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Abstract

A newly developed calculational model for nucleus-nucleus collisions has been applied to obtain secondary-neutron spectra from 100-MeV/nucleon alpha particles incident on ^{12}C and from 100-MeV/nucleon ^{12}C incident on ^{12}C. These data can be used in estimating shielding requirements for medium-energy heavy-ion machines. Also included is a comparison between a previous model used only for calculating secondary-particle spectra from alpha-particle nuclear reactions and the new, more general nucleus-nucleus collision model.

I. INTRODUCTION

In a previous paper,[1] an approximate alpha-particle-nucleus-collision model, based on the intranuclear-cascade-evaporation interpretation of nuclear reactions, was presented. Similar calculations to account for nonelastic interactions of high-energy helium nuclei with atomic nuclei have also been made by Barashenkov *et al.*[2] Since then, a calculational method, which is similar in concept to that described in ref. 1 but which has undergone considerable refinement, has been developed to take into account high-energy nucleus-nucleus collisions[3] ($\gtrsim$ 50 MeV/nucleon). Both models rely heavily on the concept that the individual bound nucleons within the projectile can interact independently with the individual bound nucleons of the target, thereby generating a particle cascade within the colliding system. No cluster collisions are at present considered.

The nucleus-nucleus collision model has been used to obtain secondary-neutron spectra from 100-MeV/nucleon alpha particles incident on ^{12}C and from 100-MeV/nucleon ^{12}C incident on ^{12}C. These data can be used in estimating the shielding requirements for medium-energy heavy-ion machines. Also, since two methods are available for calculating secondary-particle spectra from alpha-particle-induced nuclear reactions, it is illuminating to compare the results obtained by both approaches. Since the techniques employed in both models are described in detail elsewhere,[1,3] only the major differences will be discussed here. The discussion of these differences is given in Section II, and the results of the calculations and a comparison of the models are presented in Section III.

II. DISCUSSION

Three major differences in the collision models exist: In the nucleus-nucleus collision model, one difference is the nuclear structure envisioned for the incident alpha particle; secondly, simultaneous intranuclear cascades which can occur in the target and in the projectile as the two nuclei collide are approximately included; and thirdly, the changes in velocity and direction of the projectile following collision are taken into account.

In ref. 1, the nucleons comprising the alpha particle were arranged in a "dumbbell" configuration, i.e., two neutron-proton pairs separated by a fixed distance. The distance between the proton and the neutron in each pair was zero and the separation distance of the pair was set to the root-mean-square alpha radius. The axis of the alpha particle (defined by a line joining the two pairs) was set perpendicular to the axis of the incidence, i.e., parallel to the impact parameter. The relative motion of the nucleons within the alpha particle was not considered and the binding energy of each nucleon was set at 7 MeV. The only justification for describing the alpha particle as above was that within the framework of the model described in ref. 1 it yielded the best results.

In the nucleus-nucleus collision model, the properties of the projectile are obtained in the same way as for the target nucleus. These nuclei (assumed spherical) are made to have density distributions (both neutrons and protons) that approximate the Fermi-type charge-distribution function given by Hofstadter.[4] By using these distributions, the location of each nucleon within the projectile can be determined by standard sampling schemes. The nucleons within the projectile (as well as in the target) are assumed to have energies corresponding to a zero-temperature Fermi-energy distribution

with the momentum components being isotropically distributed. The zero-temperature Fermi energies of the neutrons and protons are determined by the neutron and proton densities at the spatial locations within the nucleus. The minimum energy per nucleon required to free the most loosely bound nucleon is set at 7 MeV. Therefore, by sampling from the appropriate Fermi-energy distribution, the internal energy of each nucleon, as well as its binding energy, can be determined.

To approximately account for the simultaneous particle cascades that occur in both the projectile and target as the two nuclei collide, the projectile with velocity $\bar{V}$ is allowed to impinge upon a stationary target that can remove nucleons from the projectile through nucleon-nucleon collisions. The resulting cascade is allowed to occur only in the target. The projectile with nucleons removed is allowed to proceed with an excitation energy produced by the removal of some of the nucleons. This is called the forward reaction.

