $(N-Z)/A \rightarrow -(N-Z)/A$, with a Coulomb correction to the real central potential of $0.4Z/A^{1/3}$. Potentials for deuterons and alphas up to high energies were obtained using the method of Watanabe, as implemented by Madland [35].

C. Preequilibrium Emission

Preequilibrium nucleon emission was obtained mainly from the FKK quantum mechanical theory [6,37,38], and preequilibrium deuteron and alpha clusters were obtained from the semiclassical model of Kalbach [36]. In some cases we modified the calculations to agree better with experimental measurements where they exist. We have not relied solely on calculated results since an accurate description of fast particle emission is critical for correctly determining absorbed dose, and our comparisons with measurements, particularly for deuteron emission, show that the model's accuracy can be limited [1]. Preequilibrium gamma-ray emission through the Giant Resonance is modeled using a semiclassical exciton model [4].

We described preequilibrium calculations of reactions on biological nuclei in Ref. [1], where we compared results based on FKK, exciton, and hybrid models with experimental measurements. We have modified the FKK-GNASH code to use pre-evaluated primary (i.e. first emitted particle) preequilibrium spectra for n, p, d, and α particles. When evaluating these spectra we considered: (1) Experimental measurements of the emission spectra, where they exist; (2) Results obtained from model calculations, using FKK, hybrid, and exciton models; (3) Constraints arising from flux conservation (unitarity) [38]; (4) Systematics first reported by Kalend *et al.* [39] indicating that preequilibrium (p, xp) differential spectra are about twice as high as (p, xn) (due to a factor of 2 in the accessible phase space). From these systematics we can infer that (n, xn) differential spectra should be about twice those for (n, xp) in the preequilibrium regime; (5) Where Bertand and Peelle (p, xp) data exists we take them as a guide for the (n, xn) cross sections.

Contributions from multiple preequilibrium emission (MPE) processes (where more than one particle is emitted through a preequilibrium mechanism) become important for calculating emission spectra and excitation functions for incident energies above 50 MeV [38]. We use the generalized MPE theory of Ref. [38] to determine nucleon MPE. When modeling reactions on carbon at the higher energies, the MPE mechanism is also important for correctly describing the magnitude of alpha emission since these processes suppress the cross section for the 3α break-up process and prevent an overprediction of alpha production.

D. Equilibrium Emission

We use Hauser-Feshbach theory to calculate equilibrium emission of particles and gamma rays, conserving angular momentum and parity in an open-ended sequence of decay chains. As the incident energy increases, the number of different reaction pathways increases and it becomes impractical to consider all decay possibilities. Furthermore, since many of the decay sequences contain a negligibly small amount of cross section, it is unnecessary to calculate them explicitly; instead, we performed trial calculations to determine the most important reaction pathways and ignore paths that contain < 1 mb of cross section. We explicitly model the decay of carbon isotopes ranging from ^{13}C to ^{9}C, boron isotopes from ^{12}B to ^{8}B, beryllium isotopes from ^{11}Be to ^{7}Be, lithium isotopes from ^{8}Li to ^{5}Li, and helium isotopes from ^{7}He to ^{5}He. We included gamma, neutron, proton, deuteron, and alpha particle decay channels.

Transmission coefficients for equilibrium particle decay were obtained using the optical potentials described in Sec. III B Gamma-ray transmission coefficients were obtained from the generalized Lorentzian model of Kopecky and Uhl [40]. This model modifies the Brink hypothesis by including an energy-dependent giant resonance width from Fermi-liquid theory. The giant resonance formulation of Kopecky and Uhl was used for E1, E2 and M1 radiation. Even though photonuclear data on light elements shows strong nuclear structure effects, we obtained Lorentzian parameters approximating the total photoabsorption measurements of Ahrens *et al.* [41] for use in the above model.

E. Level densities and discrete levels

We determine nuclear level densities using the Ignatyuk model [42], as implemented by Arthur *et al.* [15]. This model uses a Gilbert-Cameron-type level density expression (constant temperature plus Fermi-gas), but unlike the original Gilbert-Cameron model it includes an energy-dependent Fermi-gas level density parameter. This allows for the physically-expected behavior of a washing out of shell effects with increasing excitation energy, and enables level densities to be determined with increased accuracy in these high-energy calculations. Pairing energies were obtained from the Cook systematics with the Los Alamos extensions to light nuclei from Ref. [32].

The above continuum level density formulation is matched continuously onto discrete low-lying levels at the lower excitation energies. Experimental discrete level information is specified up to an excitation energy below which the experimental measurements were judged complete. Discrete level information (energy, spin, parity, gamma-ray branching ratios) is tabulated for each nuclide in an input file, which is based on a number of different sources including the Ajzenberg-Selove compilations [43]. For each nucleus we performed a level-density analysis and determined the excitation energy at which we judged the level data complete. Table III below lists the number of discrete levels used, and the matching energy, for the residual nuclides that can be produced (many of which are unstable). As an example of our results, in Fig. 2 we show the experimental cumulative number of levels matched on to our continuum statistical description for ^{12}C.

