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Abstract

A method for correcting target-thickness-induced Doppler broadening in γ-ray spectra from weakly populated, very short-lived (femtosecond) states is presented. The method is illustrated by an analysis of superdeformed transitions in ^{152,153}Dy for which the validity of the procedure could be verified consistently from previous lifetime measurements in ^{152}Dy. Furthermore, estimates of the superdeformed lifetimes, previously not measured in ^{153}Dy, are obtained.

A well-known problem commonly encountered with in-beam γ-ray spectroscopy using heavy-ion beams on thin targets is associated with the large Doppler shift and the loss of energy resolution due to Doppler broadening. In the following we will address experiments performed with multidetector Ge arrays in which the individual detectors have many different orientations relative to the beam axis. Doppler broadening of γ-ray lines in these heavy-ion compound-nucleus experiments arises from uncertainty in the angles between the direction of the recoiling nuclei and the direction of the detected γ rays and uncertainty in the velocities of the recoiling nuclei. For thin-target experiments, the main component of this broadening effect normally results from the finite acceptance angles of the γ-ray detectors. However, velocity variations due to energy-loss straggling of the projectiles and of the recoiling nuclei in the target, as well as the emission of evaporated particles, also make significant contributions. The former effect is proportional to $\sin\Theta$, where Θ is the detector angle relative to the beam, and is therefore dominant for $\Theta \approx 90°$. The latter effect depends on the detector angle as $\cos\Theta$ and is thus most important for detector angles close to 0° and 180°. The effect of the target thickness can be reduced by using thin target foils. However, for self-supporting target foils, thicknesses of less than around $300-500\mu g/cm^2$ are normally not practically achievable.

The feeding of the low-spin yrast nuclear states is normally sufficiently slow so that their decay occurs predominantly outside the target (in vacuum) where the recoiling nuclei have a well-defined velocity distribution and the Doppler shift can be corrected for using the average velocity. However, for the study of γ decays of states with very short lifetimes and feeding times, such as for superdeformed (SD) bands, a large portion of the highest spin states may decay while still in the target material. The γ rays from these decays will therefore be emitted from nuclei for which the velocity distribution is changing as a function of the time traveled in the target material. For the SD bands, another complication arises from the relative weakness of the transitions, typically of the order of 2% or less intensity relative to low-lying yrast lines. This means that the gain matching of the Ge detectors, which can only be done with reasonable accuracy using strong low-lying yrast lines in the spectra, does not account for the larger and variable Doppler shifts for the SD lines. This effect may be present as an anomalous broadening or splitting of the SD lines at the highest angular momenta [1] and could be observed to some extent already in the earlier results on SD bands around ^{152}Dy using the first generation large Ge detector arrays but has become much more evident in spectra produced with the higher resolving power of the second generation detector systems; EUROGAM [2], GASP [3] and GAMMASPHERE [4].

We present here a Doppler correction technique for γ decays of weakly populated, short-lived states based on the Doppler-shift attenuation method (DSAM). This procedure can be applied in cases where the transition quadrupole moments Q_t of the states are known (or can be estimated from measurements for a similar configuration in, e.g., a neighboring nucleus). However, a selfconsistency check is provided since the applied Q_t values should give the optimal corrections. Therefore it is also possible, under certain assumptions, to make corrections when the Q_t-values are unknown, in which case a lifetime estimate is also obtained.

In the following, we discuss the details of the method using the example of ^{152,153}Dy [1]. Excited states were populated using the reaction ^{110}Pd(^{48}Ca,xn)^{152,153}Dy, for which a target stack of two isotopically enriched ($\approx$ 98%), self-supporting Pd foils (each $\approx$ 0.5 mg/cm^2) were bombarded at a projectile energy of 220 MeV. The γ rays emitted in the compound-nucleus reactions were detected by the GAMMASPHERE detector array [4] in its Early Implementation configuration, then consisting of 32 large ($\sim$ 78% efficiency) escape-suppressed germanium detectors. Thirty of the detectors were situated symmetrically at backward and forward angles ($17 \leq \Theta \leq 37°$) relative to the beam axis and the remaining two detectors were placed at 90° relative to the beam. Of the order of 10^9 three- and higher-fold events were collected. In addition to five SD bands assigned to ^{153}Dy [1], SD bands belonging to ^{152}Dy [5,6] were also observed in the experiment. In particular the yrast SD band in ^{152}Dy was populated with a strength comparable to the most intense SD band in ^{153}Dy. In this typical thin-target, heavy-ion experiment, the final nuclei recoil out of the target and the majority of the yrast γ decay takes place in vacuum from nuclei with a well-defined velocity distribution. However, due to the very large collective E2 transition strengths ($\sim$ 2000 W.u.), the lifetimes of the SD states are much shorter than those for the low-lying yrast states. The emission of γ rays in the SD bands is so fast that the highest-lying states decay during the slowing down of the nuclei in the target material and these γ rays are thus emitted at a different (higher) velocity distribution than the low-lying, low-spin yrast lines. Since the SD lines are weak, a primary gain matching, correcting for shifts in the spectra due to gain and offset variations in the amplifiers or the analog-to-digital converters, was done using strong low-lying yrast lines from the decay of ^{153}Dy. This gain matching then corrects for the different Doppler shifts of the yrast lines at the different detector angles. However, for the SD lines there remain "residual" Doppler shifts due to their emission while the nuclei are still traveling through the target material. Unless corrected for, this leads to erroneous Doppler adjustments for the highest SD transitions. Due to the relatively large SD transition energies in the A $\approx$ 150 region (normally in the range $E_\gamma \approx 0.5 - 1.5$ MeV) the Doppler effects are large, which can readily lead to errors of several keV.

