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INTRANUCLEAR CASCADE AND EXCITON MODEL CALCULATION OF 100-MEV α-PARTICLE-INDUCED REACTIONS ON LIGHT NUCLEI*

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Abstract: Theoretical interpretation of fast-charged-particle spectra, observed in the α-particle-induced reactions on the s-d shell nuclei (A = 24-28), in terms of the Intranuclear Cascade Model and the GDH exciton model (ALICE) is presented. The de-excitation of the excited residual nuclei is accounted for by the evaporation process. The theoretically predicted fast-proton and α′ spectral shapes compare reasonably well with the corresponding measured spectra. However, the magnitude depends critically (as expected) on the reaction cross section employed by the model. As a first step to improve the model predictability of the reaction products, a closer look at the calculation of the α-particle reaction cross sections was undertaken. A microscopic approach using the optical theorem of Glauber's theory was employed to estimate the α-induced reaction cross sections for the light target nuclei under consideration. The calculated particle spectra were renormalized as required by the different model reaction cross section predictions for a meaningful comparison with experimental data. Agreement between the experimental data and the Intranuclear Cascade Model predictions for proton and α′ angle-integrated and doubly-differential inclusive spectra is very good. Exciton model predictions limited to the nucleon spectra only, are also in good agreement with the data.

Introduction

In the present work we examine the applicability of two of the reaction mechanisms employed in the intermediate energy region. In particular the α-induced reaction charged particle spectra measured at KFA on light nuclei in the s-d shell region was studied. Initial attempts to interpret the α-induced reaction particle-spectra has met with limited success. Machner[1] attempted to interpret the 100 MeV α-induced gross-energy spectra (angle-integrated) for A = 24 - 28 target nuclei. Most of the prevalent reaction models that attempt to explain the outgoing particle spectra are generally suitable for heavier nuclei, some are applicable at high energies and the others are employed at low-to-medium energies. We have chosen two different reaction models (Intranuclear Cascade and Exciton) in an attempt to interpret the fast charged particle spectra (angle-integrated and doubly-differential) measured with 100 MeV α-induced reactions on ^{24}Mg, ^{25}Mg, ^{26}Mg, ^{27}Al and ^{28}Si. The Intranuclear Cascade Model has been employed[2] to investigate the nucleon spectra measured in proton induced reactions on Aℓ, Zr and Pb at intermediate energies. A sensitive test of the reaction mechanisms to be described below is accomplished by comparing the model predictions for the angle-integrated spectra and doubly-differential particle spectra with the corresponding experimental data. In the present paper, to focus on the reaction mechanism, we confine ourself to the case of proton and α-particle as the outgoing particles.

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Intermediate-Energy Reaction Mechanisms

Intranuclear Cascade and Evaporation Model

Serber[3] in 1947 proposed the idea that the high energy nucleon induced reactions may be described in terms of essentially a two-step model. A similar two-step model is employed for the medium-energy nucleon induced reactions.

At high energies ($E_{proj} \geq 100$ MeV/nucleon) the reaction is assumed to proceed in two steps; 1) fast process, and 2) slow process based on the interaction time scale. In the first step, the incident nuclear interaction develops a series of binary nucleon-nucleon collision cascades with allowance for some particles to escape. At the end of the first step, the residual nucleus deexcites (after immediate equilibration) through statistical evaporation of other nucleons/light ions. In this step, it is tacitly assumed that the residual nucleus is in statistical equilibrium prior to the commencement of the evaporation process. It should be pointed out that the transition from the first step to the second one is abrupt. No time lag or emission of particles is considered before the onset of statistical equilibration process, which supposedly takes place immediately after the end of the cascade process. We will touch upon this point in the last section of this paper.

For the medium-energy (10-50 MeV) nucleon induced reactions, again, a two-step model is assumed. The only difference, being that in the fast process, the incident nucleon interaction takes place with one or very few nucleons, some of which may escape the nucleus. This process is referred to as the direct component of the interaction. The first step in this case is just an extension of the intranuclear cascade process to medium energies.