IV. RESULTS AND COMPARISONS WITH EXPERIMENTS

A. Total, Elastic, and Reaction Cross Sections

In this section we describe the evaluated total, elastic, inelastic, and reaction (nonelastic) cross sections for neutrons on carbon, based on our coupled-channel optical model calculations. There is excellent agreement between the total cross section that we calculate and the measurements, except at energies below 35 MeV where the calculation overestimates the data by about 2%. In this case we apply a small renormalization to the elastic cross sections to remove this discrepancy. The cross sections are shown in Table IV.

In Fig. 3 we show the evaluated total cross sections compared with experimental measurements, taken from the Brookhaven National Nuclear Data Center CSISRS file. When evaluating the total cross sections for neutrons on carbon most weight was given to the recent measurements by Finlay *et al.* [44] at the LAMPF/WNR Los Alamos white neutron source facility, which have a reported uncertainty of less than 1%.

There are a number of elastic scattering cross section measurements in the 20-100 MeV region [45–51], and we compare them to our evaluation in Fig. 4. Where the original authors published values for the integrated cross sections we use their values. To integrate the elastic 40 MeV data of DeVito [47] we used the Meigooni "best individual fit spherical parameters" (p. 91 of Ref. [52]) in a SCAT2 optical model calculation, since the calculated angular distribution described the differential data very well (see Fig. V-1 of Ref. [52]). Likewise, since our coupled-channel calculation at 28.15 MeV and 65 MeV described the Yamanouti *et al.* [49] and Hjort *et al.* [48] differential data well (see Fig. 5), we used the integrated elastic cross section from our calculation. In Fig. 5 we show some of the (c.m.) angular distributions compared with our evaluations. It is evident that the coupled-channel analysis provides a good representation of the measurements, which span a large fraction of the energy range that we are analyzing. Additionally, proton elastic scattering measurements at 30, 46, and 65 MeV [53–55] provide a useful further check on the optical model analyses since the proton potential was obtained from the neutron potential by applying a Coulomb correction (the isospin correction is zero here). Our calculations in Fig. 6 again show good agreement with the experimental data, which is particularly notable since the proton data were not used in any of the potential parameter searches.

Experimental reaction (nonelastic) cross sections are compared with our evaluation in Fig. 7. The experimental values of DeVito [47], Meigooni [46], Hjort [48], Olsson [45], and Yamanouti [49] shown in Fig. 7 were obtained by subtracting experimental elastic cross sections from the total (Finlay [44]) cross sections. The numerical values of the experimental reaction and integrated elastic cross sections are tabulated in Ref. [9]. While our evaluation describes these measurements well, the uncertainty in the reaction cross section is about 5% at the lower energies, increasing to about 10% at the higher energies.

In Figure 8 we show our calculated coupled-channels inelastic scattering to the 2+ (4.4 MeV) and 3– (9.6 MeV) states in carbon, compared with measurements. Scattering to the 4.4 MeV state is followed by gamma decay to the ground state, whereas the 9.6 MeV state decays by alpha emission. We therefore include in Fig. 8 the Antolkovic [61] kinematically-complete nuclear emulsion experimental results for the $^{12}\mathrm{C}(n,n'3\alpha)$ reaction via the 3– state. We also show experimental data from proton inelastic scattering (taken from Ref. [52]). Rather than represent scattering to these states separately in the libraries, for simplicity we add their angle-integrated cross sections into the neutron production cross section file (and consequently in applications use the Kalbach systematics to obtain their angular distributions).

B. Inclusive production Cross Sections

In Table V we present our calculated production cross sections and average kinetic energies for the light ejectiles. The large cross section for alpha production at low energies is due to the importance of the 3α break-up mechanism. The exact variation of the production cross sections depends in a complicated manner on the different competing reaction mechanisms. These cross sections do not increase strongly with incident energy for two reasons: firstly, the reaction cross section decreases by over a factor of two between 20 and 100 MeV;

and secondly, at a relatively low incident energy significant fragmentation of carbon occurs, and so an increasing incident energy does not result in a significant increase in particle production.

In Fig. 9 we show our calculated charged-particle production cross sections compared with experimental data. Both the Louvain-la-Neuve and the UC-Davis experiments did not detect low-energy emitted particles below their detector thresholds. To obtain the total production cross sections, the low-energy behavior of the spectra have to be estimated, and a variety of approaches for this have been reported in the literature. The original UC-Davis report [21] assumed a constant differential cross section from the lowest measured energy to zero. However, this approach may significantly underestimate the low-energy cross section in some cases, particularly for alpha emission. In 1986 Romero [63] modified these UC Davis results based on the Brenner and Prael INC calculations at low-energies, resulting in increased cross sections (and kerma factors). Similarly, the recent Louvain-la-Neuve experiments used the Brenner and Prael calculations to extrapolate below their experimental threshold energy [22].

Since our calculations describe measured emission spectra well (see the next section), we have used them to extrapolate the experimental measurements to low-energies. In Table VI we show the uncorrected experimental data, our threshold correction estimates, and the total experimental production cross sections that result. We have assigned an uncertainty of 30% to our threshold corrections, estimated by comparing our corrections with those obtained from the Brenner and Prael calculations [11]. Note that in both the UC-Davis and the Louvain-la-Neuve experiments the threshold corrections for alpha-particle emission often exceed the uncorrected experimental results – and therefore the term "experimental" for the total cross sections we obtain here is rather tenuous. Our estimated total experimental production cross sections are consistent with those presented by Slypen *et al.* [22]. Agreement between our evaluation and the UC Davis and Louvain-la-Neuve measurements seen in Fig. 9 is fairly good, and our results are also in reasonable agreement with the older measurements by Kellogg at 90 MeV [62]. Our total production cross sections differ from those found by Axton [10] since he assumed a constant cross section variation at low energies. For instance, at 27.4 MeV we obtain an experimental UC-Davis alpha production cross section of 777 mb, compared to Axton's inferred experimental value of 431 mb. This resolves the discrepancy (p. 15 of Ref. [10]) that his evaluated alpha production here (760 mb) differed significantly from his integrated "experimental" UC-Davis result (431 mb, which we argue should be 777 $\pm$ 146 mb).

