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Abstract :

Inelastic scattering of ^{84}Kr on ^{232}Th has been measured at 371 and 450 MeV incident energies and at different angles using the particle-gamma coincidence technique. It is found that for distances of closest approach smaller than about 20 fm, the scattering of Kr on Th is mostly inelastic. At forward angles, the data are in agreement with predicted values from a Coulomb excitation program, but some differences are observed at backward angles.

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INELASTIC SCATTERING OF ^{84}Kr ON ^{232}Th

In a recent publication 1) we reported results on the scattering of ^{84}Kr from ^{208}Pb and ^{232}Th obtained with quartz track detectors. With these detectors, one is not able to separate the non-elastic processes from the elastic ones ; therefore, besides the elastic scattering, the data also contained the inelastic scattering and some few nucleon transfer reactions. A marked difference observed between Kr + Pb and Kr + Th angular distributions led us to measure the non-elastic processes separately, to see if the difference occurs in the elastic scattering or is rather due to the different amount of non-elastic processes in the cases of Pb and Th, respectively. In the present letter, we report a study of the inelastic processes in the Kr + Th system and their implications on the data of ref. 1.

The high resolution required in this experiment was achieved by measuring the gamma rays in coincidence with the scattered particles. A 47 cm^3 Ge (Li) detector was placed 33 mm from the target, perpendicular to the reaction plane. The particle detectors consisted of a solid state detector used as a monitor, placed at 54° with the beam direction and a moveable large area detector (335 mm^2) at a distance of 48 mm from the target (8° aperture in the reaction plane). Measurements were made below (371 MeV) and just at the Coulomb barrier (450 MeV), using the ^{84}Kr beam of the Orsay Alice accelerator. A 2, 7 mg/cm^2 ^{232}Th target was used in which the loss of energy of Kr ions is about 30 MeV. The energies quoted in this letter are average values.

The random coincidence gamma spectra were measured during the subsequent beam burst of the cyclotron and substracted from the prompt coincidence data. Single gamma and particle spectra were also recorded.

The actual efficiency of the Ge (Li) detector, including the absorption in a 0, 32 mm thick tin foil, has been measured with calibrated sources at the target position with an accuracy of about 10 %.

The absolute values of the number of gamma rays per scattered particle at 450 MeV (the 371 MeV data are only relative values) were obtained by the ratio :

$$N_{\gamma} \; / \; N_{Kr} \; = \; N_{coinc.} \; / \; N_{single}$$

where $N_{coinc.}$ is the number of counts in a gamma ray of the coincidence spectrum, corrected for internal conversion [3] and for the efficiency of the Ge (Li) detector, and N_{single} is the number of Kr ions in the single particle spectrum. Since the Kr peak at backward angles is not well separated from the background, the value N_{single} for 134° has been deduced from the data of ref. 1 for the same distance of closest approach.

A calculation of the particle - γ angular correlation from the Winther-De Boer Coulomb excitation program [4] showed that this correction could be neglected, since the correlation function is similar in our geometrical arrangement for all transitions (anisotropy of less than 20 % at 144°, 371 MeV), and is appreaciably smeared out by the large solid angles of our detectors. Considering the short lifetimes of the states of the nuclei involved in the experiment, the geometrical correction due to the spatial deviation of the origin of gamma emission from the target position (about 0,5 cm for back scattered ^{232}Th) was also neglected.

Fig. 1 shows the coincidence gamma-ray spectra at 450 MeV ; similar spectra were obtained at 371 MeV. Excitation of the ground state rotational band of ^{232}Th dominates the spectra at all angles ; the large probability of exciting high spin states at larger angles is clearly seen. The levels above 12^+ were not known before ; the energies of these transitions are given on fig. 1 with an uncertainty of ± 2 keV. It is interesting to note that the level energies of the ground state band up to 16^+ (18^+) in ^{232}Th, deviate from I (I + 1) rule rather smoothly without any evidence for back-bending in the moment of inertia. Above the energy range shown in fig. 1, weak gamma-lines from other states of Th besides the g. s. band were seen ; the total excitation probability of these states is less than 10 % of the g. s. band excitation. The excitation of the

2^+ (882 keV) state in ^{84}Kr has also been observed.

Fig. 2 shows the number of gamma-rays per scattered Kr ion at 371 MeV (46° and 144°) and 450 MeV (46° and 134°), calculated as described above, for the transitions $I \rightarrow I-2$ (I is the spin of the state).

The data are compared in Fig. 2 with predictions of the Winther-De Boer Coulomb excitation program. Calculations were limited to E2 excitation and included only ten states of the g. s. band (up to 18^+). The B (E2) values were derived from the rotational model assuming B (E2) = 9,21 e^2 b^2 for the $0^+ \rightarrow 2^+$ transition [5]. A good agreement between theory and experiment is obtained at forward angles at both energies. However, discrepancies appear for the 144° (371 MeV) data : the upper levels are less excited than predicted. This deviation is not far outside the limits of error ; calculations with an improved version of the program including E4 excitation [6] were also done in this case, but do not show large differences with the previous one.

