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《**Original**》

A Potential Application of Ge(Li) Detectors in Fast Neutron Leakage Spectrum Determination

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Abstract

In the paper it is proposed to use Ge(Li) detectors in determining fast neutron spectra. The spectrum at 691.4 KeV which is produced by the internal conversion of Ge nuclei being broadened by the coincident ionization energy deposited by recoil Ge atoms is proposed to be analysed in estimating the fast neutron spectra.

요 약

이 논문은 Ge(Li)를 이용하여 고속 중성자 에너지 스펙트럼을 재는데 사용하는 방법을 제시한다. Ge^{72}의 고속 중성자의 비탄성 충돌에 의한 691.4 KeV에서의 스펙트럼을 분석함으로써 고속 중성자의 에너지 스펙트럼을 측정할 수 있는 방법을 가질 수 있음을 시사한다.

1. Introduction

In most experiments using high energy resolution lithium drifted germanium detectors for gamma-ray measurements in the presence of fast neutrons, two spectral lines undergo broadening, which is not observed in the pure gamma-ray fields or applications involving thermal neutron activation. These two spectral lines are at 595 KeV and 691.4 KeV, and are well broadened on the high energy side compared with any other photopeaks. In particular the peak at 691.4 KeV shows broadening of almost 100 KeV (FWHM is less than 4 KeV), so much that it could be referred to as a "spectrum" rather than as a "peak"[1,2,3,4].

The spectrum at 691.4 KeV is produced by the internal conversion of Ge^{72} nuclei excited by inelastic scattering events with the neutrons incident on the Ge(Li) detector. Internal conversion is an alternative mode of deexcitation which always competes with gamma-ray emission if the nuclear excitation energy is small and the angular momentum change is large[5]. This deexitation energy is accompanied by the ionization energy deposited by recoiling germanium atoms, which broadens the peak at 691.4 KeV. This paper discusses the potential utilization of this spectrum at 691.4 KeV in the measurement of fast neutron leakage spectra out of systems. Decoding of this observed spectrum could be possible to estimate the fast neutron spectrum.

2. Theory

When a Ge(Li) detector is exposed to fast neutrons, inelastic scattering events will occur and the Ge^{72} nuclei will recoil to conserve momentum. The electronic excitation will be produced by the recoiling Ge atoms and the peak of 691.4 KeV will shift upward when the deexcitation of the excited state is coincident in time (typically 20 μsec) with the slowing down of the recoiling Ge atoms (approximately 0.3 μsec). Actually the spectrum at 691.4 KeV will be produced by summation of hole-electron pairs in the Ge crystal by the 691.4 KeV internal conversion transition and the recoiling Ge atom.

Let $\phi(E, \underline{\Omega})$ be the steady-state angular neutron flux at energy E in the direction of $\underline{\Omega}$. Since the detector usually is far away from the source in comparison with the size of Ge crystal, the flux is assumed to be independent of the angular direction and monodirectional. The number of Ge recoils per unit time arriving in the solid angle $d\Omega'$ at $\underline{\Omega}'$, $dN(\underline{\Omega}')$ is:

$$dN(\underline{\Omega}')=Nd\Omega'\int_E \frac{\partial\sigma(E,\underline{\Omega}')}{\partial\Omega'}\ \phi(E)\ dE \quad (1)$$

where $\frac{\partial\sigma}{\partial\Omega'}$ is the differential scattering cross section, and N is the total number of Ge^{72} nuclei in the detector. In case of monodirectional neutrons, $\underline{\Omega}'$ simply denotes the cosine of the angle between the original neutron direction and the germanium nucleus recoil direction. Consequently one can transform from the variable $\underline{\Omega}'$ to the final state germanium nucleus recoil energy E'. Hence the number of germanium nuclei per unit time arriving in a final state energy interval dE' at E' becomes:

$$dN(E')=N\ dE'\int P(E\rightarrow E')\ \phi(E)\ dE \quad (2)$$

where $P(E\rightarrow E')dE'$ is defined as the probability that a germanium nucleus is recoiled with an energy between E' and $E'+dE'$ when the nucleus is struck by a neutron of energy E. Or the energy spectrum of the recoiled germanium nuclei is presented by:

$$I_R(E')=N\int P(E\rightarrow E')\ \phi(E)\ dE \quad (3)$$

For the particular value $E'=E_i'$:

$$I_R(E_i')=N\int_{E_{min}}^{E_{max}} P(E\rightarrow E_i')\ \phi(E)dE \quad (4)$$

Assuming the neutron fluxes are constant within small energy intervals ΔE_j, it is:

$$I_R(E_i')=N\sum_j C_{ij}\ \phi_j \quad (5)$$

$$\text{where}\quad C_{ij}=\int_{\Delta E_j} P(E\rightarrow E_i')\ dE \quad (6)$$