An alternate approach to the intranuclear cascade was proposed by Griffin[3] in 1966. In Griffin's model the fast particle decay probability of an excited nucleus is calculated during the time-period of interaction that leads to the statistical equilibrium. Griffin's original concept has been employed (with modifications) by various investigators (Harp and Miller,[5] Blann,[6] Kalbach-Kline,[7] Machner,[8] etc.) to interpret the medium energy nucleon induced particle spectra. On the formal side of the theoretical developments, Feshbach, Kerman and Koonin,[9] Tamura and Udagawa,[10] Agassi, Weidenmuller and Montzuranis,[11] have developed different theoretical approaches to interpret the continuum part of the emitted particle spectra. Use of the DWBA calculations is made in the former two approaches.

Serber's model, though originally intended for intermediate–to–high energy nucleon induced reactions, has been extended to light and heavy ions as well as to low–to–medium energy regions, while the exciton models originally developed for the 20–50 MeV region are now being extended to intermediate–to–high energy regions.

Nuclear Model Codes

Intranuclear Cascade Model

The main ingredients of the Intranuclear Cascade Model are the free nucleon–nucleon cross sections that are based on experimental results. The code VEGAS was developed at Brookhaven National Laboratory by Chen, Frankel, Friedlander, Grover, Miller and Shimamuto,[12] and has been discussed extensively in the literature. Monte Carlo techniques are used to simulate the intranuclear interactions. VEGAS was subsequently modified by Mathews, Glagola, Moyle and Viola[13] at IUCF to include the collision pairs p–d, n–d, p–α, d–d, d–α, and α–α with their corresponding cross sections in addition to the collision pairs n–n, n–p, and p–p that are included in VEGAS. The modified version of VEGAS is referred to as CLUST. Both VEGAS and CLUST codes are valid for up to the free NN pion threshold $\leq$ 300 MeV. CLUST code can be used for nucleon, deuteron, and α–particle induced reaction study. The choice of collision partner type (n, p, d, or α) for reactions in which clusters are allowed to exist in the target is determined by random number selection and the relative spectroscopic factors for the target. Since the energy dependent spectroscopic factors were not available, a spectroscopic factor of unity for the α–cluster was used.

In the VEGAS (CLUST) code the nuclear density distribution is approximated by a series of eight concentric shells of constant density which approximate the measured nuclear charge distribution functions. In the cascade model the nucleons are treated as degenerate fermi gas which occupy well defined orbits. It is assumed that the cluster distribution is the same as the nucleon density distribution.

Evaporation Model

At the end of the cascade process described above, the "residual" nucleus after ejecting a few nucleons is in an excited mode which can deexcite via evaporation process. The evaporation code DFF was developed by Dostrovsky, et al.[14] to calculate the process of deexcitation by evaporation by using Monte Carlo method. Relative probability of emission of two particles is based on the statistical theory of a fermi gas model. The step–wise Monte Carlo method has been adopted for following the fate of a given excited nucleus and the average behavior is deduced from an analysis of a large number of cascades. Six particles n, p, d, t, h and α are allowed to be emitted from the excited nucleus.

Exciton Model and Evaporation Model

Several exciton model codes are available for studying precompound emission. One of the most widely used codes is that due to Marshall Blann of Livermore. Blann's code overlaid ALICE,[6] originally valid for 100 MeV/nucleon was extended to higher energy on the BNL VAX Cluster. ALICE code treats the preequilibrium emission only for nucleons. The deexcitation of the equilibrated intermediate nuclei are allowed to emit n, p, d and α particles via evaporation process.