The comparison of the (371 MeV, 144°) and (450 MeV, 134°) data shows that the excitation of the highest spins is about the same, and in each case the last transition observed is $18^+ \rightarrow 16^+$; as the 450 MeV results are obtained in the vicinity of the Coulomb barrier, this seems to indicate that the nuclear effects reduce the excitation probability of the high spin states. In this case, the experimental results are appreciably lower than the theoretical curve (which is doubtful because of the limitation in the number of states involved) but a complete Coulomb excitation calculation would certainly lead to the excitation of still higher states, and the discrepancy would remain. This case excepted, the overall agreement between calculation and experimental results is obvious and proves that the dominant interaction between Kr and Th is the electromagnetic one, with large probabilities for Coulomb excitation of ^{232}Th.

The implications of the results of this experiment on the scattering data of ref. 1 are demonstrated in fig. 3 which shows data of these two experiments on a common scale of distance of closest approach. In the lower part of fig. 3, we give the total probability of exciting ^{232}Th to a state 4^+ or higher together with an indication of which of these states gives the strongest contribution. Assuming that the excitation probabilities are determined mainly by the distance of closest approach, the lower part in fig. 3 gives the proportion of inelastic events in the scattering data shown in the upper part. It proves that in nearly the entire angular range $(\theta > 40^\circ)$ the inelastic scattering (a strong 2^+ excitation should be added below 60°) gives the major contribution to measured data, the elastic scattering being confined to very forward angles only. The excitation probability of the 2^+ level (882 keV) of ^{84}Kr is also given in fig. 3 ; it can be seen that the Kr nuclei are also appreciably excited in the major part of the angular range.

We observed previously [1, 2] that the scattering angular distributions of Kr + Pb and Kr + Th both follow roughly the semi-classical form of a Fresnel distribution [7], but with a marked slower fall-off in the Th case. The following explanations can be given, taking into account the very different excitation probabilities of these target nuclei. :

- The pure elastic scattering of Kr on Pb would show a very different angular distribution from the one for Kr on Th, very far from the Fresnel form in this last case. However, if one assumes that Coulomb excitation simply acts to draw the flux out of the elastic channel into the inelastic ones, without changing the trajectories, it is the total cross section rather than the elastic one which should show the classical pattern. This explains the gross structure of the angular distributions for Kr + Th and Kr + Pb which roughly have Fresnel patterns.
- The difference between the two systems is the slower fall-off from Rutherford scattering of the Th angular distribution compared to Pb case ;

as a consequence, the quarter point (angle θ_c where $\sigma/\sigma_R = 1/4$) appears at a larger angle than expected. After necessary corrections for charge and mass change from one system to the other, a shift in θ_c of about 10° is indeed observed. To explain this difference, two effects should be taken into consideration :

i) Rowley [8)] recently included the deformation of Kr and Th in classical calculations and obtained an improved fit to the data in the fall-off region, by averaging Fresnel distributions corresponding to the different relative orientation of the nuclei.

ii) The large angular momentum transfer in the Kr + Th inelastic scattering leads to a change in the trajectory of the scattered particles and a re-distribution of the cross section ; in a classical calculation, a transfer of 16 units of angular momentum at the distance of closest approach would change the grazing trajectory of Kr + Th by about 3.5° to more backward angles, compared with no ℓ-transfer. Therefore, it seems that the ℓ-transfer cannot explain the whole effect but, nevertheless, should be included in the calculations.

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Figure Captions

Fig. 1 : Energy spectra of gamma rays in coincidence with a scattered particle in the moveable detector. The laboratory angle θ is the averaged (weighted with $\sigma_R(\theta)$) value seen by the particle detector. The low energy part of the gamma-spectra is cut by an absorber foil in front of the Ge (Li) detector.

Fig. 2 : Total yield of gamma-rays N_γ for the transition $I \rightarrow I-2$ per scattered Kr-ion to a given laboratory angle θ . The solid line is the theoretical value obtained by the Coulomb excitation program of Winther and DeBoer. Calculations were limited to E2 excitation and to states of the g. s. band up to 18^+. At (371 MeV, 144°), the dashed line gives the result of a calculation including E4 excitation.

Fig. 3 : Upper part : differential cross section of scattering of ^{84}Kr from ^{232}Th at $E_{Lab.}$ = 500 MeV (from ref. 1).
Lower part : total probability of exciting ^{232}Th to a state of the g. s. band with $I \geq 4$ and excitation probability of the 2^+ (882 keV) state of ^{84}Kr as a function of the distance of closest approach ; (common scale with the upper part). The most strongly excited states of Th are given above each experimental point.

