PHYSICAL REVIEW C VOLUME 51, NUMBER 5 MAY 1995

No evidence for a 17-keV neutrino in the electron-capture decay of ^{55}Fe

I. Sykora, K. Janko, and P. P. Povinec*

Department of Nuclear Physics, Comenius University, 84215 Bratislava, Slovakia

(Received 10 March 1994; revised manuscript received 31 October 1994)

Internal bremsstrahlung spectrum associated with electron-capture decay of ^{55}Fe was measured using a HPGe detector to search for the presence of a heavy neutrino in the mass range 5–30 keV. A 17-keV neutrino with $\sin^2\theta \leq 0.007$ has been excluded at the 5σ confidence level.

PACS number(s): 23.40.Bw, 14.60.Pq

I. INTRODUCTION

Since 1985 when Simpson [1] reported a distortion in the tritium β-decay spectrum which he interpreted to be the result of emission of a 17-keV neutrino, the possibility that the electron neutrino couples to a 17-keV mass eigenstate with a mixing probability of some percent has been investigated in many experiments. Several results obtained with semiconductor detectors have been interpreted as an evidence of emission of a 17-keV neutrino [2–6]. However, some semiconductor experiments reported negative results [7,8] and in the recent high-precision experiment [9] with a superconducting solenoid focusing β electrons from ^{35}S on a Si(Li) detector no evidence for a heavy neutrino has been found. All results obtained with magnetic spectrometers have been negative [10–15]. Attempts have been made to describe the observed spectrum distortion in semiconductor detectors by screening effects, calibration effects, and by absorption and backscattering of β electrons. A recent comprehensive study of this problem has stressed the role of systematic errors and application of proper statistical criteria in data evaluation [16].

The investigation of internal bremsstrahlung accompanying electron-capture decay (IBEC) has been another approach in the semiconductor sector. The measurement of IBEC spectra eliminates many problems of β spectrometry, as absorption and backscattering of electrons, external bremsstrahlung of electrons, calibration problems, etc., because this technique has the advantage of detecting photons rather than electrons. The first IBEC investigations showed negative results, however, they did not achieve the statistical accuracy of the most accurate β spectrometry experiments and the mass range investigated was too limited [17–19]. Zlimen *et al.* [20] using a ^{71}Ge source reported positive findings for a 17-keV neutrino in the mass range $17.2^{+1.3}_{-1.1}$ keV with $1.6 \pm 0.79\%$ probability at 95% confidence level. However, another group recently excluded these results at a 99% confidence level [21]. A preliminary result obtained with a high-activity ^{55}Fe source suggested neutrino existence in the mass range 21 ± 2 keV [22], however, the final results supported with high statistics data excluded the existence of a 17-keV neutrino [23]. In a very recent experiment Hindi *et al.* [24] using a ^{125}I source excluded a 0.8% admixture of a 17-keV neutrino at the 99.6% confidence level.

These experiments are close to their limits of observability and therefore the question of why some semiconductor experiments have seen kinks in the spectra is still open. While statistical accuracy is of obvious importance, systematic errors and overestimates of a spectrometer's sensitivity are probably even more important.

The aim of the present study was to measure the IBEC spectrum of a low-activity ^{55}Fe source in low background installation, where the role of pileup effects would be negligible, and to rule out detector response function problems with proper detector calibration, spectrum evaluation, and Monte Carlo modeling. Preliminary results were reported in [25].

If we suppose the existence of a heavy neutrino in the EC decay, the observed IBEC spectrum will be a superposition of two spectra given by

$$\frac{dN(k)}{dk} = \frac{dN(k,m_e)}{dk}\cos^2\theta + \frac{dN(k,m_h)}{dk}\sin^2\theta \qquad (1)$$

or in a more suitable form for spectrum evaluation [26]

$$\frac{dN}{dk} \propto \frac{dN(k,m_e=0)}{dk}\left[1+\tan^2\theta\left(1-\frac{m_h^2}{(Q-k)^2}\right)^{1/2}\right], \qquad (2)$$

where k is the photon energy, m_e and m_h are masses of the electron and heavy neutrinos (considering $m_e = 0$), respectively, θ is the mixing angle, and Q is the total decay energy. The fraction of heavy neutrinos is given as $R = \sin^2\theta$. The test of the presence of a heavy neutrino in the EC decay is based on the study of the spectrum shape as given by Eq. (2). The spectrum will have a sharp discontinuity (kink) at $k = Q - m_h$ and the difference in amplitude above and below the kink. The kink can be associated with capture from different initial atomic states but capture from the 1s state is dominant for the investigated mass range (5–30 keV). The IBEC theory has been comprehensively reviewed in [27]. The theoretical spectrum for various values of m_h and R is

---

*Present address: International Atomic Energy Agency, MEL, Monte Carlo, 98012 Monaco.

fitting the experimental data and the lowest χ^2 determines the result. The analysis of experimental data may be influenced by unexpected smooth distortions in the spectrum, therefore various widths of the fitted energy regions and careful evaluation of the detector response function are needed.

