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Title: KERMA-FACTOR DETERMINATION BY CHARGED-PARTICLE SPECTROSCOPY

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Submitted to: 4th International Conference on Applications of Nuclear Techniques "Neutrons and their Applications"

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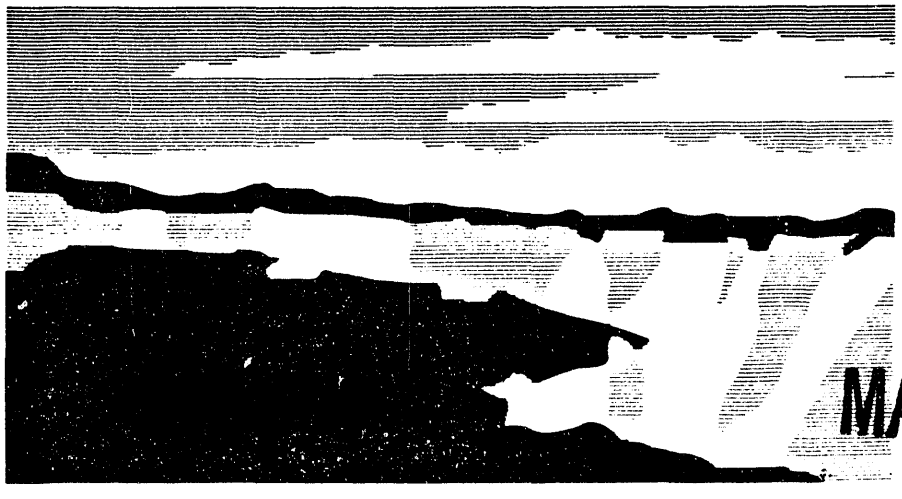

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Kerma-factor determination by charged-particle spectroscopy

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ABSTRACT

Neutron kerma factors can determined by measuring the cross sections, angular distributions and charged-particle emission spectra from (n,z) reactions where z stands for the light charged particles, namely protons, deuterons, tritons, ^{3}He, or α-particles, and combining these data with information on the heavy nuclear recoils. This approach is compared with other approaches of determining kerma factors. Data are given near 14 MeV for materials from carbon to niobium.

1. INTRODUCTION

Kerma factors relate the incident neutron fluence to the amount of energy deposited by charged particles when neutrons are incident on a material. The acronym kerma stands for kinetic energy released in matter. This quantity is important in considerations of dose imparted by neutrons to biological materials and of neutron heating of any material, such as for fission or fusion-reactor application.

Kerma is defined[1] as

$$K = dE_{tr}/dm \qquad (1)$$

where dE_{tr} is the sum of all the initial kinetic energies of charged particles liberated in nuclear interactions in a volume element and dm is the mass of that volume element. Examples of nuclear reactions included here are (n,p), (n,n'p), (n,α), (n,n' α), (n,n' 3α), (n, elastic recoil), (n, inelastic recoil), (n, capture recoil), and so forth. Units of kerma are the same as those of dose, that is, rads (100 ergs/g) or, in standard international units, grays (1Gy = 1 J/ kg).

The kerma factor is defined as the kerma per unit neutron fluence, e.g. Gy m**2. Because the reaction cross sections and charged particle energies change with incident neutron energy, both the kerma and kerma factors are functions of neutron energy.

In recent years, good progress has been made in determining kerma factors through a wide range of techniques including micro calorimeters, low-pressure proportional counters with walls of the material of interest, and by direct charged-particle spectroscopy. It is the purpose of this paper to discuss the spectroscopy technique, to present results, and to compare the approach with other techniques.

II. Detection of charged particles from neutron-induced reactions

Several approaches are used to detect charged particles from neutron-induced reactions. They all give double differential cross sections for emission of charge particles as a function of angle and charged-particle emission energy. The particle types are usually restricted to protons, deuterons, tritons, ^{3}He and alpha particles. The residual nuclei, which also have kinetic energy, are in general not detected because of their very short range in the target material and the difficulty of detecting heavy charged particles with energies of only a few hundred keV. The partial kerma factor for the reaction studied is obtained by integrating the charged-particle emission spectrum weighted by the emission energy and then adding a term for the recoil nucleus kinetic energy:

$$K_{partial}(E_n) = \int E_{cp} \cdot \sigma(E_n, E_{cp}, \Theta)\, dE_{cp}\, d\Omega + \text{Recoil} \qquad (2)$$

If the reaction has only two bodies in the final state, then the recoil contribution can be determined exactly. Otherwise some model-dependent value must be taken.

Angle-integrated information can be obtained by studying the pulse-height distribution in an appropriate detector, where the neutron-induced reaction takes place on an element of the detector (e.g. Ref. 2). Here all of the kinetic energy is deposited in the scintillator. For reactions with heavy recoiling nuclei, however, most of the recoil energy is not converted

into signal because of charge recombination (in semiconductor detectors) or non-linear light output (in scintillators). Again, then, a correction must be made for the kinetic energy of the heavy nuclear recoil.