Total Reaction Cross Section

One of the basic ingredients in the estimation of a particular reaction channel cross section is the total reaction cross section, σ_R. In the absence of a reliable experimental σ_R value for the incident projectile, projectile energy and the target, an optical model estimation of the needed reaction cross section would require the experimental elastic cross sections. In order to compare the cascade model and the exciton model predictions on an equal footing with the experimental data, an independent method of estimating the reaction cross section was considered in lieu of a detailed optical model calculation for each target under consideration. The optical limit of Glauber's theory was employed to calculate the total reaction cross section σ_R. The microscopic nucleus–nucleus (and nucleon–nucleus) reaction cross section (σ_R) evaluation makes use of the basic free nucleon–nucleon interaction cross sections. The simple microscopic calculational approach[15,16] has been found to reproduce experimental reaction cross section values for a wide range of projectiles, projectile energy and target mass numbers.

Model Calculations and Comparison with Experiment

In this section we present a comparison of model calculated (α, p) and (α, α') inclusive spectra with the corresponding experimental data. CLUST and DFF calculations for ^{24}Mg, ^{25}Mg, ^{26}Mg, ^{27}Al, and ^{28}Si targets were performed for 30,000 cascades. Standard options were selected for the CLUST part of the calculations. The use of cluster (α–particle) spectroscopic factors was invoked in the present investigation. In addition, reflection and refraction at the nuclear density distribution layers were not considered. Similarly ALICE (Exciton + Evaporation) calculations were performed with default options. The initial exciton number 4 was chosen for all the calculations. Since our aim was to focus on the reaction mechanism for α–particles, no parameter variation was entertained. Both sets of the theoretical model predictions were normalized with respect to the σ_R values based on a formalism[15] which makes use of Glauber's optical limit. Soft–Spheres model of Karol[16] predicted similar σ_R values.

On the experimental side the α–induced inclusive particle spectra show a large continuous part with rather remarkable differences in shape for different particle spectra (see Machner et al.[1]). Machner's exciton model interpretation of the KFA data was limited to angle–integrated data for p, d, t, h, and α'. The (α, p) angle–integrated spectra for the five nuclei under consideration are similar in shape but fall off rapidly with energy. On the other hand, the (α, α') angle–integrated spectra are somewhat flat with respect to α' energy. The yield of high energy α–particles far exceeds that of other particles. The characteristics observed in (α, α') inclusive spectra present a challenge to any model of α–particle reactions.

The following discussion is restricted to ^{24}Mg due to space limitations.

Angle–Integrated Proton Spectra

The CLUST + DFF model, and Exciton + Evaporation model, calculated gross–energy proton spectra are compared with the corresponding KFA data for ^{24}Mg in figure 1. The cascade model and the exciton model predictions bracket the experimental data. The general shape of the spectra are reproduced by both the models. However, the CLUST + DFF calculated results are underestimated in the 30–70 MeV region, whereas the exciton model overpredicts in the same energy region. The first step in CLUST + DFF model prediction represents an average over 10 MeV interval; the predicted sharp rise in the cross section is not obvious in the plot. At the high energy end, the Exciton model prediction falls off rapidly in comparison to the experimental data. while the cascade model predictions extend almost up to 100 MeV.

The underprediction by the Cascade model may be attributed to the use of the α–particle spectroscopic factor of unity. Lowering the spectroscopic factor would increase the magnitude of the (α, p) cross section.

Angle–Integrated α Spectra

Figure 2 presents a comparison of experimental (α, α') inclusive spectra with the model calculated results for ^{24}Mg target. The CLUST + DFF predicted spectra are in excellent agreement with the experimental angle–integrated (α, α') spectra. Noticeable exceptions are in the low and the high energy regions. In the low energy region, use of an energy dependent Coulomb barrier penetrabilities would improve the fit. At the high energy end the excitation of the discrete inelastic states gives rise to rapid fluctuations in the data. In the current version of the cascade model such detailed representation of the target nucleus is not considered.

As can be noticed from figure 2, the exciton model predictions correspond to evaporation process only. The preequilibrium component is not included for deuteron and α–particle channels.