It should be noticed that $P(E\rightarrow E')$ only exists within the energy interval of:

$$\alpha_1 E\leq E'\leq\alpha_2 E \quad (7)$$

where $\alpha_1=A\left(\frac{D-1}{A+1}\right)^2$,

$\alpha_2=A\left(\frac{D+1}{A+1}\right)^2$, and

$D=\sqrt{1+\frac{A+1}{A}\ \frac{Q}{E}}$

Hence $E_{max}=\frac{E'}{\alpha'}$ and (8)

$$E_{min}=\frac{E'}{\alpha_2} \quad (9)$$

Finally, equation 4 becomes in the matrix form:

$$[I_R]=N[C][\phi] \quad (10)$$

where $[I_R]=\mathrm{Col}\{I_R(E_1),\ I_R(E_2)\cdots,\ I_R(E_M)\}$

$$[C]=\begin{pmatrix} C_{11} & C_{12} & C_{13}\cdots\cdots\cdots\cdots C_{1M} \\ C_{21} & C_{22} & C_{23}\cdots\cdots\cdots\cdots C_{2M} \\ C_{M1} & C_{M2} & C_{M3}\ \cdots\cdots\cdots C_{MM} \end{pmatrix}$$

$$[\phi]=\mathrm{Col}\{\phi_1,\ \phi_2,\ \cdots\cdots\cdots\cdots\cdots\phi_M\}$$

3. Recoiling Kernel $P(E\rightarrow E')$

By applying the conservation of mass-energy and of linear momentum to the collision between a neutron of unit mass and a nucleus of mass A, a relationship between the neutron energy before and after the collision and the recoiling angle can be derived:

$$\frac{E'}{E}=\frac{A}{(A+1)^2}[D^2+1-2D\mu] \qquad (11)$$

where $\mu=\cos\theta$; θ is the scattering angle in the C-system.

Meanwhile the recoiling kernel is:

$$P(E\rightarrow E')=\frac{d\sigma}{d\Omega'}\ \frac{\partial\Omega'}{\partial E'} \qquad (12)$$

or

$$P(E\rightarrow E')=-\frac{2\pi\sigma(E,\theta)}{\sigma(E)}\ \frac{d\mu}{dE'} \qquad (13)$$

where $d\Omega=-2\pi d\mu$

$\sigma(E)=\int_{4\pi}\sigma(E,\theta)\ d\Omega$, and

$\sigma(E,\theta)$ is the differential recoiling cross-section of the germanium nucleus

From equations 11 and 12,

$$P(E\rightarrow E')=\begin{cases}\frac{\pi(A+1)^2}{\mathrm{DAE}}\ \frac{\sigma(E,\theta)}{\sigma(E)}; & \alpha_1 E\leq E'\leq\alpha_2 E \\ 0 & ;\text{otherwise}\end{cases} \qquad (14)$$

For isotropic recoil within the C-system, the recoiling kernel becomes:

$$P(E\rightarrow E')=\begin{cases}\frac{(\mathrm{A}+1)^2}{\mathrm{ADE}};\alpha_1 E\leq E'\leq\alpha_2 E \\ 0 \qquad ;\text{otherwise}\end{cases} \qquad (15)$$

This classical collision theory is good near the threshold energy. As the energy of the incident neutrons increases, the anisotropic effect migh be corrected.

4. Applications Using a Standard CF-252 Source

As shown in the previous sections, with a known recoiling kernel the incident neutron energy spectrum can be estimated using broadening of the 691.4 KeV spectrum of Ge(Li) detectors. The utilization of Ge(Li) detectors in determining the neutron energy spectra is a great advantage in addition to its applications in photo-peak analyses. A great deal of development is expected.

For simplicity, with a very thin Ge crystal in the detector, if it is assumed that $P(E\rightarrow E')$ only have a significant value at and around E' ($\theta=0$ in the C-system), the C_{ij} of equation 6 can be given:

$$C_{ij}=\begin{cases}\int_{E_j'/\alpha 2}^{E_j'/\alpha 1} P(E\rightarrow E')dE;i=j \\ 0 \qquad ;i\neq j\end{cases} \qquad (16)$$

Hence, the $[C]$ matrix can be presented as a diagonal matrix:

$$[C]=\mathrm{dia}\{C_{11}, C_{22}, \cdots\cdots\cdots\cdots, C_{MM}\} \qquad (17)$$

This response diagonal matrix can be corrected by utilizing a standard Cf-252 source as follows:

$$[C]=[C]_M[\lambda]^T \qquad (18)$$

where, $[C]_M$ is the measured response matrix using a Cf-252 source, the elements of $[\lambda]^T$ are ϕ_{Mi}/ϕ_{Si}, and ϕ_{Mi} and ϕ_{Si} are the elements of measured and standard flux column vectors of Cf-252, respectively.

This corrected response diagonal matrix will enable one to cover a fairly good estimate of incident neutron spectrum without a great deal of distortion.

It is very important to have an exact neutron spectrum available as a reference. In Cf-252 spontaneous fission, the neutrons have the typical shape of fission neutron spectra.

$$\phi(E)\sim\sqrt{E}\quad \exp\left(-\frac{E}{T_c}\right) \qquad (19)$$

where $T_c=1.39$ MeV[6,7,8,9,10].

The Cf-252 neutron source has the most probable energy of 700 KeV and the average number of neutrons emitted per fission is 3.77. The use of a Cf-252 source is recommended to correct the response function of the detector.

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