III. Other contributions to kerma

The other major contributions to kerma for fast neutrons are the recoils from elastic scattering and from non-elastic interactions that do not produce charged particles such as (n,n'), (n,2n) and so forth. If elastic scattering data are available, they can be used to compute the angular distribution of the recoiling nucleus, with its energy being determined by two-body kinematics. For non-elastic events, the recoil cross sections must be calculated with a model code. In the simplest approximation, a compound nuclear mechanism is assumed and the recoil nucleus goes in the direction of the incident neutron with an energy of

$$E_r = E_{inc} \circ M_r \circ M_n / (M_t + M_n)^2 \qquad (3)$$

where E_{inc} is the incident neutron energy, M_r is the residual mass, M_n is the mass of the neutron and M_t is the mass of the target nucleus. No consideration is given in this approximation to the momentum added to the recoil from emission of neutron(s) and/or charged particles from the compound nucleus. If the contribution to kerma from the recoil energy E_r is small compared with other contributions, then this simple model may be adequate.

IV. Results near 14 MeV

Values of kerma factors were obtained in previous works near 14 MeV[3-7] but not published heretofore. Selected values are presented in Table I. Estimates of the contribution from the recoil of the heavy nuclei from elastic and non-elastic interactions are included in the table.

Several features of kerma for these materials should be noted. The kerma values vary markedly from material to material, with the highest values generally being for the lower atomic masses. Two factors contribute to this effect, namely the larger cross section for charged-particle emission from lighter nuclides because of the lower Coulomb barrier and the definition of kerma being energy deposited per unit mass of material (the denominator is therefore lower for the lighter mass nuclides). These factors overcome the larger total and non-elastic cross sections characteristic of the heavier nuclides for neutron energies near 14 MeV.

A second feature is that there is a large variation (up to a factor of 6) in kerma values near 14 MeV even for nuclides that are very close in atomic mass, such as $^{46,48}Ti$, ^{51}V and $^{54,56}Fe$. The specific binding energies of neutrons and charged particles in the compound nuclei and the number of available channels for charged particle emission relative to neutron emission are mostly responsible for these differences.

Finally, the contribution of charged particle emission to kerma is seen to be more than half of the total. For selected nuclides, such as the neutron-deficient isotopes of iron and nickel, this contribution can be over 90%.

V. Comparison of techniques

Charged-particle spectroscopic determinations of kerma factors yield data that are generally consistent with those of other approaches. This can be seen even for "difficult' cases such as carbon where the alpha-particle energy spectrum from the 12C(n,n'3α) breakup extends to very low energies. Because the kerma factor is an energy-weighting of the emission spectrum, the lower-energy charged particles are not so important. Thus even though there is a discrepancy in the cross section values, the deduced kerma factor[7] is quite consistent with that from an evaluation of many data.[8] An example from the heavier nuclides is aluminum where the value (1.06 ± 0.12) given in Table I is consistent with that from a study with a cylindrical proportional counter (1.22 ± 0.18).[9]

The spectroscopic approach requires measurements at many angles and is therefore more time-consuming and more complex than the cylindrical or spherical proportional counter approach. On the other hand, directional information is obtained and this can be important for following the energy deposition. Both approaches give information on the quality (the LET, linear energy transfer) of the ionizing radiation.

Kerma factors can also be studied by microcalorimeter experiments (e.g. Ref. 10). An intense, monoenergetic neutron source is required for this technique. Contributions to the measured temperature increases from gamma-ray heating can be important in the calorimetry data, and they must be removed to deduce the neutron kerma. No angular information is of course obtained in these studies.

VI. Future Possibilities

With the availability of intense spallation neutron sources,[11] spectroscopic measurements are possible over a wide range of neutron energies. An example of data for the alpha-particle emission spectra from carbon is shown in Fig. 1.[12] where the neutron energy range extends from threshold to 30 MeV. A significant increase in the data for kerma factors can therefore be expected in the near future.

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Table I - Partial kerma factors from (n,z) measurements. The uncertainty in the sum of these partial kerma factors is estimated to be ± 12% from the present work. Estimates for the remaining contributions to the kerma factor from heavy-ion recoils are given based on angular distributions for elastic scattering and from the total non-elastic cross section as given by ENDF/B-VI.

Target	En	Partial Kerma Factors*			Sum	Recoils		Total	Fraction
		Protons	Deuterons	Alphas	p+d+a	Elastic	Non-elastic		c.p. **
		fGy m**2	fGy m**2	fGy m**2	fGy m**2	fGy m**2	fGy m**2	fGy m**2	
natC	14.1	0	0	1.050	1.050	0.540	0.250	1.840	0.571
***	14.1	0	0	1.230	1.230	0.540	0.240	2.010	0.612
27Al	15	0.495	0.024	0.286	0.805	0.071	0.185	1.061	0.759
46Ti	15	0.545	0.009	0.151	0.705	0.052	0.066	0.823	0.857
48Ti	15	0.094	0.006	0.044	0.144	0.052	0.060	0.256	0.563
51V	15	0.060	0.007	0.026	0.093	0.050	0.054	0.197	0.472
natFe	15	0.200	0.007	0.065	0.272	0.048	0.045	0.365	0.745
54Fe	15	0.767	0.010	0.127	0.904	0.048	0.048	1.000	0.904
56Fe	15	0.150	0.007	0.062	0.219	0.048	0.045	0.312	0.702
natNi	15	0.653	0.013	0.148	0.814	0.040	0.042	0.896	0.908
58Ni	15	0.850	0.015	0.166	1.031	0.040	0.042	1.113	0.926
60Ni	15	0.259	0.011	0.109	0.379	0.037	0.039	0.455	0.833
93Nb	15	0.039	0.007	0.018	0.064	0.013	0.016	0.093	0.688