(α, p) Doubly-Differential Proton Spectra

A comparison of the ^{24}Mg model calculated 20°, 30°, 70°, 90° and 110° doubly–differential spectra with the corresponding experimental data are shown in figure 3. The proton spectral shapes predicted by the Intranuclear Cascade model follow the general trend of the experimental data, however theory somewhat underestimates the cross sections for all but the highest angle (110°). As pointed out earlier, some portion of the difference between model calculated and experimental data at a given outgoing particle energy may be attributed to the fact that α–particle spectroscopic factor of one was used in the Intranuclear Cascade calculations. The exciton model predicted doubly–differential spectra are overestimated for all angles except for the smallest angle of 20°.

(α, α') Doubly-Differential Spectra

Figure 4 presents a comparison of CLUST + DFF predictions with experimental data at 20°, 30°, 40°, 50°, 70°, and 110° angles. Quantitative agreement between theory and experiment is achieved both in shape and magnitude, except that the agreement between theory and experiment needs improvement at outgoing α–particle energies beyond 60 MeV for 30° and 50°. The spectral shape of the experimental 110° data appears to be questionable. On the theoretical side inclusion of target discrete–inelastic state excitations in the model would improve the fit at the α'–particle high energy end.

ALICE code does not predict the doubly–differential cross sections for the outgoing α' particles.

Summary and Conclusions

Intranuclear Cascade + Evaporation Model

Intranuclear Cascade + Evaporation model predictions for the 100 MeV α–induced reaction on ^{24}Mg have been compared with experimental proton and α–particle gross–energy spectra and doubly differential cross sections. The CLUST α–particle angle–integrated spectra are in excellent agreement with the corresponding KFA experimental data, whereas the proton spectra are slightly underestimated in the 30–70 MeV region. The low–energy part of the predicted spectra may be improved by including the energy dependent Coulomb penetrabilities. In the case of the (α, α') angle–energy spectra, the agreement between theory and experiment is good for most of the angles considered. Any noticeable discrepancy between theory and experiment may be attributed to the breakup of α–particle and fusion process as well as the target fragmentation. These processes can be accommodated by employing the Cascade + Fermi–Breakup processes[17,18] and the Breakup–Fusion model.[8] The (α, p) doubly differential spectral shapes are reproduced fairly well by the Cascade model, however the model slightly underestimates the cross section in the 30–70 MeV region for most of the angles considered. This problem may be alleviated by reducing the α–particle spectroscopic factor, without disturbing the (α, α') spectral fits between theory and experiment.

It was pointed out earlier that at the end of the cascade process, the onset of the deexcitation of the intermediate excited nuclei is rather too sudden without allowance for gradual equilibration of the nucleus. To alleviate this problem one might consider a three–step model: Cascade + Exciton + Evaporation. The three–step model may easily be extended to nucleon induced reactions, however such an extension to the α–particle induced reactions will be rather involved due to the preformed cluster aspect of the α–particle.

Exciton + Evaporation Model

ALICE predictions agree fairly well with the experimental data in the case of proton angle–integrated and doubly–differential cross sections; the model predictions are somewhat overestimated. ALICE code has limitations with regard to deuteron and α–particle emission spectra. The exciton precompound model is applicable only in the case of nucleon emission.