To account for the particle cascades in the projectile, the target with velocity $-\bar{V}$ is made to impinge upon a stationary projectile that can remove nucleons from the target through nucleon-nucleon collisions. The cascade is now allowed to occur only in the projectile. When the cascade is completed, the directions and energies of all particles and fragments produced in the collision are transformed back to the original laboratory frame of reference. This case is referred to as the inverse (or backward) reaction. The results from the forward and inverse reactions are then weighted by one-half. In the alpha-particle model described in ref. 1, the inverse reaction is not included.

In the nucleus-nucleus collision model, the remains of the incident projectile following the interaction are allowed to change velocity and direction due to the collision and due to evaporation. This is in contrast to the model in ref. 1 in which the uncollided nucleons in the alpha particle were assumed to emerge with the same velocity and direction as the incident projectile and were not allowed to break up due to the remaining excitation energy. The directional change given to the projectile is that suggested by experimental data.[5] The recoil energy and direction of the target and the recoil energy of the projectile are then determined by conservation of total energy and momentum. Also, a directional change due to Coulomb repulsion is taken into account in an approximate way in the nucleus-nucleus collision model.

III. RESULTS

The secondary-neutron spectra averaged over the angular intervals of 0-15, 15-30, 30-60, 60-120, and 120-180° for 100-MeV/nucleon alpha particles incident on ^{12}C (σ_{nonel} = 0.52 b) and from 100-MeV/nucleon ^{12}C incident on ^{12}C (σ_{nonel} = 0.89 b) are given in Figs. 1 and 2. All data in these figures were generated using the nucleus-nucleus collision model and can be used in estimating the shielding requirements for medium-energy heavy-ion machines. It should be noted that neutrons are emitted with energies greater than the per-nucleon energy of the projectile. This is one advantage of the newer model over the old alpha-particle model in which the maximum possible emission energy was (E - 28)/4, where E is the total energy of the alpha particle.

Comparisons between the old and the new calculated secondary-proton spectra resulting from the interaction of 205-MeV alpha particles on targets of Al and Ag are given in Figs. 3 and 4. Also shown are the experimental data of Bailey.[6] For the forward angles (0-65°) in both figures, the newly calculated data generally fall slightly below the older data, especially in the low-energy regions. For the backward angles (100-180°), the newer data are a factor of ~ 3 too low in the Al case and ~ 5 too low in the Ag case. These differences in the calculated data are partially due to differences in the calculated nonelastic cross sections (for example, σ_{Ag}(old) = 2.57 b and σ_{Ag}(new) = 1.83 b) and to the inclusion of the inverse reaction in the new nucleus-nucleus collision model. For the heavier target considered here, there is a reduction in the number of low-energy particles from the inverse reaction (see Section II). Since both the forward and backward reactions are each weighted by one-half, a factor of ~ 2 in intensity is lost. For heavier projectiles, and especially for projectiles and targets of comparable A number, the above difficulty vanishes.