Spallation yield data [64] for proton-induced reactions have been measured at 75 MeV. Harrison *et al.* argued [64] that these data ought to be similar to those from neutron reactions since the incident energy far exceeds the Coulomb barrier, and $N = Z$ for the target. In Fig. 10 we compare our calculated yields as a function of A, compared to the experimental data (which extend only up to $A = 11$). The agreement is seen to be reasonable: modeling of spallation yields is always more challenging than light-particle emission yields. Our results appear to describe the data more accurately than the INC with Fermi break-up model in Ref. [64].

C. Emission Spectra

An accurate modeling of angle-integrated emission spectra is particularly important for calculating absorbed dose, since they determine the average energies, and hence the kerma for the charge particles.

In Fig. 11 we show our calculated (lab) angle-integrated emission spectra of protons, deuterons, and alphas, compared with measurements. We show results at incident neutron energies of 27, 40, 60, and 70 MeV, which correspond approximately to the energies measured in the UC-Davis [20] and Louvain-la-Neuve [22] experiments. The end-points of the Louvain-la-Neuve spectra extend a few MeV further than the other measurements due to the slightly higher incident energies used. In the case of alpha emission, the new Haight *et al.* measurements [23] (incident energies ≤ 40 MeV) are in good agreement with the other experiments. For comparison we also show the model calculations of Brenner and Prael [11] (dashed-lines), at incident energies of 25, 40, and 60 MeV. Compared to Brenner and Prael's [20] calculated cross sections, ours generally agree more closely with the data for proton and deuteron emission, and the quality is comparable for alpha emission.

Our results generally describe the full experimental emission spectra well. The only case where we deviate significantly from measurements is the 70 MeV ^{12}C(n, xp) reaction, where we underpredict the Louvain-la-Neuve measurements in the preequilibrium range. However, flux conservation prevented us from increasing the proton emission. If we did so, preequilibrium neutron emission would have had to be reduced to an unphysically small level. This indicates either a problem with the experiment, or possibly that multiple preequilibrium proton emission could be more significant than our calculations suggest. This is an important reaction since it is the main reason for the high Louvain-la-Neuve total kerma factor result at 72.5 MeV, which we underpredict (see Sec. V).

In figure 12 we compare our calculated double-differential alpha, proton, and deuteron emission spectra against the UC-Davis measurements at 40 MeV. The angles that we show are the same as those presented by Subramanian *et al.*, together with Brenner and Prael's calculations, in Ref. [20]. We show similar comparisons at 27 and 60 MeV in Ref. [9]. A dramatic example of the influence of nuclear structure is seen in the ^{12}C(n, xd) spectra, where the low-lying ^{11}B states populated after high-energy deuteron emission are widely separated in energy. Structure effects are also sometimes seen in the low-energy part of the emission spectra due to particle-unstable excited nuclei decaying by equilibrium emission to low-lying or ground-state residual nucleus levels. For example, the two low-energy peaks seen in the alpha emission spectra at forward angles are due to the ground-state and first excited-state of ^{8}Be decaying to two alpha-particles. Since we have not included the finite widths of these states in our analyses, the structure is more dramatic than is observed experimentally.

Our calculations generally account for the angular variations seen in the data, showing that the phenomenological systematics of Kalbach provide a good representation of angular distributions. At the higher emission energies the spectra show a dramatic forward peaking, typical of preequilibrium and direct reactions, since the incident projectile's direction of motion is partially preserved. At the lowest energies, the particles are emitted from compound nucleus reactions. In the center-of-mass these are emitted with angular distributions symmetric about 90-degrees (and almost isotropic), but in the laboratory frame there remains a small amount of forward-peaking. Our calculations also clearly show how discrete structure effects in the spectra track with emission angle and energy due to kinematics.

D. Neutron Emission Compared With (p,xp) Data

There are no measurements of (n,xn) emission spectra with which we can compare our calculations. However, Bertrand and Peelle have measured $^{12}\mathrm{C}(p,xp)$ cross sections at 40 and 60 MeV [65]. It would be expected that $^{12}\mathrm{C}(p,xp)$ and $^{12}\mathrm{C}(n,xn)$ spectra should be similar, particularly for the higher emission energies where Coulomb effects are negligible. Some differences would be expected due, for instance, to different Q-values in the competing channels in the two cases, but we expect such effects to have a small impact. Therefore we have used the Bertrand and Peelle measurements to benchmark our neutron emission calculations. An example is shown in Fig. 13, where we compare our results against the 40 MeV angle-integrated measurements. The calculated emission spectrum agrees well with data except at the lowest energies, where the calculation lies below the measurements.