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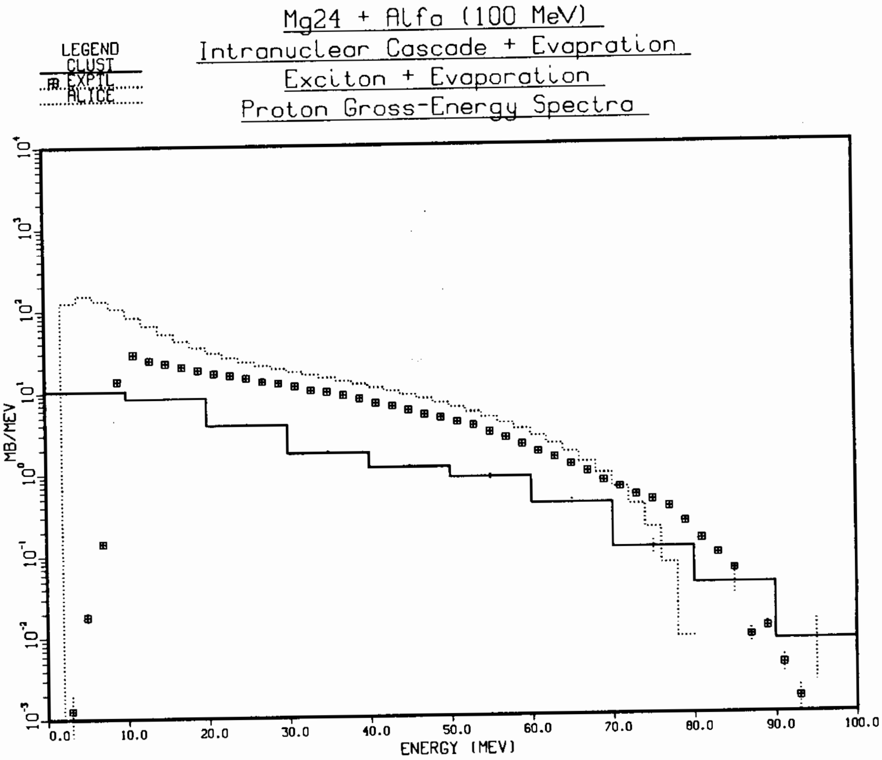