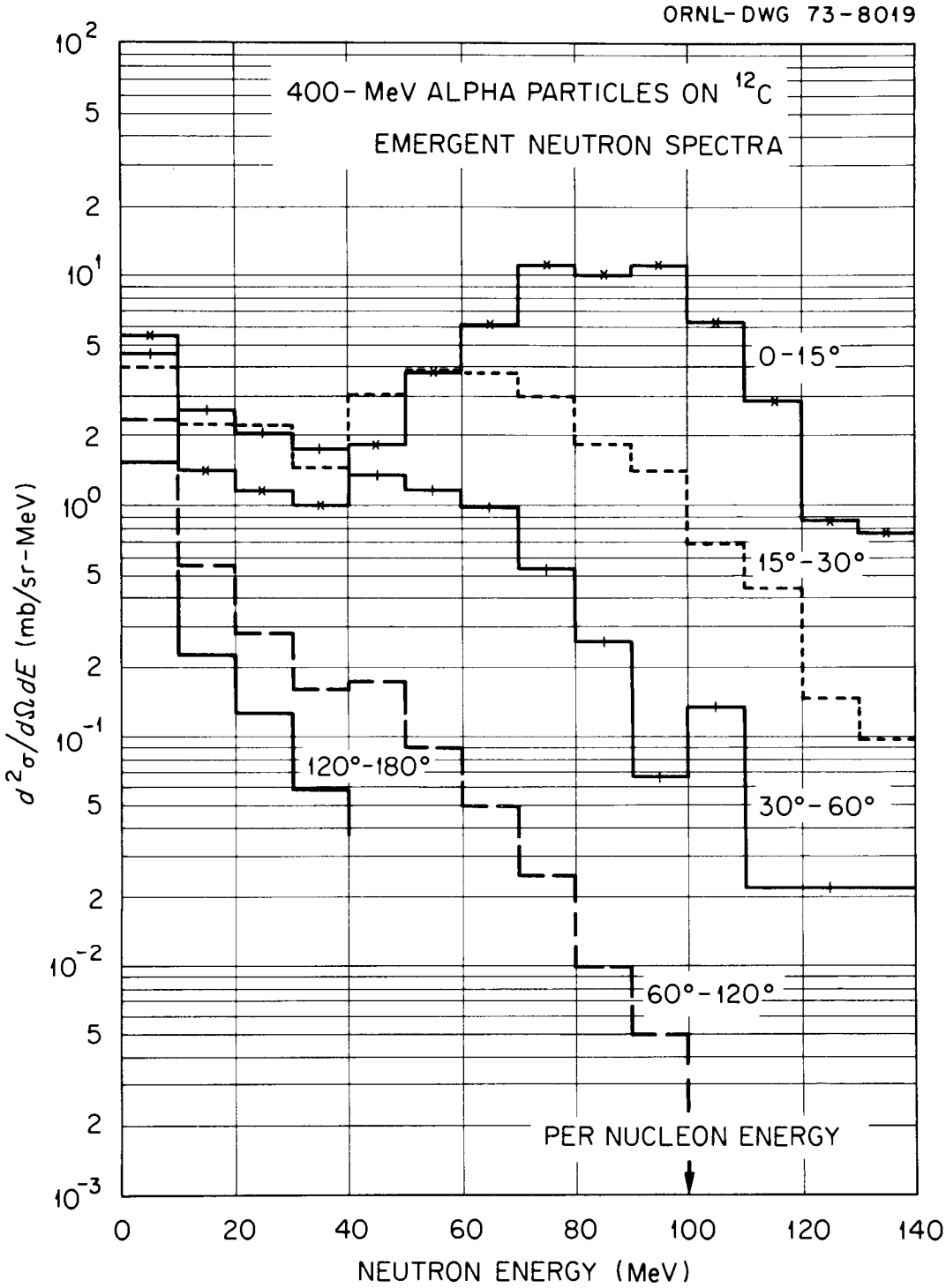

Fig. 1. Neutron energy spectra averaged over the angular intervals of 0-15, 15-30, 30-60, 60-120, and 120-180° from the interaction of 400-MeV alpha particles on ^{12}C.