E. Gamma-Ray Production Spectra

A measurement of the gamma-ray emission spectra at 60 MeV by Auchampaugh *et al.* [66] at Los Alamos is compared against our calculations in Fig. 14. These (unpublished and preliminary) experimental results are at an emission angle of 90 degrees, and are seen to agree very well with our calculation.

The structure seen in both the measurements and the calculation is due to the dominance at these energies of discrete gamma-rays from low-lying bound nuclear states. The individual strengths of the various gamma-ray lines are closely related to the production cross sections of the various residual nuclei, and modeling such production cross sections provides a stringent test for the theory. For example, the peak in the spectrum at 4.4 MeV is due mainly to the de-excitation of the 4.4 MeV state in $^{12}\mathrm{C}$ following neutron inelastic scattering, and the fact that our calculations describe this measurement well provides support for the accuracy of our coupled-channel calculations. When new LANL results [67] become available for gamma-ray production, they will be useful for checking our calculations further.

F. Exclusive $(n,n'3\alpha)$ and $(n,2n)$ measurements

Although our evaluation represents inclusive, and not exclusive, cross sections it is useful to compare our calculations against exclusive measurements where they exist. The partial cross section for the $(n,n'3\alpha)$ reaction is shown in Fig. 15, compared with the emulsion measurements by Antolkovic [61] with the Brenner and Prael corrections [79]. The good agreement that is seen between our calculation and the measurements is important since this reaction channel makes up such a large fraction of the total nonelastic cross section. Our calculation of this channel agrees with the data better than that of Brenner and Prael [68], which lies below the measurements. This is the main reason for the fact that our total nonelastic cross section at 20 MeV is 7 % higher than Brenner and Prael's [68].

Experimental data also exist for the $(n,2n)$ reaction channel [69–72]. Our calculated cross section is approximately half that of these measurements (see Fig. 16). Fortunately the small cross section to this channel means that these differences have a minor impact on our evaluated inclusive spectra. At the higher energies it is the emission of two high-energy neutrons in direct knockout-type processes that produce ^{11}C nuclei in the $(n, 2n)$ reaction, and this mechanism is included in our calculations using our multiple preequilibrium (MPE) model. The failure of our calculation here is linked to our modeling of such processes. But the general success of our modeling for other (more important) decay channels, along with the fact that our MPE model has worked well in other analyses [38], makes us reluctant to adjust model parameters to try to improve our $(n, 2n)$ results.

V. KERMA FACTORS

It is important to model kerma factors accurately when calculating absorbed dose in radiotherapy. The partial kerma factor for a certain secondary charged-particle type is obtained from the product of the cross section (in b) and the average energy (in MeV), in units of b.MeV/atom. To convert to the SI unit of Gy.m^2 (where 1 Gray (Gy) = 1J/1Kg) we multiply by 0.804044 $\times 10^{-15}$, which is the product of three factors: the number of atoms per Kg of ^{12}C (6.0221367 / 12) $\times$ 10^{26}; J/MeV (1.60217733 $\times 10^{-13}$); and m^2/b (10^{-28}) [10].

The kerma factors are obtained from our microscopic cross section files in the following way. We partition the total kerma factor into contributions from elastic ^{12}C recoils, light ejectiles with A $\leq$ 4, and nonelastic recoils with A $>$ 4. To determine these kerma factors one must determine the production cross sections and the average laboratory emission energies. The elastic recoil average energy is obtained using the calculated elastic angular distribution, with relativistic two-body kinematics. Likewise, the average energies of the A $\leq$ 4 ejectiles are obtained by transforming the FKK-GNASH emission spectra into the laboratory frame. While the FKK-GNASH code does give production cross sections for the A$>$ 4 residual nuclides, it does not determine their energies. Therefore to determine the nonelastic recoil kerma we use energy balance considerations [9,63], as well as results from a version of the ALICE code. Full details are given in Ref. [9].

In Table VII we show our calculated partial and total kerma factors based on our evaluated cross section libraries. At the lowest energies, the total kerma factor is dominated by the alpha contribution, much of which comes from the 3α beak-up mechanism. The large production cross section for alphas at these energies, which follows from the large multiplicity (three), results in this large partial kerma. As the neutron incident energy increases the 3α break-up cross section falls resulting in a decreasing alpha kerma factor. The increasing proton and deuteron partial kerma factors are due to the importance of preequilibrium emission with increasing incident energy. The elastic and nonelastic recoil kerma factors, on the other hand, decrease with increasing energy. This is because the $A < 4$ angular distributions become increasingly forward-peaked, resulting in a reduced recoil kinetic energy (even though the incident energy is increasing). We compare our calculated elastic partial kerma factor with experimental measurements in Fig. 17.

