Radiation Physics and Chemistry (2015) 175–183

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem

Radiation shielding effectiveness of newly developed superconductors

Vishwanath P. Singh [a,b,*], M.E. Medhat [c,d,**], N.M. Badiger [a], Abu Zayed Mohammad Saliqur Rahman [d]

[a] Department of Physics, Karnatak University, Dharwad 580003, India
[b] Health Physics Section, Kaiga Atomic Power Station-3&4, NPCIL, Karwar 581400, India
[c] Experimental Nuclear Physics Department, Nuclear Research Centre, P.O. 13759, Cairo, Egypt
[d] Institute of High Energy Physics, CAS, Beijing 100049, China

HIGHLIGHTS

- Radiation shielding properties of superconductors were investigated.
- μ/ρ, mean free path, and exposure buildup factor were calculated.
- $CaPtSi_3$, $CaIrSi_3$, and $Bi_2Sr_2Ca_1Cu_2O_{8.2}$ were found superior for γ-ray shielding.
- $Tl_{0.6}Rb_{0.4}Fe_{1.67}Se_2$ was found superior for fast neutron shielding.

ARTICLE INFO

Article history:
Received 22 February 2014
Accepted 21 July 2014
Available online 30 July 2014

Keywords:
G-P fitting
Geant4
Buildup
Shielding
Superconductors

ABSTRACT

Gamma ray shielding effectiveness of superconductors with a high mass density has been investigated. We calculated the mass attenuation coefficients, the mean free path (mfp) and the exposure buildup factor (EBF). The gamma ray EBF was computed using the Geometric Progression (G-P) fitting method at energies 0.015–15 MeV, and for penetration depths up to 40 mfp. The fast-neutron shielding effectiveness has been characterized by the effective neutron removal cross-section of the superconductors. It is shown that $CaPtSi_3$, $CaIrSi_3$, and $Bi_2Sr_2Ca_1Cu_2O_{8.2}$ are superior shielding materials for gamma rays and $Tl_{0.6}Rb_{0.4}Fe_{1.67}Se_2$ for fast neutrons. The present work should be useful in various applications of superconductors in fusion engineering and design.

1. Introduction

Superconductor materials are very much attractive in condensed matter physics with potential applications in various fields like trains, electricity, accelerators, astrophysics, electronics, energy efficient savers, magnetic resonance imaging scanners, nuclear power stations, magnetic confinement fusion reactors (e.g. tokamaks), beam-steering and focusing magnets in particle accelerators, particle detectors, magnetic shielding, superconducting coils, satellites etc. Some of these devices are made of superconducting materials which may be exposed of wide energy range of photons and neutrons as in the case of nuclear reactors and satellites. The high temperature superconductor materials are being used as shielding materials in Fusion reactors (Bromberg et al., 2001). So, it is extremely important to study the gamma and neutron shielding effectiveness of the superconducting materials for readily available radiation characteristics. The mass attenuation coefficients, mean free path and effective atomic numbers are essential quantities required for studying the interactions, they depend on the incident energy and the nature of the absorbing material. In addition, the photon buildup factors (depends on energy, chemical compositions and thickness) are crucial parameters required for shielding effectiveness of a compound or mixture. In the fusion reactors, high-energy (≈ 14.1 MeV), high-intensity neutrons are produced during deuterium–tritium fusion reaction. The high-energy neutrons induce various reactions with construction materials of the fusion reactor for emission of gamma rays having energies up to 10–20 MeV (Kiptily et al., 2004).

Recently new superconducting materials such as non-centrosymmetric (NCS), iron-based and oxide-based have been discovered. NCS superconductors which lack inversion symmetry

* Corresponding author at: Department of Physics, Karnatak University, Dharwad 580003, India. Tel.: +91 8382264225.
** Corresponding author at: Institute of High Energy Physics, CAS, Beijing 100049, China. Tel.: +86 13693344534.
E-mail addresses: kudphyvps@rediffmail.com (V.P. Singh), medhatme@ymail.com (M.E. Medhat).

http://dx.doi.org/10.1016/j.radphyschem.2014.07.013
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Table 1
Chemical compositions of the investigated superconductors.

Chemical components (%)				
NCS superconductors		**Iron-based superconductors**		**Oxide-based superconductor**
$CaPtSi_3$ (CPS) ρ=4.48 g/cm^3	**$CaIrSi_3$ (CIS)** ρ=4.51 g/cm^3	**$Tl_{0.6}Rb_{0.4}Fe_{1.67}Se_2$ (TRFS)** ρ=5.28 g/cm^3	**$K_{0.8}Fe_{1.7}Se_2$ (KFS)** ρ=3.5 g/cm^3	$Bi_2Sr_2Ca_1Cu_2O_{8.2}$ (**BSCCO**) ρ=3.7 g/cm^3
Si (0.263784)	**Si (0.263784)**	**Fe (0.228589)**	**K (0.110082)**	**Ca (0.044952)**
Ca (0.125473)	**Ca (0.126607)**	**Se (0.387057)**	**Fe (0.334132)**	**Cu (0.142549)**
Pt (0.610742)	**Ir (0.6107226)**	**Tl (0.300563)**	**Se (0.555785)**	**Sr (0.196553)**
		Rb (0.083791)		**O (0.147151)**
				Bi (0.468794)

Table 2
Equivalent atomic numbers and G-P fitting parameters for CPS for photon energy 0.015–15 MeV.