* Uncertainties in the partial kerma factors are approximately 12% for protons, 20% for deuterons and 15% for alpha-particles.

** Fraction of the kerma factor that comes from the light charged particles: protons, deuterons and alpha-particles.

*** Data from the evaluation of Ref. 8. The total kerma factor is 2.010 ± 0.100 compared with 1.840 ± 0.160 from Ref. 7.

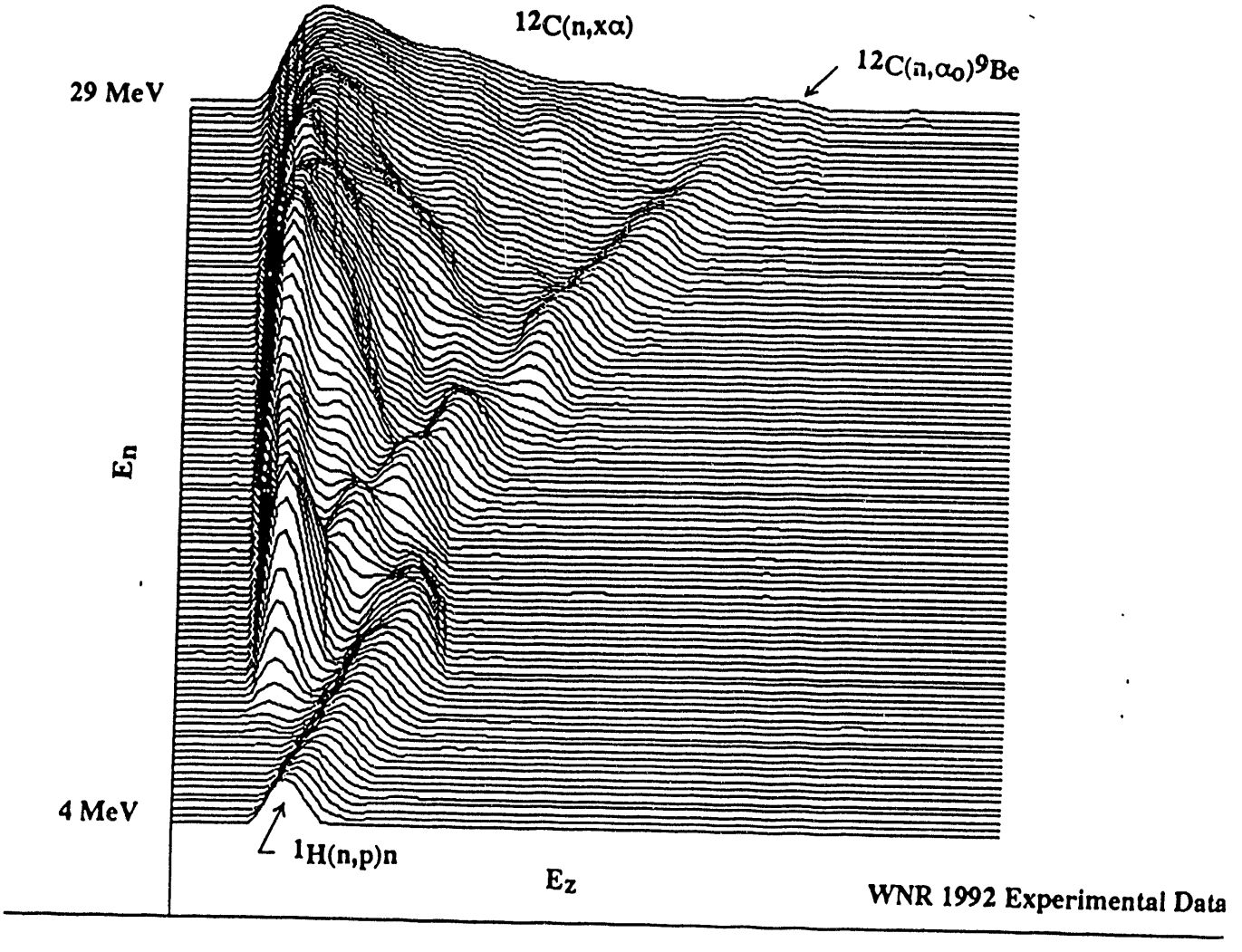

Figure 1 - Spectra of alpha-particles emitted at 30 degrees from carbon bombarded with neutrons up to 30 MeV (from Ref. 12).

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