II. EXPERIMENTAL PROCEDURES

^{55}Fe decays via EC to the ground state of ^{55}Mn by allowed transition with $Q = 231.7 \pm 0.7$ keV, a probability of IB emission of 3.25×10^{-5} and $T_{1/2} = 2.73$ yr [28]. Two sources of ^{55}Fe of different activities have been used during measurements. The first source, a low activity one, was a 15-yr-old $\sim$ 3-MBq source with small impurities ($\sim 3.4 \times 10^{-2}$ Bq of ^{60}Co and $\sim 1.6 \times 10^{-2}$ Bq of ^{137}Cs). The second source of higher activity ($\sim$110 MBq) was a 3-yr-old ^{55}Fe source with impurities of ^{60}Co ($\sim 4.2 \times 10^{-2}$ Bq) and ^{137}Cs ($\sim 1 \times 10^{-2}$ Bq). Both sources were purchased from Amersham Intern. The ^{55}Fe sources were prepared as pointlike sources by evaporation of dropped radioactive solution on the plastic foil. The source was placed in a holder to keep reproducible conditions during measurements. A HPGe detector (70% relative efficiency, 1.2-keV energy resolution at 200 keV) placed in a low-level background shield [29] has been used for IBEC spectrum measurements. The low background Cu cryostat of the Ge detector with thickness of 1.5 mm sufficiently suppressed the Mn x rays from the ^{55}Fe decays. Silena electronics (Amplifier 7716, ADC 7419) has been used during the measurements. A total of over 200 days of data collection were split in 10-day intervals using a PC-based acquisition system. Background spectra were accumulated between IBEC measurements in 10-day intervals, too. The raw IBEC and background spectra are shown in Fig. 1. After subtracting background and impurity lines, the IBEC spectrum of the low-activity ^{55}Fe source contained 4.1×10^4 counts/keV at 208 keV (the expected place for the most dominant $1s$-capture kink for a 17-keV neutrino) and 7.6×10^7 counts in the 65–231 keV energy interval. The IBEC spectrum of the "high"-activity ^{55}Fe source contained after pileup corrections 8.2×10^5 counts/keV at 208 keV and 1.6×10^9 counts in the 65–231 keV energy interval.

The photon response of the HPGe detector was measured using test sources of ^{241}Am, ^{109}Cd, ^{57}Co, ^{139}Ce, ^{203}Hg, and ^{85}Sr in a similar geometry as the ^{55}Fe sources. The 11-parameter detector response model function consisted of the full energy peak and the Compton continuum. It has been found that the full energy peak is not of pure Gaussian form. While the deformation at higher energies may be neglected, the lower-energy part should be taken into account. The function describing the deformation may be added to the main Gaussian multiplicatively, by convolution or additively [30]. In our case the peak shape function composed from five parts (Gaussian, distortion, step function, background, and Compton continuum) was incorporated into the main Gaussian additively. The Compton response was approximated by a six-parameter function. The response model function fitted the normalized test source experimental spectra and a simple function in energy fitted the energy dependence of the parameters of the response model function. In this way all possible effects on the efficiency and response functions (including absorption of Mn x rays in the detector's cryostat) have been included in calculations.

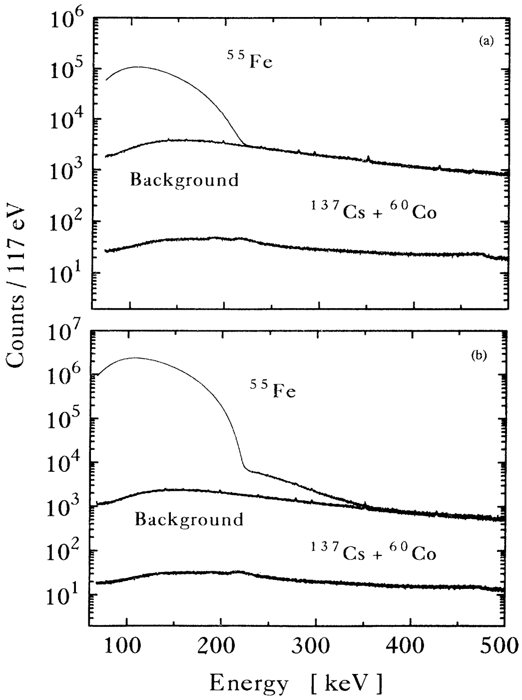

FIG. 1. The raw ^{55}Fe IBEC spectra for low- (top) and "high"- (bottom) activity sources with background and impurity spectra.