Energy (MeV)	CPS					
	Z_{eq}	*a*	*b*	*c*	*d*	X_K
1.50E−02	61.762	0.246	1.003	0.335	−0.204	18.284
2.00E−02	62.706	0.191	1.005	0.397	−0.077	13.682
3.00E−02	63.748	0.241	1.015	0.326	−0.089	13.873
4.00E−02	35.500	0.157	2.625	0.326	−0.061	19.320
5.00E−02	35.817	−0.076	2.233	0.173	−0.029	12.360
6.00E−02	36.097	0.749	1.877	0.151	−0.143	15.892
8.00E−02	60.984	0.090	2.081	0.434	−0.098	16.118
1.00E−01	61.939	0.182	1.575	0.184	−0.003	17.954
1.50E−01	63.173	0.460	1.198	0.159	−0.254	13.820
2.00E−01	63.858	0.228	1.160	0.390	−0.121	14.180
3.00E−01	64.714	0.145	1.228	0.540	−0.067	13.795
4.00E−01	65.158	0.102	1.310	0.661	−0.055	14.219
5.00E−01	65.418	0.079	1.379	0.733	−0.046	14.147
6.00E−01	65.594	0.062	1.424	0.787	−0.037	13.740
8.00E−01	65.761	0.042	1.487	0.858	−0.029	13.694
1.00E+00	65.817	0.027	1.509	0.914	−0.023	13.485
1.50E+00	64.982	0.004	1.487	1.018	−0.018	14.040
2.00E+00	62.205	0.001	1.510	1.042	−0.020	13.133
3.00E+00	56.656	0.018	1.542	1.011	−0.044	13.372
4.00E+00	53.444	0.027	1.497	1.002	−0.053	13.588
5.00E+00	51.608	0.052	1.519	0.940	−0.077	13.755
6.00E+00	50.526	0.060	1.493	0.929	−0.085	13.942
8.00E+00	49.269	0.076	1.526	0.910	−0.098	14.159
1.00E+01	48.590	0.050	1.504	1.022	−0.072	14.185
1.50E+01	48.000	0.028	1.588	1.186	−0.057	13.969

Table 3
Equivalent atomic numbers and G-P fitting parameters for CIS for photon energy 0.015–15 MeV.

Energy (MeV)	CIS					
	Z_{eq}	*a*	*b*	*c*	*d*	X_K
1.50E−02	61.194	0.233	1.003	0.354	−0.185	17.515
2.00E−02	62.065	0.189	1.006	0.399	−0.075	14.050
3.00E−02	63.045	0.241	1.016	0.325	−0.089	13.880
4.00E−02	34.992	0.162	2.512	0.326	−0.064	18.974
5.00E−02	35.307	−0.055	2.154	0.186	−0.036	12.396
6.00E−02	35.574	0.715	1.826	0.165	−0.142	15.736
8.00E−02	60.541	0.067	2.077	0.410	−0.080	16.146
1.00E−01	61.269	0.244	1.562	0.165	−0.025	17.497
1.50E−01	62.448	0.449	1.197	0.167	−0.249	13.811
2.00E−01	63.100	0.225	1.163	0.396	−0.120	14.182
3.00E−01	63.904	0.143	1.234	0.544	−0.066	13.810
4.00E−01	64.360	0.100	1.318	0.666	−0.054	14.227
5.00E−01	64.638	0.078	1.387	0.739	−0.045	14.149
6.00E−01	64.802	0.060	1.433	0.793	−0.037	13.745
8.00E−01	64.979	0.040	1.495	0.864	−0.028	13.692
1.00E+00	65.045	0.025	1.517	0.921	−0.023	13.500
1.50E+00	64.226	0.003	1.493	1.022	−0.018	14.017
2.00E+00	61.316	0.001	1.517	1.043	−0.020	13.124
3.00E+00	55.869	0.017	1.540	1.016	−0.043	13.329
4.00E+00	52.788	0.025	1.492	1.008	−0.052	13.558
5.00E+00	51.006	0.050	1.508	0.947	−0.075	13.731
6.00E+00	49.962	0.059	1.478	0.933	−0.084	13.918
8.00E+00	48.781	0.077	1.526	0.908	−0.098	14.159
1.00E+01	48.141	0.050	1.504	1.018	−0.073	14.187
1.50E+01	47.568	0.029	1.587	1.182	−0.058	13.981