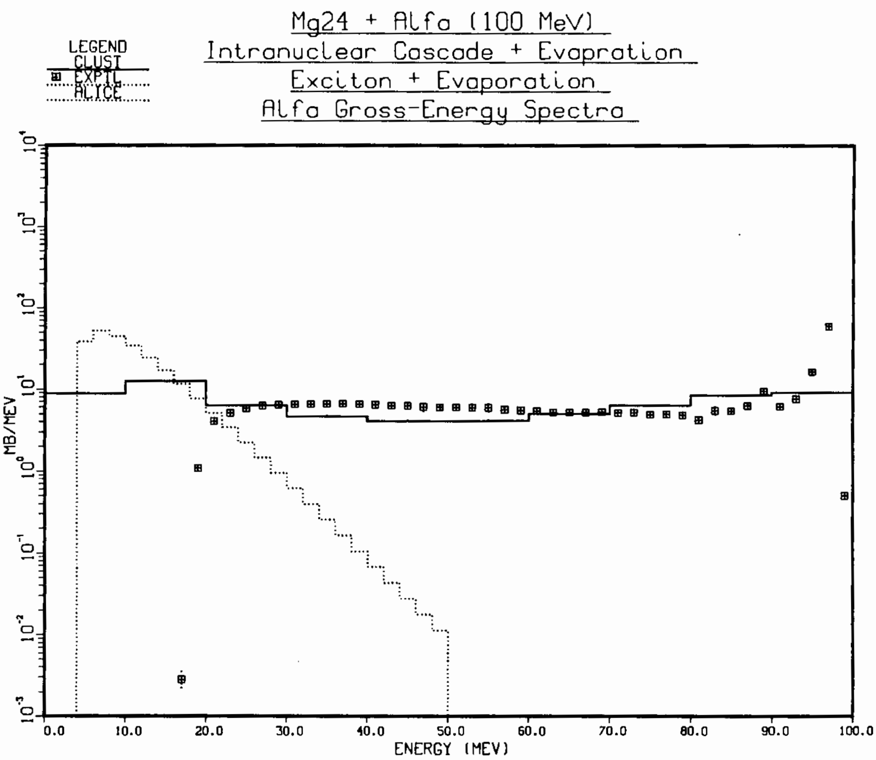
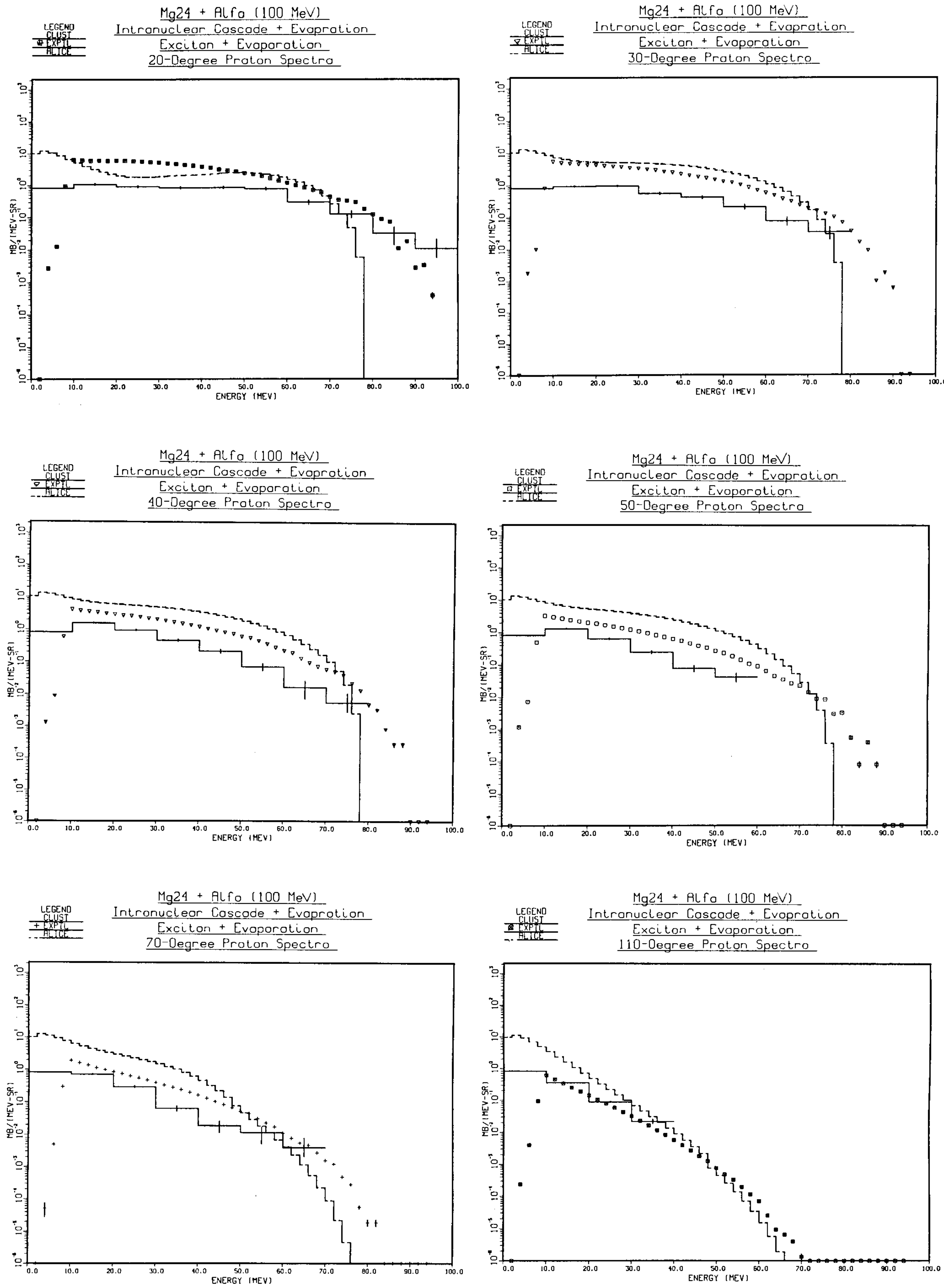