For verification of the detector response in the investigated energy region a Monte Carlo model of the photon response of the detector based on the GEANT code [31] has been developed. A very good agreement between the response determined by both methods has been found. The detector full energy peak efficiency was measured by a set of calibration γ-ray sources and a semiempirical six-parameter function [32] fitted the experimental data well.

As the IBEC spectra were investigated in the 170–230 keV energy region, it was sufficient to consider the detector response in the energy interval given by the full energy and 50% of the energy distance between the full energy peak and the Compton edge (the 50% region). The probability that photons will be registrated in this 50% region $[e_{50}(k)]$ is given by a shape of the detector response function and it was determined using test sources. This approach was necessary because we used theoretical IBEC spectra convoluted not only by pure Gaussian, but by the whole response function. A comparison of the full energy peak area with the 50% region shows that the rest of the area (i.e., the area of the 50% region without the full energy peak area) is not negligible.

A pileup rejection has been used only with the "high"-activity source. The IBEC spectrum obtained with the "high"-activity source was corrected for residual pile-up effects using the IBEC spectrum measured in the same geometry as the low-activity source.

III. RESULTS

The theoretical IBEC spectrum was calculated on the basis of the theory developed by Martin and Glauber [33,34] and Inteman [35] for $1s$,$2s$ states and De Rujula [36] for $2p, 3s$ states. The IBEC associated with the capture of s initial states is given by

$$\frac{dN_{ns}(k,m)}{dk} \propto k(Q-B_{ns}-k)\sqrt{(Q-B_{ns}-k)^2-(mc^2)^2}R_{ns}(k) \tag{3}$$

and p initial states by

$$\frac{dN_{np}(k,m)}{dk} \propto k(Q-B_{np}-k)\sqrt{(Q-B_{np}-k)^2-(mc^2)^2 P_{np}^2(k)}\ . \tag{4}$$

B_{ns} and B_{np} are binding energies of the s and p states, m is the mass of neutrino, and $R_{ns}(k)$ and $P_{np}(k)$ are correction factors for relativistic and Coulomb effects. The IBEC spectra have been calculated for $1s$, $2s$, $2p$, and $3p$ transitions. Contributions from different atomic shells have been corrected for screening effects, too [27]. A two-decay-channel mode as given by Eq. (1) has been assumed in the calculations. The decay spectrum (calculated for $1s$, $2s$, $2p$, and $3p$) multiplied by the efficiency function $e_{50}(k)$ and convoluted with the detector response function $ResF(a_1(k),\dots,a_{11}(k),k)$ was compared with experimental data in different energy intervals. This instrumental spectrum dN_{instr}/dk, with respect to $e_{50}(k)$ and $ResF$ is valid from 170 keV. The energy interval (170$-Q$) (keV), i.e., approximately 510 degrees of freedom (DOF) allows one to obtain optimum results corresponding to given statistics. The χ^2 minimalization procedure

$$\chi^2 = \sum_{0}^{N} \frac{(N^i_{\mathrm{instr}} - N^i_{\mathrm{expt}})^2}{(\sigma^i_{\mathrm{expt}})^2} \tag{5}$$

has been applied in two different ways looking for a minimum value: (a) for the four free parameters: A (a pulse height normalization factor), Q, m_h, and R; and (b) for the given values of m_h and R (over the physically acceptable space, m_h from 5–30 keV, R from 0–4%) and two free parameters A and Q.

Figure 2 shows the ratio of the experimental data (compressed to 1.17-keV bins) to the theoretical fit. The solid line represents the ratio of the theoretical prediction obtained with $m_h = 17$ keV and a mixing fraction $R = 0.7\%$ to that obtained with $m_h = 0$. It can be seen that there is a significant deviation of the experimental data from the theoretical prediction.