In order to improve the accuracy of the Doppler corrections for SD transitions, the slowing-down of the recoiling nuclei in the target was modeled using electronic and nuclear stopping powers according to Ziegler et al. [7]. The velocity distribution of the recoiling nuclei was calculated as a function of decay time (including the feeding time) by integrating over the target material, averaging over three different reaction points in each of the two target foils. Since we are dealing with very high-spin states, where the sensitivity of DSAM lies almost completely in the centroid shifts, the lineshapes are not considered in the analysis. Finally, the decay of the recoiling nuclei is modeled assuming a side feeding (applied according to the experimental feeding pattern) consisting of rotational cascades of two transitions with the same Q_t values as for the in-band transitions, yielding velocity distributions as a function of SD transition energy, $v_{SD}(E_\gamma)$. The ratio $\overline{v}_{SD}(E_\gamma)/\overline{v}_f$ (referenced to the average final velocity $\overline{v}_f$ in vacuum outside the target) was used to correct the "residual" Doppler shift of SD lines with energy E_γ. Fig. 1 shows gated spectra for the strongest populated SD band in ^{153}Dy. Only the high-energy part of the band is included to provide sufficient detail. In Fig.

1 **a)** the uncorrected spectrum, without the residual variable Doppler correction, is shown. Figs. 1 **b)** and **c)** show this uncorrected spectrum split according to the main backward and forward detector angles, respectively. The forward-backward residual Doppler shift due to the target-thickness effect on the SD lines is clearly visible. Fig. 1 **d)** shows the total gated spectrum after the energy-dependent residual Doppler correction was applied. After the correction, peaks at the top of the bands that otherwise were split corresponding to the forward and backward detector angles have reverted to the expected resolution and less intense peaks are more visible in the spectra. For instance, for the 1409 keV peak in band 1 the FWHM was reduced from 11.1 keV to 6.2 keV and the improvement was even better for the higher-lying transitions. From the relative shift between the peaks in the spectra of Figs. 1 **b)** and **c)** we can derive the ratio of the average recoil velocity to the maximum velocity as a function of γ-ray energy between the SD and low-lying yrast decays. This is illustrated in Fig. 2 where the $F(\tau)$ values have been extracted for both the ^{152}Dy and ^{153}Dy yrast SD bands. The curves represent values calculated within the simple rotational decay model described above. We find a good agreement ($Q_t = 18 \pm 4eb$) with the transition quadrupole moment values measured previously for the yrast SD band in ^{152}Dy [8]. In the calculated curves for $Q_t = 18eb$ the differences in the experimental feeding patterns between the two bands are taken into account (solid and short-dashed lines). These calculated $F(\tau)$ values were the ones used for the residual Doppler correction.

Concerning the ^{153}Dy band (for which no lifetimes have previously been measured), the experimental $F(\tau)$ values show a slightly different behavior, even though the agreement with the calculated $F(\tau)$ curve for $Q_t = 18eb$ is reasonably good. Although the differences in the experimental feeding patterns between the two bands have been taken into account, this seems only partly to explain the differences in the $F(\tau)$ values. These differences seem to reflect an apparently slightly smaller deformation ($Q_t = 16 \pm 5eb$) or a slower side-feeding for ^{153}Dy. Quite possibly should a more complex feeding mechanism be taken into account in the model calculation. This question is of considerable interest and should be addressed with a full DSAM experiment.

In summary, a technique based on DSAM to correct for target-thickness induced Doppler shifts of very fast γ-ray transitions from (thin-target) heavy-ion reactions is presented. The technique also provides an estimate of the state lifetimes.