In Fig. 18 we show our evaluated total kerma from 20-100 MeV (derived from our microscopic cross section libraries) compared with experimental measurements [22,63,73–78]. There are two different types of measurements of total kerma factors: direct measurements of the ionization effects of the charged particles using a proportional counter; and indirect determination from cross section measurements. Below we describe these two methods and note some of the uncertainties inherent in them. The direct kerma measurements recently reported by Schrewe *et al.* [77,78], for incident energies between 30 and 70 MeV, use a proportional counter to measure the total kerma factors. Such experiments, however, are very difficult to perform and the uncertainties reported are fairly large. Kerma factors derived from cross section measurements have been presented by the UC-Davis and Louvain-la-Neuve groups [63,22]. These experiments measured the inclusive production cross sections of light charged particles, for emission energies above the detector thresholds. To obtain the total kerma factors, additional assumptions have to be made: (1) angle-integrated spectra need to be inferred from the double-differential measurements; (2) the cross sections have to be extrapolated from the threshold emission energy measured to zero energy; (3) elastic recoil kerma have to be added; and (4) the (unmeasured) contributions from nonelastic recoil fragments have to be estimated. A range of total kerma factors based upon the UC-Davis measurements have been reported in the literature. Brady *et al.* [21] initially gave experimental total kerma factors based upon the uncorrected experimental measurements. Later, Dimbylow [13] added contributions due to nonelastic recoils, as well as low emission energy threshold corrections, as estimated by Brady *et al.* [21]. In a subsequent work, Romero *et al.* [63] further refined the estimated experimental total kerma factors by assuming an extrapolation to zero emission energy, and a nonelastic recoil contribution, based upon the model calculations of Brenner and Prael. Therefore there are significant uncertainties in estimating the total kerma factors from the cross section measurements, and the error bars on the UC-Davis results are probably too small. Likewise, the corrections that are added to the "raw" Louvain-la-Neuve results are large and there are significant uncertainties involved.

The general consistency seen in Fig. 18 between our evaluation and the measurements provides an important integral benchmarking of our work. Our calculated kerma factor at 73 MeV is lower than the Louvain-la-Neuve measurement due to our lower proton emission spectrum compared to experiment, as seen in Fig. 11. However, as discussed in Sec. IV C, we did not increase the proton emission because of constraints arising from flux conversation and systematics. At 27 MeV our result agrees well with the kerma factor measurements near this energy by Brady *et al.* [13,63], Hartmann *et al.* [75], and Schrewe *et al.* [77], but is lower than the Antolkovic measurement [73]. Antolkovic determined the total kerma factor here by adding her result for the $(n, 3\alpha)$ partial kerma (averaged with Antolkovic's estimate of the UC-Davis value), with the UC-Davis other partial kerma factors. The reason for the discrepancy is due to the fact that the partial kerma factor to the $(n, n'3\alpha)$ reaction is significantly higher than our result. This is because her $(n, n'3\alpha)$ cross section exceeds ours, and her average alpha-particle kinetic energy exceeds ours. But Brenner and Prael [79] have re-estimated the corrections that must be made to obtain the experimental $(n, n'3\alpha)$ cross section and argue for a 15 % smaller value. Additionally, our alpha emission spectrum is in good agreement with the measurements from Los Alamos and UC-Davis (see Fig. 11), which we believe to be of higher accuracy than those from the emulsion experiment (compare Fig 11 with Fig. 2 of Ref. [73]). If we repeat Antolkovic's procedure for obtaining the total kerma factor at 27 MeV, but use our estimation of the UC-Davis threshold correction, along with the Brenner 15% reduction in the $(n, n'3\alpha)$ cross section, we obtain an average alpha partial kerma factor of 2.2 and a total "experimental" kerma factor of 4.2 f Gy m^2 in better agreement with the other measurements near 27 MeV.

Our calculated total kerma factor is in good agreement with the 1992 evaluation by

White *et al.* [3], with our results being slightly higher at the higher energies. In Fig. 19 we show our results compared with other calculations and measurements. The Brenner and Prael [68] and the Wells [29] calculation appear rather low, and the rapid rise seen in the Behrooz calculation [27] seems unjustified. The results of Alsmiller *et al.* [26], Dimbylow [13], and Watanabe *et al.* [30], agree fairly closely with our work. In the next section we discuss why our kerma evaluation differs significantly from the ENDF/B-VI evaluation by Axton [10] between 26 and 32 MeV.

The magnitude of the non-elastic recoil kerma remains an open question. Our results are approximately consistent with the energy-balance estimates of Brady *et al.* [21], and at 60 MeV and 27 MeV, for example, the non-elastic recoil kerma accounts for about 10 % and 15 % respectively of the total kerma. These values are also comparable with those calculated by Brenner and Prael [63]. Yet a calculation by Harrison *et al.* [64], using a reaction model very similar to that of Brenner and Prael, gave non-elastic kerma factors 2-3 times larger.

VI. COMPARISON WITH ENDF/B-VI

While our evaluation represents reactions in terms of inclusive emission spectra, it is useful to compare our calculated exclusive cross sections with the ENDF/B-VI evaluation [8], which extends up to 32 MeV. The extensions from 20 – 32 MeV were recently performed by Axton, and the very comprehensive report [10] describing his methodology is also a useful source of references to experimental measurements. In Table VIII we show our calculated exclusive reaction cross sections for the main break-up channels up to 30 MeV, compared with the ENDF/B-VI evaluation. Above this energy the number of such channels becomes too large to practically extract this information from our calculations.