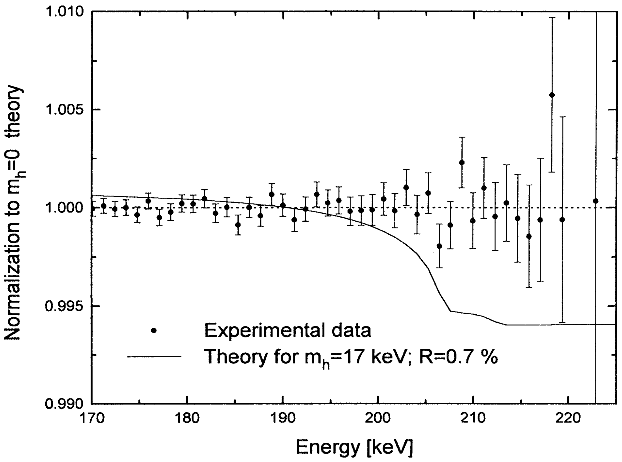

FIG. 2. The experimental data normalized to the theoretical spectrum for $m_h = 0$. The solid line represents the ratio of the theoretical prediction obtained with $m_h = 17$ keV and $R = 0.7\%$ normalized to that obtained with $m_h = 0$. The experimental data are compressed to 1.17-keV bins (sum of 10 channels).

To check the sensitivity of the method of analysis a Monte Carlo program was developed to generate data sets according to the experimental arrangement. Figure 3(a) shows χ^2 contours of the fit to Monte Carlo data with a 17-keV neutrino and 1% mixing. The χ^2 analysis gives in the energy range 170–230 keV the minimum χ^2 value ($\chi^2 = 519.8$ units/510 DOF) for the neutrino mass $m_h = 17.1 \pm 0.8$ keV and $R = 1.05 \pm 0.22\%$ at 68.3% C.L. (1σ). The Monte Carlo data generated for $m_h = 0$ [Fig. 3(b)] ($\chi^2 = 513.4$ units/510 DOF) excluded a 17-keV heavy neutrino for $R > 0.7\%$ at 99.9997% C.L. (4.7σ).

The experimental data, similarly as synthetic data, were analyzed in different energy regions for m_h from 5 to 30 keV to eliminate an unexpected smooth distortion [Fig. 3(c)]. The obtained results show that the difference between the null and a 17-keV neutrino with 0.7% mixing is 24.4 units, i.e., a 17-keV neutrino with 0.7% mixing is excluded at 99.9997% C.L.(4.7σ). The best fit in the energy region 200–220 keV (Fig. 4) with $\chi^2 = 156.2$ units (for 168 DOF) is of 6.7 units below the fit with a 17-keV neutrino and 0.7% mixing, i.e., the null hypothesis excludes a 17-keV neutrino at 96.5% C.L. (2.1σ). The end-point energy (Q) has been assumed in all fits as a free parameter, because the experimental data define different Q for $m_h = 0$ and for the two-neutrino decay mode. For the best fit ($R = 0$) we have found $Q = 231.0 \pm 0.1$ keV.

For the spectrum calculated with photopeak response function and pure Gaussian shape a value of χ^2/DOF was acceptable only for short energy intervals of experimental (and Monte Carlo) data. A combination of pure Gaussian convolution with the polynomial

$$P_3 = a_0 + a_1 k + a_2 k^2 + a_3 k^3 \tag{6}$$

gives acceptable χ^2/DOF on short intervals, but we could

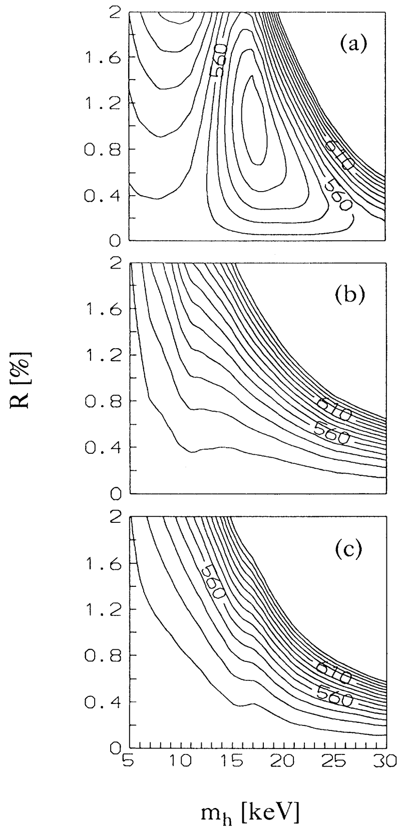

FIG. 3. χ^2 contours of fits of Monte Carlo generated data sets with $m_h = 17$ keV, $R = 1\%$ (a), $m_h = 0$, $R = 0$ (b), and experimental data (c) in the energy region 170–230 keV (510 DOF).