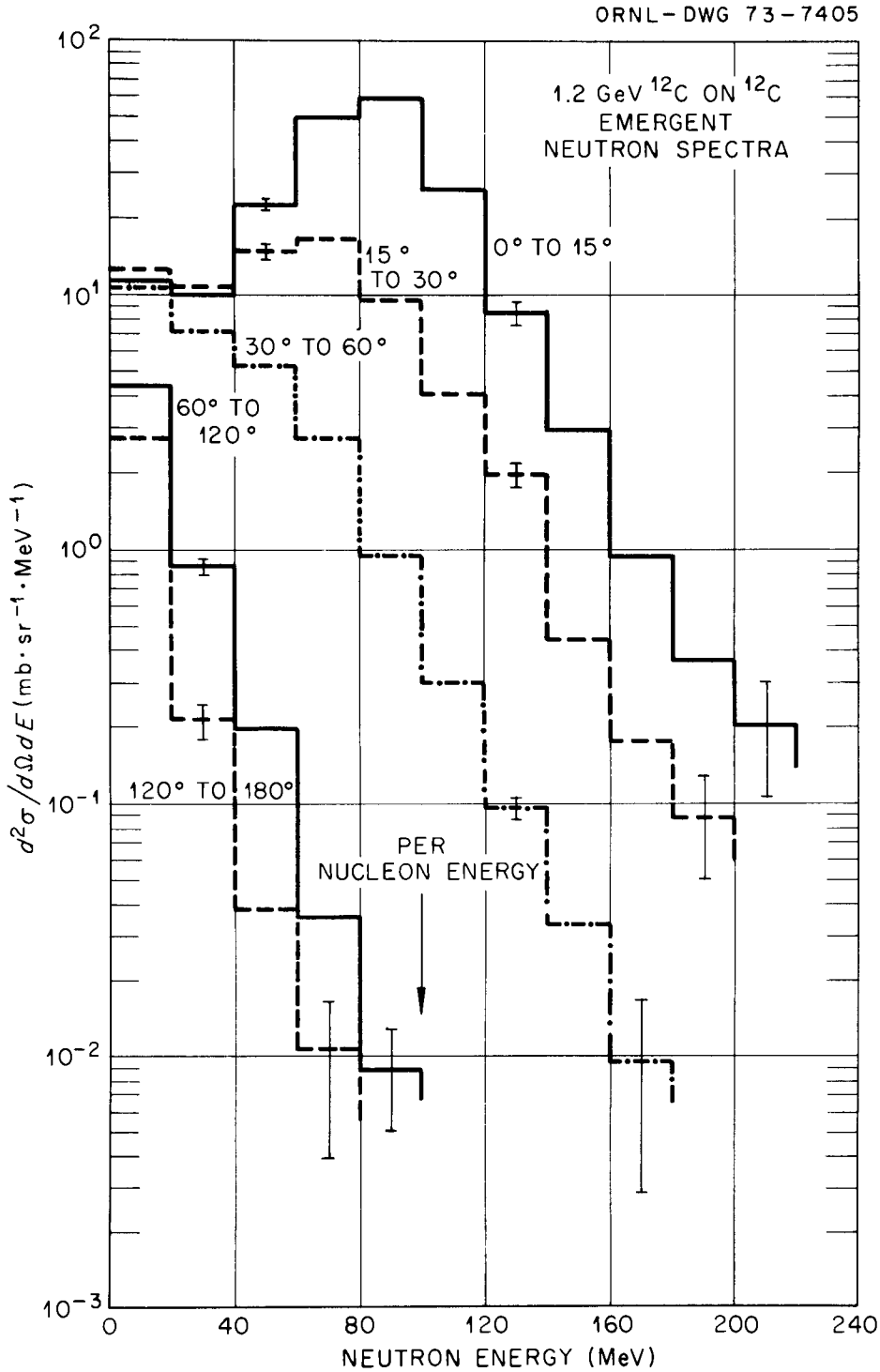

Fig. 2. Neutron energy spectra averaged over the angular intervals of 0-15, 15-30, 30-60, 60-120, and 120-180° from the interaction of 1.2-GeV ^{12}C on ^{12}C.