A controversial consequence of Axton's evaluation methodology is the large importance assigned to the ^{12}C(n,^{6}Li)^{7}Li channel. At 26 MeV he assigned a peak cross section of 100 mb here, about 20 % of the nonelastic cross section. In the region 20-26 MeV seven new channels open up including (n,^{6}Li). But since Axton extrapolated such small cross sections for channels such as (n,np), (n,p), and (n,d) beyond 20 MeV, he assigned a large cross section to the (unmeasured) ^{7}Li – ^{8}Li break up, to reproduce the total nonelastic cross section. Where we differ is mainly in the (n,p), (n,d), and (n,np) channels, which our calculations indicate to be far larger than he supposed, due to the importance of preequilibrium and direct emission. Also, our larger cross sections are consistent with the inclusive production cross sections from UC-Davis, since our determination of these values gave numbers significantly higher than those obtained by Axton (see Sec. IV B). Regarding the "controversial ^{12}C(n,^{6}Li)^{7}Li reaction, with its 100 mb", Axton stated (p. 27 of [10]) that "If the reaction is eliminated, another home has to be found for this 100 mb at 26 MeV. There appears to be nowhere to go without conflicting with the available evidence upon which the evaluated cross sections are based." The "available evidence" here is, primarily, Axton's extrapolated values for the UC-Davis total production cross sections of protons and deuterons. But since we have argued that his extrapolated values here are too small, we have opened up the possibility for more cross section to deuteron and proton emission. In particular, we have shown that cross section to the ^{12}C(n,^{6}Li)^{7}Li reaction can be ignored, and reassigned mainly to the (n,np), (n,p), and (n,d) channels, without any inconsistencies. Moreover the UC-Davis emission spectra themselves support significant cross section to these channels, due to the observed importance of high-energy proton and deuteron emission.

Between 20 and 26 MeV the Axton ENDF/B-VI kerma evaluation agrees fairly well with our evaluation and with experimental measurements, but above 26 MeV it is higher than most of the experimental measurements and model calculations, as seen in Fig. 19. The lower kerma factor that we obtain compared to the ENDF/B-VI evaluation is due, in part, to the above differences in cross sections. For instance, at 27 MeV over 10 % of the total kerma comes from the controversial ^{12}C(n,^{6}Li)^{7}Li channel. Also, it was assumed that residual nuclei are produced in their ground states, which tends to overestimate the calculated kerma (Axton assessed that the overestimate is about 2.5% at 28 MeV).

In addition to the above differences, we think that the procedure used by Axton to unfold the $(n,n'3\alpha)$ cross section via intermediate excited states in ^{12}C, and hence determine the average alpha emission energy, gives an overestimate for the alpha kerma factor. This can be shown by considering the situation at 27 MeV, where there are alpha spectrum measurements from UC-Davis and Los Alamos, and a $(n,n'3\alpha)$ alpha spectrum measurement by Antolkovic *et al.* [73]. At 27 MeV, Axton's evaluation for the (n,α) and $(n,n'3\alpha)$ cross sections are 7 and 254 mb respectively, while we obtain 5 and 252 mb respectively (in close agreement). The partial kerma factors for these two exclusive reactions obtained by Axton are 0.13 and 2.84 f Gy m^2 respectively, and other reactions involving alphas are small and can be omitted here. Thus the Axton evaluation predicts an alpha production inclusive kerma factor in the range 2.84-2.97 f Gy m^2 (we cannot be more precise here since the fraction of the 0.13 carried by the ^{9}Be recoil in the ENDF/B-VI evaluation is not stated). However, our calculations show an inclusive partial kerma factor to alphas of 1.97 f Gy m^2, in reasonable agreement with the UC-Davis measurement [63] of 2.11 f Gy m^2. We note, though, that the Antolkovic measurement [61] gives a larger partial kerma to the $(n,n'3\alpha)$ channel, in closer agreement to the Axton evaluation. However, the uncertainties in this emulsion experiment are large (as indicated by the large reported error-bars [61]) and we suspect that the Antolkovic result is too high, as discussed in Sec. V

VII. CONCLUSIONS

We have produced an evaluated nuclear data base for neutrons incident on carbon with energies up to 100 MeV. The evaluation rests upon recent cross section measurements from Louvain-la-Neuve, Los Alamos, and UC-Davis, and new nuclear modeling capabilities we have developed for high-energy reactions, particularly in the preequilibrium, direct, level density, and optical model calculations.

We have extensively benchmarked our results to experimental measurements of total cross sections, emission spectra, angular distributions, and kerma factors, and obtained a good representation of these measurements. Compared to Brenner and Prael's [20] calculated cross sections, ours generally agree more closely with the data for proton and deuteron emission, and the quality is comparable for alpha emission. The libraries can be updated when new experimental results (such as the 20-90 MeV data currently being measured by Baba *et al.* [80]) and new modeling capabilities become available.

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TABLES

Reaction type	Cross section	Angle-energy correlated lab spectra	Average lab energy deposition
n,total	$\surd$	–	–
n,nonelastic	$\surd$	–	–
n,elastic	$\surd$	(c.m. angular distributions)	$\surd$
n,xn	$\surd$	$\surd$	$\surd$
n,xp	$\surd$	$\surd$	$\surd$
n,xd	$\surd$	$\surd$	$\surd$
n,xα	$\surd$	$\surd$	$\surd$
n,xγ	$\surd$	(isotropic)	$\surd$
n,nonelastic recoils	–	–	$\surd$

TABLE I. Contents of Evaluated Data Library for ^{12}C+n.