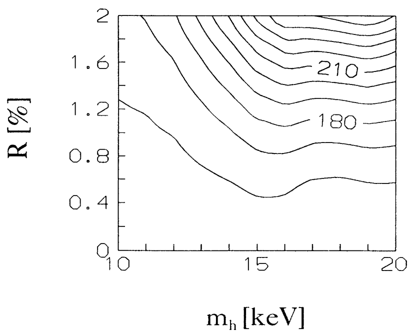

FIG. 4. χ^2 contours of fits of experimental data in the energy region 200–220 keV.

not use it on the long interval (170–230 keV) because this polynomial has appeared not to be flexible enough (χ^2/DOF$\gg$1 has been obtained).

IV. CONCLUSIONS

The presented analysis of continuous IBEC spectra is based on the careful experimental evaluation of detector response (verified by Monte Carlo calculations) and the efficiency function in the energy region satisfying the data analysis interval (170–230 keV). The decay energy Q as a free parameter reduces the influence of an uncertainty in the tabulated Q value (±0.7 keV [27]). The analysis is very sensitive to the precise evaluation of the detector response function. An incorrect shape or an insufficient approximation of the response function may considerably influence the results. An incorrect response function may cause distortions interpretable as the presence of a heavy neutrino at a significant confidence level. For example, for Monte Carlo generated data with real shape of *ResF* ($m_h = 0$ keV, $R = 0\%$ and of total counting rate $\sim 10^8$ in the energy interval 65–231 keV) and analyzed using the FEP convoluted spectrum, a 17-keV neutrino with mixing ratio $R = 2\%$ may be found at 4σ C.L. The magnitude of R depends on shape differences between the used approximation and the real *ResF*. A fit in a wide energy interval may be influenced by an unexpected smooth distortion. Therefore data analysis in different energy intervals is needed. The results obtained for shorter intervals (at lower confidence levels) and the possibility of fitting the wide energy interval (170–230 keV, i.e., 510 DOF) without other corrections have been found essential for the proper data evaluation.

The analysis of experimental data showed no evidence of a kink or other distortion, and obtained results did not confirm any heavy neutrino in the 5–30 keV energy interval. The presented result gives the lowest limit on the emission probability in the widest mass range as obtained from IBEC measurements. The effects reported previously and interpreted incorrectly to be due to a 17-keV neutrino are not in fact caused by a massive neutrino but by a nonproper use of detector response functions. It is very probable that detector response functions will also play a dominant role in other experiments. Reported distortions in spectrum shapes might be due to a nonproper evaluation of spectra.

---

[1] J. J. Simpson, Phys. Rev. Lett. **54**, 1891 (1985).
[2] J. J. Simpson and A. Hime, Phys. Rev. D **39**, 1825 (1989).
[3] A. Hime and J. J. Simpson, Phys. Rev. D **39**, 1837 (1989).
[4] A. Hime and N. Jelly, Phys. Lett. B **257**, 441 (1991).
[5] B. Sur, E. B. Norman, K. T. Lesko, M. M. Hindi, R. M. Larimer, P. N. Luke, W. L. Hansen, and E. E. Haller, Phys. Rev. Lett. **66**, 2444 (1991).
[6] A. Hime and N. Jelly, Oxford University Report No. OUNP-91-21, 1991.
[7] T. Ohi, M. Nakajima, H. Tamura, T. Matsuzaki, T. Yamazaki, O. Hashimoto, and R. S. Hayano, Phys. Lett. **160B**, 322 (1985).
[8] V. M. Datar, C. V. K. Baba, S. K. Bhatacherjee, C. R. Bhuinya, and A. Roy, Nature (London) **318**, 547 (1985).

[9] J. L. Mortara, I. Ahmad, K. P. Coulter, S. J. Freedman, B. K. Fujikawa, J. P. Greene, J. P. Schiffer, W. H. Trzaska, and A. R. Zueli, Phys. Rev. Lett. **70**, 394 (1993).

[10] T. Altzitzoglou, F. Calaprice, M. Dewey, M. Lowry, L. Piilonen, J. Brorson, S. Hagen, and F. Loeser, Phys. Rev. Lett. **55**, 799 (1985).