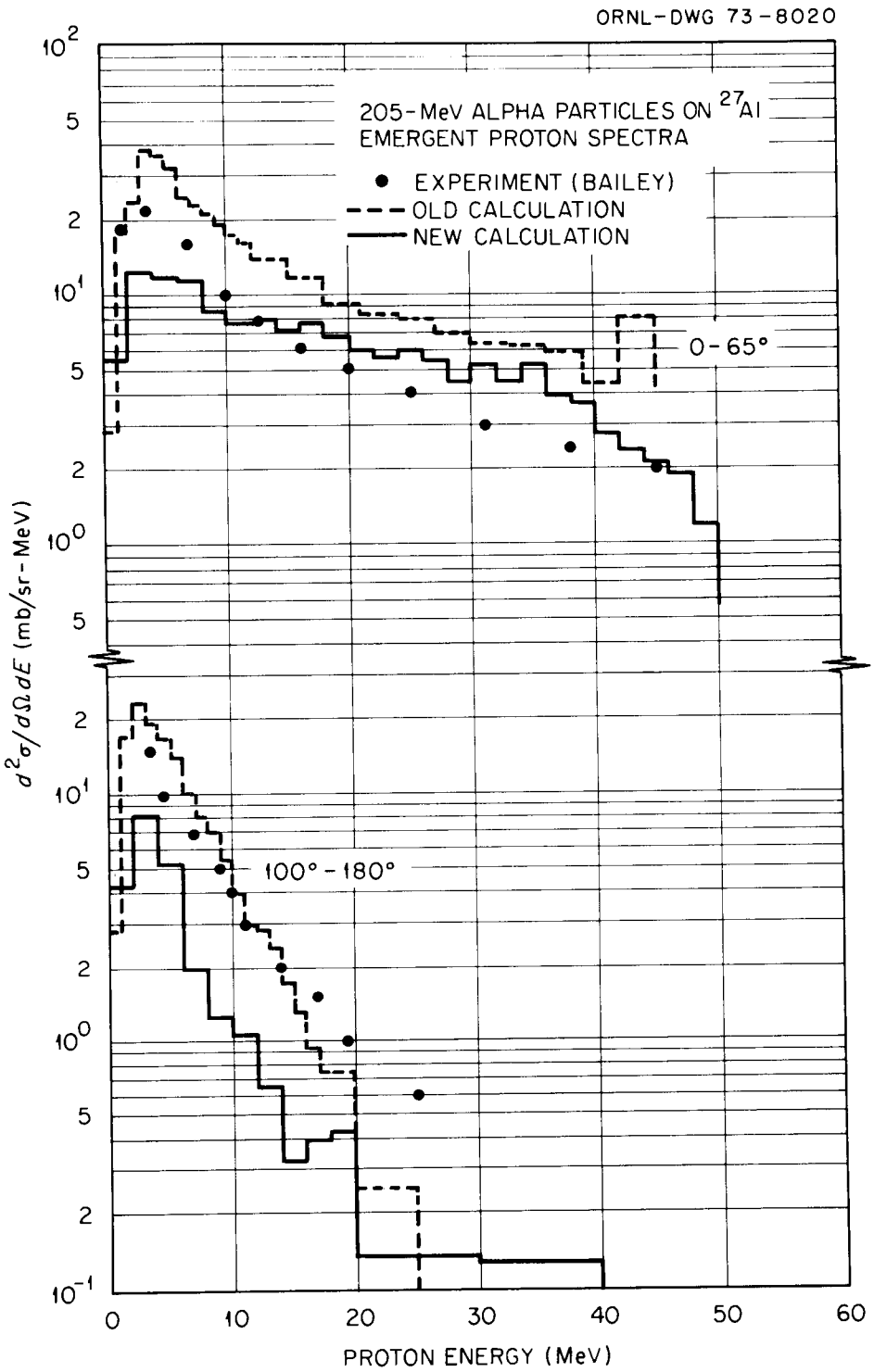

Fig. 3. Energy spectra for emergent protons averaged over the angular intervals of 0-65° and 100-180° from the interaction of 205-MeV alpha particles on ^{27}Al.