Reaction type	Citation to experimental measurement
Total	See Fig. 3
Elastic	See Fig 4
Nonelastic	See Fig 7
Inelastic neutron scattering	See Fig. 8
p, d, α production	27, 40, 61 MeV UC-Davis [20,21] (Figs. 11-12)
	43, 63, 73 MeV Louvain-la-Neuve [22] (Figs. 11-12)
α production	20-40 MeV Los Alamos [23] (Fig. 11)
Gamma-ray production	60 MeV Los Alamos [66], see Fig. 14
$(n, n'3\alpha)$	Antolkovic [61], see Fig. 15
$(n, 2n)$	See Fig. 16
Spallation data	Harrison *et al.* [64] 75 MeV proton data, see Fig. 10
(p, xp)	Bertrand and Peelle [65], see Fig. 13 (guide for (n, xn) calcs.)

TABLE II. Summary of experimental cross section data guiding this evaluation

Nucleus (1000Z+A)	Number of levels	Matching energy	Nucleus (1000Z+A)	Number of levels	Matching energy
6013	10	9.190	4007	6	10.300
6012	8	12.162	4006	2	2.505
6011	12	8.724	3010	1	0.000
6010	5	7.180	3009	5	6.955
6009	2	3.330	3008	8	7.385
5012	14	6.138	3007	8	9.940
5011	22	12.057	3006	6	5.792
5010	25	8.895	3005	1	0.000
5009	4	3.005	3004	3	4.100
5008	3	3.090	2009	1	0.000
4011	7	3.990	2008	1	0.000
4010	10	9.465	2007	1	0.000
4009	6	5.531	2006	4	16.450
4008	14	20.250	2005	2	6.000

TABLE III. The number of low-lying discrete levels included, along with the matching excitation energy (in MeV) above which we used the Ignatyuk continuum level density description.

Energy (MeV)	Total	Elastic	Reaction	Inel. 2+	Inel. 3–	inel. 4+
20	1507	1016	491	105	36	4
23	1404	922	482	86	29	3
27	1357	904	453	64	25	2
30	1295	861	434	55	20	2
35	1204	798	406	43	16	1
40	1111	728	383	35	13	1
50	946	603	343	24	9	1
60	812	504	308	18	7	1
70	704	428	276	14	5	0
80	612	368	244	11	4	0
90	540	317	223	8	3	0
100	485	262	223	6	3	0

TABLE IV. Evaluated total, elastic, and reaction cross sections (in mb) for n+^{12}C for various laboratory neutron energies. Also shown are the (coupled-channels) inelastic scattering cross sections to the 2+ (4.4 MeV), 3– (9.6 MeV), and 4+ (14.1 MeV) states in ^{12}C.

Energy	$\sigma(n)$	$E_{av}(n)$	$\sigma(p)$	$E_{av}(p)$	$\sigma(d)$	$E_{av}(d)$	$\sigma(\alpha)$	$E_{av}(\alpha)$	$\sigma(\gamma)$	$E_{av}(\gamma)$
20	421	6.7	36	4.1	13	3.3	887	2.6	144	4.0
23	423	7.6	48	4.8	28	5.2	907	3.0	137	3.8
27	376	8.9	66	6.5	54	7.5	766	3.5	135	3.8
30	361	10.0	83	7.6	52	8.4	700	3.9	140	3.7
35	335	11.7	109	9.6	59	10.5	579	4.4	150	3.6
40	324	13.1	126	11.2	62	12.6	495	4.8	145	3.5
50	323	16.3	142	13.4	68	16.3	399	5.2	140	3.4
60	313	20.2	148	16.6	68	19.4	328	5.5	129	3.5
70	300	21.1	158	19.6	79	21.0	293	6.3	109	3.5
80	280	23.9	156	23.7	71	23.7	250	6.4	95	3.5
90	273	26.0	153	24.7	71	25.5	229	7.0	81	3.7
100	305	26.3	172	22.7	81	25.3	236	7.6	73	4.3

TABLE V. Evaluated production cross sections (in mb) and average energies (in MeV) in the n+^{12}C reaction, for various laboratory neutron energies (in MeV).

UC-Davis measurements:					
Reaction	Incident energy (MeV)	Detector Threshold (MeV)	Experimental measurement (mb)	LLNL threshold correction (mb)	Total Production (mb)
	27.4	3.0	290.8 ± 3.1	486.0 ± 145.8	776.8 ± 145.8
^{12}C$(n, x\alpha)$	39.7	2.9	216.5 ± 2.3	239.0 ± 71.7	455.5 ± 71.7
	60.7	3.2	166.5 ± 2.4	148.0 ± 44.4	314.5 ± 44.4
	27.4	3.0	57.2 ± 1.5	13.3 ± 4.1	70.5 ± 4.4
^{12}C(n, xp)	39.7	1.8	93.9 ± 2.1	13.9 ± 4.2	107.8 ± 4.7
	60.7	2.1	126.7 ± 2.4	13.1 ± 3.9	139.8 ± 4.6
	27.4	3.7	55.5 ± 1.5	8.1 ± 2.4	63.6 ± 2.8
^{12}C(n, xd)	39.7	2.7	52.5 ± 1.2	5.9 ± 1.8	58.4 ± 2.2
	60.7	2.1	63.7 ± 1.2	3.8 ± 1.2	67.5 ± 1.7
Louvain-la-Neuve measurements:					
	42.5	12.0	25.9 ± 2.6	452.0 ± 135.6	477.9 ± 135.6
^{12}C$(n, x\alpha)$	62.7	15.0	19.2 ± 1.9	309.0 ± 92.7	328.2 ± 92.7
	72.8	9.0	43.4 ± 4.3	239.0 ± 71.7	263.5 ± 71.7
	42.5	4.0	110.2 ± 5.5	28.3 ± 8.6	138.5 ± 10.2
^{12}C(n, xp)	62.7	6.0	116.4 ± 5.8	43.0 ± 12.9	159.4 ± 14.1
	72.8	6.0	141.8 ± 7.1	37.7 ± 11.3	179.5 ± 13.3
	42.5	6.0	63.6 ± 3.1	16.0 ± 4.8	79.6 ± 5.7
^{12}C(n, xd)	62.7	10.0	46.1 ± 2.3	22.3 ± 6.8	68.4 ± 7.2
	72.8	8.0	62.4 ± 3.1	20.6 ± 6.2	83.0 ± 6.9