[11] A. M. Apalikov, S. D. Boris, A. I. Golutvin, L. P. Laptin, V. A. Lyubomov, N. F. Myeasoedov, U. V. Nagovitsyn, E. G. Novikov, V. Z. Nozik, V. A. Suloshchenku, I. N. Tikhomirov, and E. F. Tretyakov, Pis'ma Zh. Eksp. Teor. Fiz. **42**, 233 (1985) [JETP Lett. **42**, 289 (1985)].

[12] J. Markey and F. Boehm, Phys. Rev. C **32**, 2215 (1985).

[13] D. W. Hetherington, R. L. Graham, M. A. Lone, J. S. Geiger, and G. E. Lee-Whiting, Phys. Rev. C **36**, 1504 (1987).

[14] H. Kawakami, S. Kato, T. Oshima, C. Rosenfeld, H. Sakamoto, T. Sato, S. Shibata, J. Shirai, Y. Sugaya, T. Susuki, K. Takahashi, T. Tsukamoto, K. Ueno, K. Ukai, S. Wilson, and Y. Yonozawa, Phys. Lett. B **287**, 45 (1992).

[15] M. Chen, D. A. Imel, T. J. Radcliffe, H. Henrikson, and F. Boehm, Phys. Rev. Lett. **69**, 3151 (1992).

[16] G. Bonvicini, Z. Phys. A **345**, 97 (1993).

[17] M. J. G. Borge, A. De Rujula, P. G. Hansen, B. Johnson, G. Nyman, H. L. Rawn, and K. Riisager, Phys. Scr. **34**, 591 (1986).

[18] I. Zlimen, S. Kaucic, A. Ljubicic, and B. A. Logan, Phys. Scr. **38**, 539 (1988).

[19] I. Zlimen, A. Ljubicic, S. Kaucic, and B. A. Logan, Fizika **22**, 423 (1990).

[20] I. Zlimen, A. Ljubicic, S. Kaucic, and B. A. Logan, Phys. Rev. Lett. **67**, 560 (1991).

[21] D. E. DiGregorio, S. Gil, H. Huck, E. R. Batista, A. M. J. Ferrero, and A. O. Gattone, Phys. Rev. C **47**, 2916 (1993).

[22] E. B. Norman, B. Sur, K. T. Lesko, M. M. Hindi, R. M. Larimer, T. R. Ho, J. T. Witort, P. N. Luke, W. L. Hansen, and E. E. Haller, J. Phys. G **17**, S291 (1991).

[23] F. E. Wietfeldt, Y. D. Chan. M. T. F. da Cruz, A. Garcia, R. M. Larimer, K. T. Lesko, E. B. Norman, R. G. Stokstad, and I. Zlimen, Phys. Rev. Lett. **70**, 1759 (1993).

[24] M. M. Hindi, R. L. Kozub, and S. J. Robinson, Phys. Rev. C **49**, 3289 (1994).

[25] I. Sykora, K. Janko, J. Stanicek, and P. Povinec, *Verhandlung. der Duetsch. Phys. Gesellschaft* (DPG, Salzburg, 1992), p. 89.

[26] A. Hime, Mod. Phys. Lett. A **7** 1301 (1992).

[27] W. Bambinek, H. Behrens, M. H. Chen, B. Crasemann, M. L. Fitzpatrick, K. W. D. Ledingham, H. Genz, M. Mutterer, and R. L. Intemann, Rev. Mod. Phys. **49**, 77 (1977).

[28] E. Browne and R. B. Firestone, *Table of Radioactive Isotopes* (Wiley, New York, 1986).

[29] I. Sykora, M. Durcik, J. Stanicek, and P. Povinec, in *Rare Nuclear Processes,* edited by P. Povinec (World Scientific, Singapore, 1992), p. 321.

[30] H. H. Jorch and J. L. Campbell, Nucl. Instrum. Methods **143**, 551 (1977).

[31] GEANT *User's Guide* (CERN, Geneva, 1992).

[32] F. Hajnal and C. Klusek, Nucl. Instrum. Methods. **122**, 559 (1974).

[33] R. J. Glauber and P. C. Martin, Phys. Rev. **104**, 158 (1956).

[34] P. C. Martin and R. J. Glauber, Phys. Rev. **109**, 1307 (1958).

[35] R. L. Intemann, Phys. Rev. C **3**, 1 (1971).

[36] A. De Rujula, Nucl. Phys. **B188**, 414 (1981).