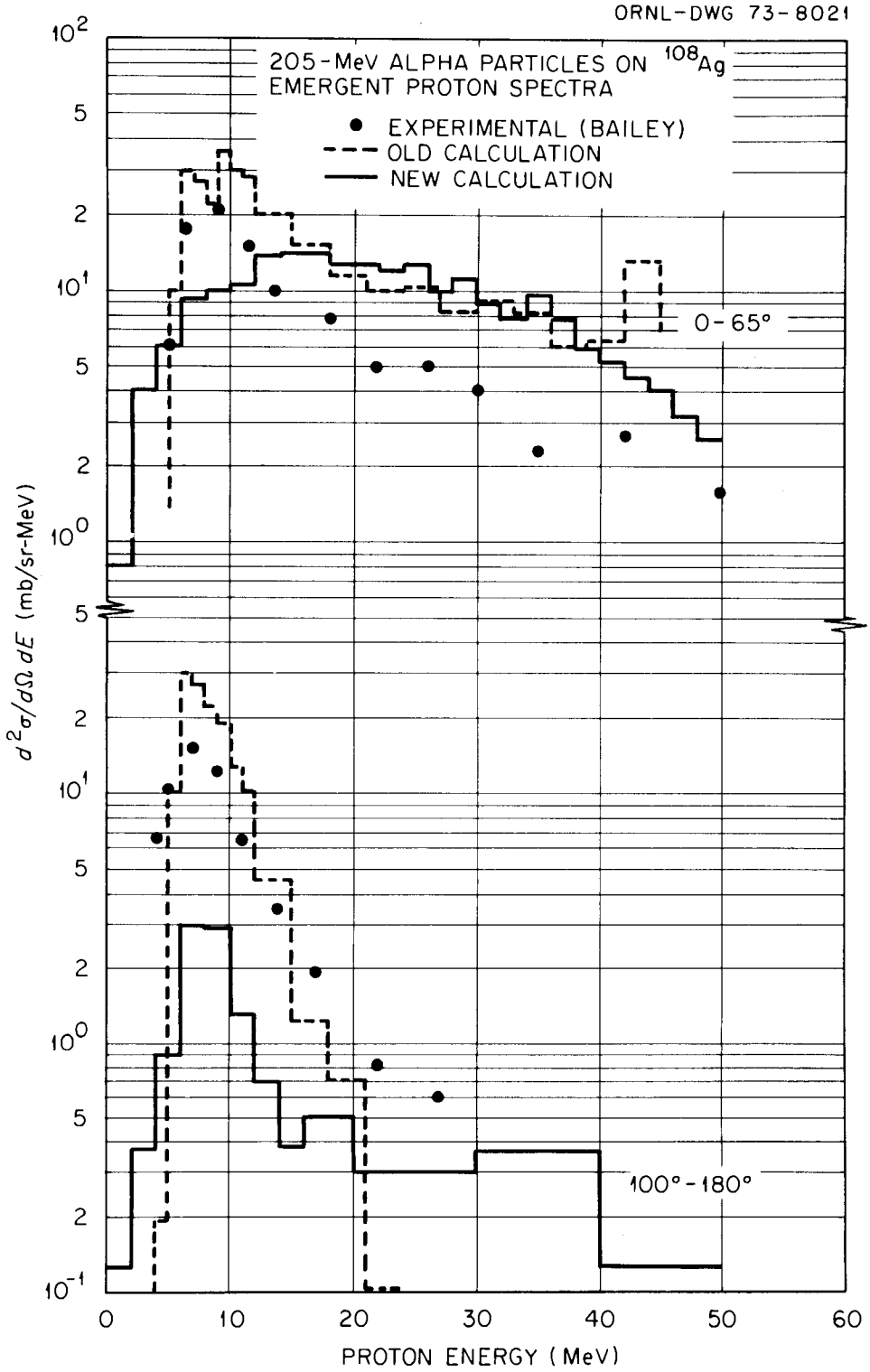

Fig. 4. Energy spectra for emergent protons averaged over the angular intervals of 0-65° and 100-180° from the interaction of 205-MeV alpha particles on ^{108}Ag.

Even though for alpha-particle-induced reactions the new model underestimates rather drastically the low-energy particle-emission spectra in the backward direction, the model still can be applied to shielding calculations dealing with incident alpha particles in situations where the effect of low-energy particles (especially neutrons) emitted in the backward direction are of little importance. However, the problem requirements may determine which model should be utilized in a transport code.

The integrated cross sections for the emission of protons, deuterons, tritons, ^{3}He's, and alpha particles from the α + Al and α + Ag reactions (E_α = 205 MeV), calculated with the old and new collision models, are presented in Table I. The calculated values are compared with the experimental results of Bailey[6] for particle emission into the angular intervals between 0-65° and 100-180° and for the energy intervals given in the table. The calculated cross sections were obtained by integration between these energy limits.

With the exception of emitted alpha particles and protons emitted in backward angles, the comparison between the calculated values from the new collision model and experimental data is in reasonable agreement. The new collision model seems to give a more consistent representation of particle emission for deuterons, tritons, and ^{3}He's. For protons, the new model yields reasonable results in the forward angular interval, but it is not totally adequate for predicting the cross sections for particle emission into backward angles when the reaction is induced by alpha particles. Since elastic collisions between individual nucleons in the target and the incident alpha particles are not included in the calculational models, it is not surprising that the estimation concerning the secondary alpha particles is grossly underestimated.

TABLE I

Integrated Cross Sections for Producing Secondary Particles Resulting from the Interaction of 205-MeV Alpha Particles on Al and Ag

Target	Angular Interval	Collision Model	Protons (3-105 MeV)		Deuterons (1.5-53 MeV)		Tritons (1-140 MeV)		^{3}He's (4-140 MeV)		Alpha Particles (3-105 MeV)	
			Cal.[a]	Exp.[b]	Cal.[a]	Exp.[b]	Cal.[a]	Exp.[b]	Cal.[a]	Exp.[b]	Cal.[a]	Exp.[b]
Al	0-65°	Old	466	277	212	54	79	11.5	72	10.6	27.2	138
		New	322		25.7		7.8		8.7		10.4	
	100-180°	Old	135	94.5	10.2	19.4	1.68	3.66	2.32	1.63	27.2	34.5
		New	37.8		12.8		2.21		4.10		4.4	
Ag	0-65°	Old	527	304	343	36.9	96	10.1	73	8.37	16.2	104
		New	447		46.3		13.6		12.5		1.9	
	100-180°	Old	147	130	9.8	14.8	1.5	4.1	0.14	0.84	16.2	43
		New	31.0		19.5		5.8		4.80		1.6	

a. Lower integration limits are the same as those of Bailey.[6]
b. Values of Bailey.[6]

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