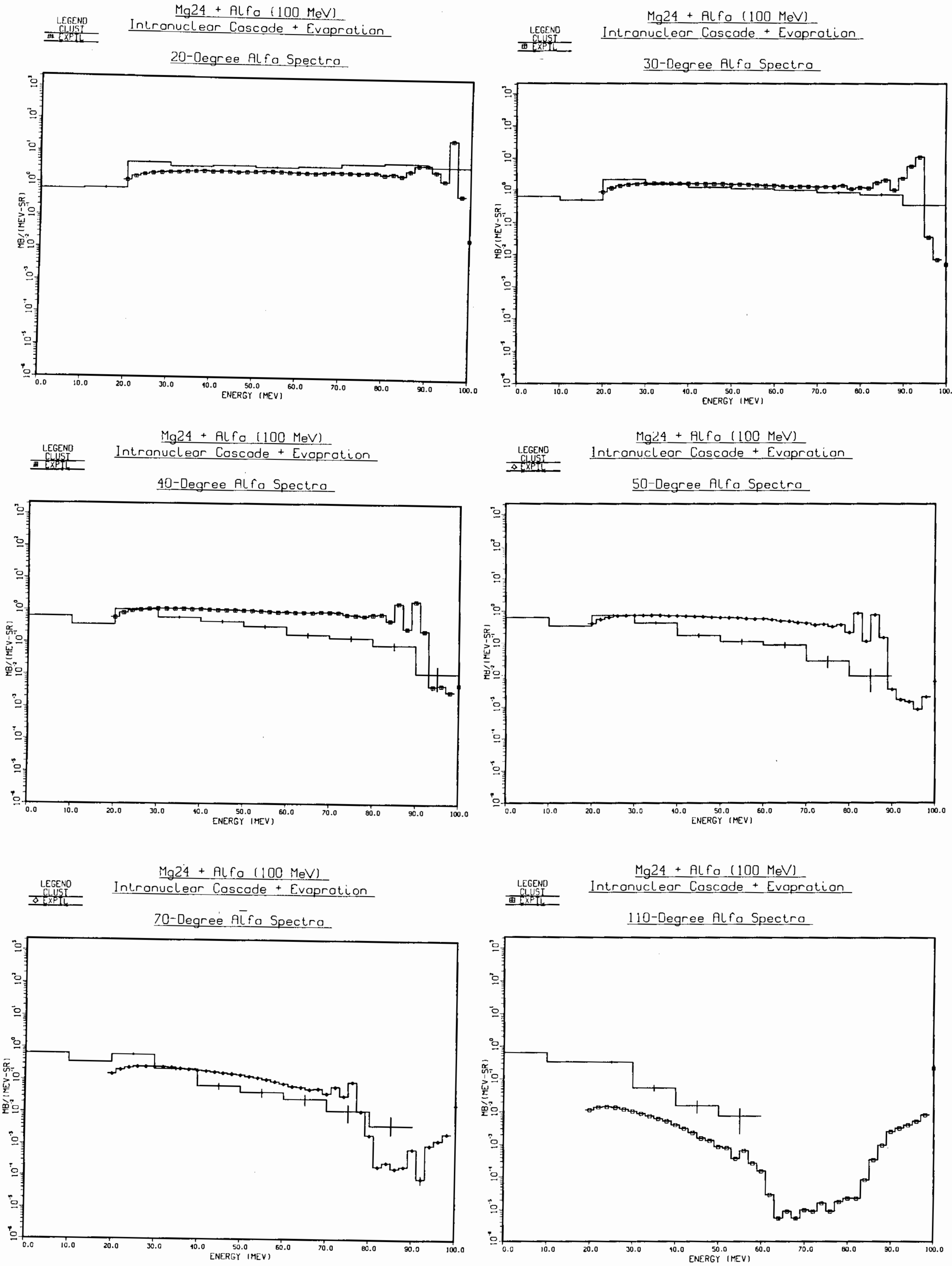
1. Angle–integrated $^{24}Mg(\alpha, p)$ spectra, E_{α} = 100 MeV. Data are from Ref. 1.



2. Angle–integrated $^{24}Mg(\alpha, \alpha')$ spectra, E_{α} = 100 MeV. Data are from Ref. 1.



3. A comparison of model predicted $d^2\sigma/d\theta dE$ for the reaction $^{24}Mg(\alpha, p)$, $E_\alpha = 100$ MeV with experimental data (Ref. 3).



4. Doubly–differential ^{24}Mg(α, α') spectra; a comparison of INC model calculations with KFA data (Ref. 1).