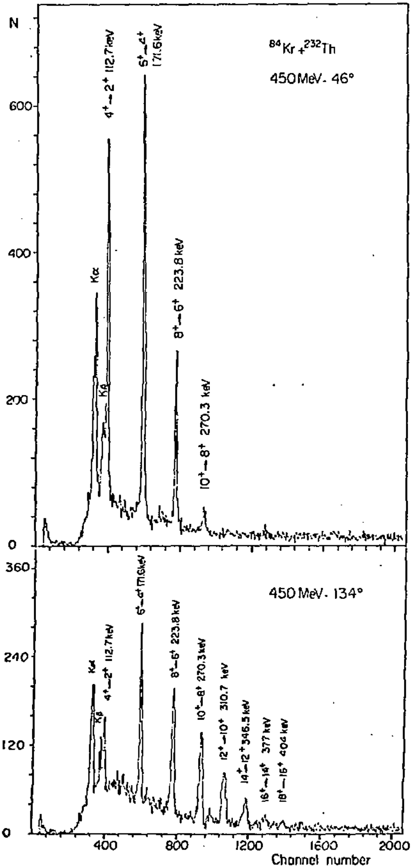
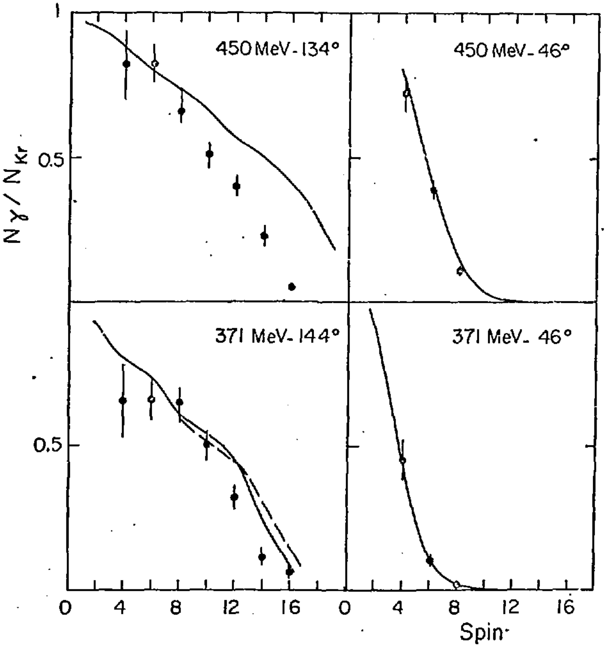

N
600
400
200
0
360
240
120
0
^{84}Kr + ^{232}Th
450 MeV - 46°
Kα
Kβ
4⁺→2⁺ 112.7 keV
6⁺→4⁺ 171.6 keV
8⁺→6⁺ 223.8 keV
10⁺→8⁺ 270.3 keV
450 MeV - 134°
12⁺→10⁺ 310.7 keV
14⁺→12⁺ 346.5 keV
16⁺→14⁺ 377 keV
18⁺→16⁺ 404 keV
400
800
1200
1600
2000
Channel number

Fig. 1



1
0.5
0.5
N_γ / N_{Kr}
450 MeV-134°
450 MeV-46°
371 MeV-144°
371 MeV-46°
0
4
8
12
16
0
4
8
12
16
Spin

Fig. 2

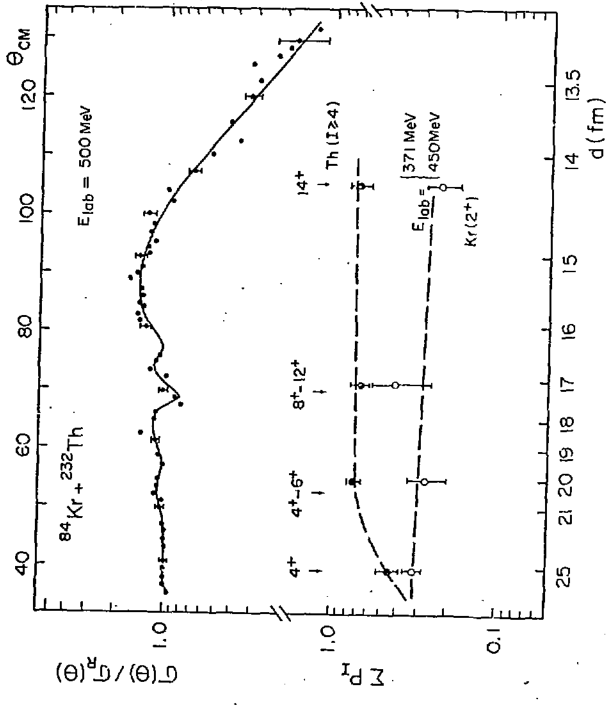

$^{84}Kr + ^{232}Th$
E_{lab} = 500 MeV
Θ_{CM}
40
60
80
100
120
$\sigma(\theta)/\sigma_R(\theta)$
1.0
ΣP_I
1.0
0.1
4+
4+-6+
8+-12+
14+
Th (I≥4)
E_{lab} = 371 MeV
450 MeV
Kr (2+)
d (fm)
25
21
20
19
18
17
16
15
14
13.5

Fig. 3