TABLE VI. Experimental charged-particle production cross sections together with the low-energy LLNL threshold corrections, and the resulting total experimental production cross sections

Energy (MeV)	p	d	α	nonel. recoils	el. recoils	Total
20	0.12	0.04	1.82	0.65	0.52	3.14
23	0.19	0.12	2.18	0.65	0.44	3.58
27	0.35	0.33	2.14	0.58	0.42	3.82
30	0.51	0.35	2.18	0.55	0.39	3.99
35	0.84	0.50	2.05	0.45	0.35	4.20
40	1.13	0.63	1.90	0.45	0.32	4.43
50	1.54	0.89	1.65	0.47	0.25	4.80
60	1.98	1.06	1.45	0.50	0.21	5.20
70	2.49	1.33	1.48	0.45	0.18	5.93
80	2.97	1.35	1.27	0.40	0.16	6.16
90	3.04	1.45	1.29	0.35	0.14	6.28
100	3.14	1.65	1.45	0.30	0.13	6.67

TABLE VII. Evaluated partial and total kerma factors (in units of f Gy m^2) for n+^{12}C, for various laboratory neutron energies.

Energy (MeV)	(n,n$'$)	(n,2n)	(n,p)	(n,d)	(n,np)	(n,α)	(n,n'3α)
Present LLNL calculations:							
20	122	0	29	13	7	20	289
23	97	1	23	28	24	12	298
27	69	4	21	52	45	5	252
30	58	8	23	46	55	3	228
Axton ENDF/B-VI evaluation:							
20	90	0	13	53	26	42	299
23	80	4	5	25	24	15	305
27	60	17	1	9	8	7	254
30	53	24	0	4	4	4	228

TABLE VIII. Calculated exclusive reaction cross sections (in mb) for n+^{12}C up to 30 MeV, for the most important reaction channels, compared with ENDF/B-VI [8]

FIGURES

FIG. 1. Calculated 80 MeV ^{12}C(n, xn) angle-integrated spectrum, with contributions from primary and multiple preequilibrium emission.

FIG. 2. Level density analysis for ^{12}C. Below 12.1 MeV experimental levels are used, and above this energy we use a statistical description.

FIG. 3. Total cross section for neutrons on carbon. The experimental data were taken from the Brookhaven NNDC CSISRS file.

FIG. 4. Elastic cross section for neutrons on carbon. Numerical values of the experimental data are given in Ref. [9]

FIG. 5. Differential elastic scattering (c.m. frame) for neutrons on carbon, compared with experiments [46–48].

FIG. 6. Differential elastic scattering (c.m. frame) for protons on carbon, compared with measurements [53–55].

FIG. 7. Reaction (nonelastic) cross section for neutrons on carbon. Numerical values of the experimental data are given in Ref. [9].

FIG. 8. Angle-integrated inelastic scattering to the 2+ (4.4 MeV) and 3− (9.6 MeV) states in ^{12}C compared with measurements [46,45,61].

FIG. 9. Total production cross sections for alphas, protons, and deuterons compared with measurements [20–23].

FIG. 10. Calculated spallation yields in the 75 MeV ^{12}C+n reaction, compared with experimental *proton*-induced measurements [64].

FIG. 11. Calculated laboratory-frame angle-integrated inclusive spectra (shown as solid lines) for alpha, proton, and deuteron emission compared with measurements [20–23], and compared with calculations by Brenner and Prael [11] (shown as dashed lines).

FIG. 12. Calculated laboratory-frame double-differential inclusive spectra for alpha, proton, and deuteron emission, compared with UC-Davis measurements [20] at various angles.

FIG. 13. Calculated 40 MeV ^{12}C(n, xn) angle-integrated emission spectrum (lab frame) compared with ^{12}C(p, xp) data [65].

FIG. 14. Calculated spectrum of gamma rays emitted in the 60 MeV ^{12}C$(n, x\gamma)$ reaction, compared with measurements at 90-degrees [66].

FIG. 15. Calculated $(n, n'3\alpha)$ cross section compared to experimental measurements [61,79].

FIG. 16. Calculated $(n, 2n)$ cross section compared to experimental measurements [69–72].

FIG. 17. Evaluated elastic partial kerma factor compared with measurements [46,47,45].

FIG. 18. Evaluated total kerma factor, from 20-100 MeV, compared with experimental measurements.

FIG. 19. Evaluated total kerma factor, from 20-80 MeV, compared with results from other calculations.