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FIGURES

FIG. 1. Coincidence γ-ray spectra for SD band 1 in ^{153}Dy. The spectra were obtained from the sum of all possible combinations of two-fold coincidence gates. In all cases, background contributions have been subtracted. The spectra have been compressed to a dispersion of 1 keV/channel for display purposes. **a)** Total spectrum before variable Doppler correction. **b)** Spectrum where only γ rays registered in backward angles are recorded. **c)** Same as for **b)** but for forward angle detectors. **d)** Total spectrum with the energy-dependent residual Doppler correction applied. The correction is based on the curve calculated for $Q_t = 18eb$ in Fig.2.

FIG. 2. Experimental and calculated $F(\tau)$ values for ^{152}Dy SD band 1 and ^{153}Dy SD band 1. The calculations are based on the simple rotational model described in the text. For $Q_t = 18eb$, the calculated values include corrections for the side feeding according to the experimentally observed intensity patterns of the bands.

Fig.1

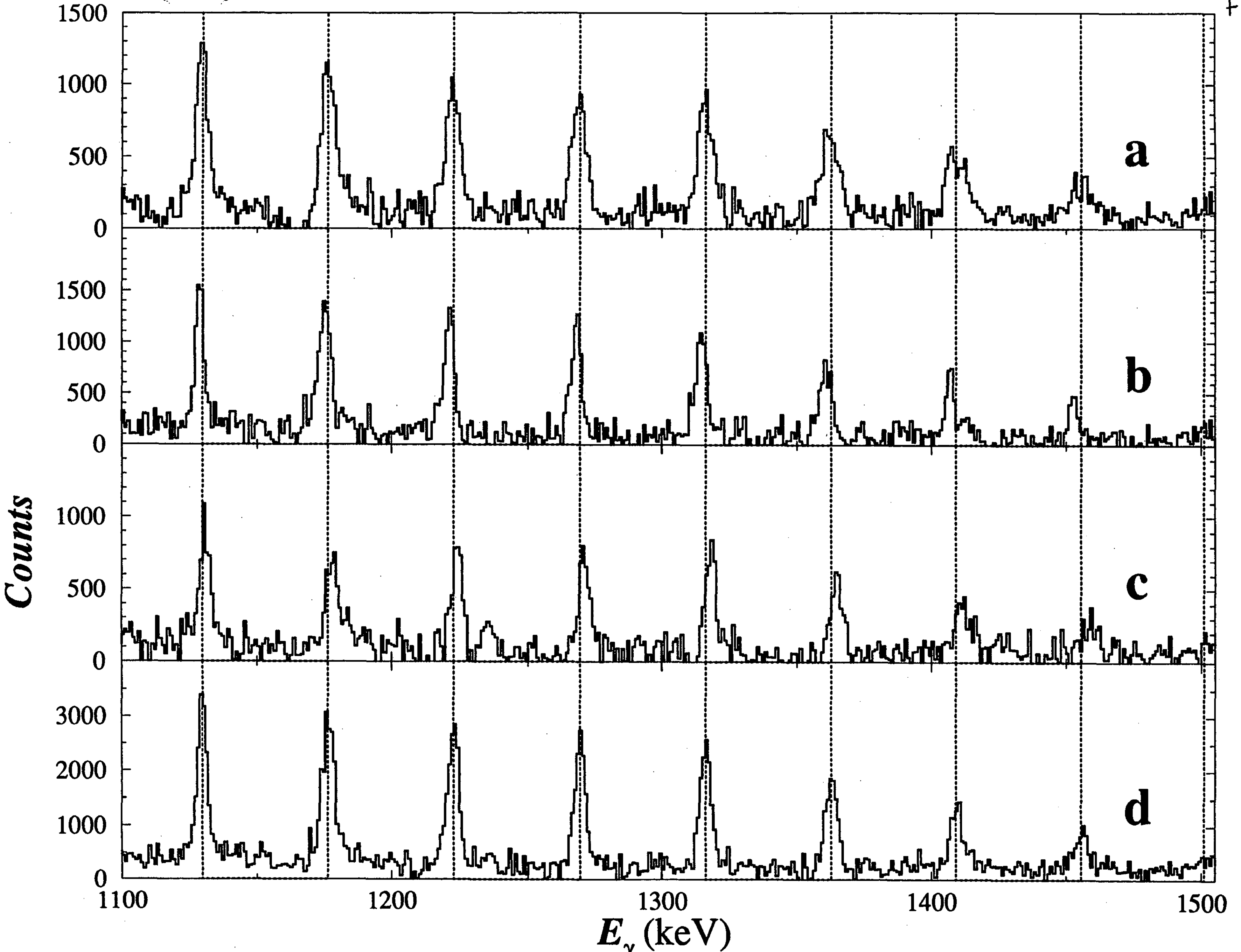
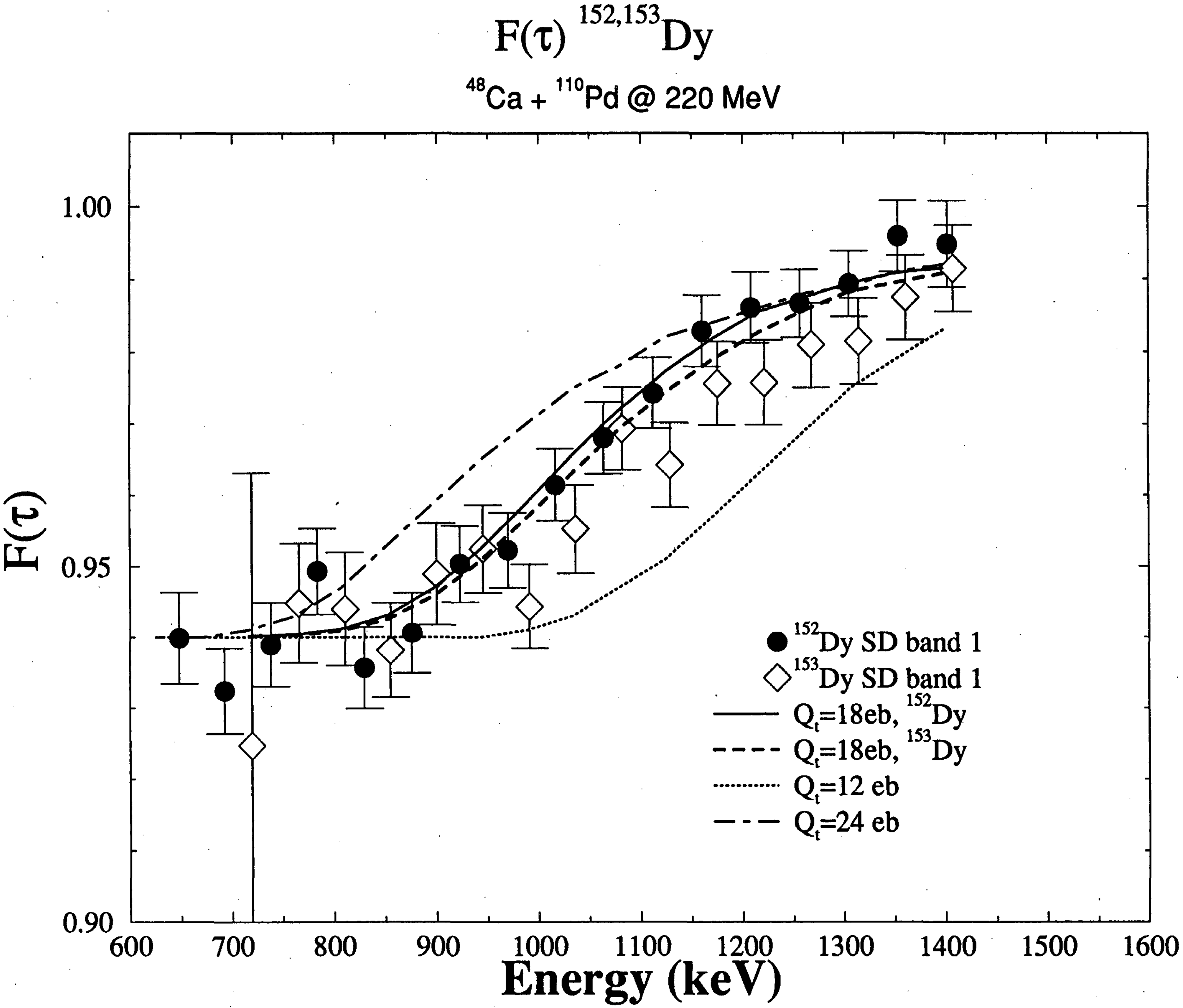

a
b
c
d
Counts
1500
1000
500
0
3000
2000
1100
1200
1300
1400
1500
E_γ (keV)

Fig. 2



F(τ) ^{152,153}Dy
^{48}Ca + ^{110}Pd @ 220 MeV
F(τ)
1.00
0.95
0.90
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
Energy (keV)
● ^{152}Dy SD band 1
◇ ^{153}Dy SD band 1
Q_t=18eb, ^{152}Dy
Q_t=18eb, ^{153}Dy
Q_t=12 eb
Q_t=24 eb

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